Neuroscience to Neuropsychology

The study of the human brain (Volume II)

Daniela Filipa da Silva Marques
José Hernando Ávila-Toscano
(Compilers)

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Academic Editors

Cognitive Neurosciences Section
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Historic-Cultural Neuropsychology Section
Yulia Solovieva, Ph. D.
Luis Quintanar, Ph. D.

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Phone: (+57) (5) 3610432 Ext: 536–537
Barranquilla
Special, Industrial and Harbor District
Atlántico–Colombia
www.unireformada.edu.co

ABOUT COMPILERS

Daniela Filipa da Silva Marques
Psychologist at the Universidade do Algarve (Portugal), Magister in Cognitive Neuroscience and Neuropsychology at the Universidade do Algarve (Portugal), Specialist in Child Neuropsychology of the Pontificia Universidad Javeriana-Cali (Colombia). PhD (c) in Psychology, Universidad Autónoma de Barcelona (Spain). Teaching Laboratory of Experimental Psychology at the Faculty of Psychology at the Universidad El Bosque (Bogota, Colombia). Researcher attached to the research group Cognitive processes and Education of the School of Psychology at the Universidad El Bosque (Bogota, Colombia). External researcher attached to the research group PSICUS (Psychology, Culture and Society) of the Corporación Universitaria Reformada (Barranquilla, Colombia). Junior Researcher classified by Colciencias.

José Hernando Ávila-Toscano
Director of research at the Corporación Universitaria Reformada (Barranquilla, Colombia); scientific leader of research group PSICUS (Psychology, Culture and Society); PhD (c) in Human and Social Sciences of Universidad Nacional de Misiones (Argentina); Master in Psychology Universidad del Norte (Colombia); psychologist of Universidad del Sinú (Colombia); Research Associate classified by Colciencias.

ABOUT ACADEMIC EDITORS

Cognitive Neurosciences Section

Alexandra Reis (Alexandra Isabel Dias Reis)
Associate Professor at the University of Algarve (Portugal) and researcher at the Cognitive Neuroscience Research Group, Department of Psychology & Center for Molecular and Structural Biomedicine, CBME / IBB, LA; Ph.D. in Biomedical (University of Lisbon, Portugal); Licentiate degree in Clinical Psychology, University Institute of Psychological Sciences, Social and Life, (Portugal); winning of Bayer Award of the Portuguese Society of Neurology (1996), Pfizer Research Prize (1999) and Ceratonia Award by the Algarve University and Caixa Geral de Depósitos (CGD) (2008).

Luís Faísca (Luís Miguel Madeira Faísca)
Researcher at the Cognitive Neuroscience Research Group, Department of Psychology & Centre for Molecular and Structural Biomedicine, CBME/IBB, LA, University of Algarve, Faro, Portugal; PhD in Experimental Psychology (University of Algarve, Portugal); MSc. in Probability and Licentiate degree in Psychology of University of Lisbon (Portugal).

Historical-Cultural Neuropsychology Section

Yulia Solovieva
Full-time research professor of the Masters in Neuropsychological Diagnosis and Rehabilitation of the Faculty of Psychology at the Benemérita Universidad Autónoma de Puebla (Mexico); Post-doctorate in neuropsychology (Universidad de Sevilla, Spain); Ph.D. Psychology (Faculty of Psychology of Moscow State University, Russia); Master and Bachelor of History (University of Humanities of the Russian Federation, Moscow).

Luis Quintanar Rojas
Full-time researcher and coordinator of the Master in Neuropsychological Diagnosis and Rehabilitation of the School of Psychology at the Benemérita Universidad Autónoma de Puebla (Mexico); He is visiting professor of the Master of Special Education of the Universidad Autónoma de Tlaxcala (Mexico); Post-doctorate in neuropsychology (Universidad de Sevilla, Spain); Ph.D. Neuropsychology (Moscow State University, Russia); Master in Psychobiology and Bachelor of Psychology (Universidad Nacional Autónoma de México).

BIOGRAPHICAL INDEX OF AUTHORS

Susana Silva
Faculty of Psychology and Educational Sciences, University of Porto (Portugal); Ph.D. in Sociology from the University of Porto; Master Sociology of Culture and Lifestyle and Sociologist of organizations (University of Minho); Senior researcher at the Institute of Public Health – University of Porto, in March 2014, coordinating the Department of Health and Society and the research group on Social Epidemiology; Professor on MSc courses at the Faculty of Medicine (University of Porto) and School of Law (University of Minho).

Karl Magnus Petersson
Director of the Center for Biomedical Research (CBMR), University of Algarve Faro (Portugal); Senior Scientist of Max Planck Institute for Psycholinguistics (Netherlands); Research fellow Donders Institute for Brain, Cognition and Behaviour (Netherlands); Invited Professor and Coordinator of the Cognitive Neuroscience (CNS) Research Group (Universidade do Algarve); Doctor of Philosophy (PhD), Cognitive Neuroscience, and Medical Doctor of Karolinska Institutet (Sweden); BSc, Mathematics and Physics of Stockholm University (Sweden).

São Luís Castro (Maria de São Luís de Vasconcelos Fonseca e Castro Schoner)
Professor at the University of Porto (Portugal), Faculty of Psychology and Educational Sciences, where he directs the Laboratory of Speech and Research Group at the Center for Psychology of Language; PhD in Experimental Psychology at the University of Oporto (Literacy and brain specialization for language); Aggregation Degree in Psychology

and Psychology of the University of Porto (language and experience); she has been Assistant Visiting Professor at Florida Atlantic University and member of the Editorial Board of the journal Current Psychology Letters: Behavior, Brain & Cognition and Reading & Writing (2002-2004).

Louis Renoult
Professor of School of Psychology in University of East Anglia (United King); PhD in neuosciencia, McGill University (Montreal, Canada); Post-doctoral researcher at the Rotman Research Institute (Baycrest, Toronto) and at the University of Ottawa from 2010 to 2013; Member of Cognitive Neuroscience Society (CNS), Heart and Stroke Foundation Centre for Stroke and Society for Neuroscience (SFN); His general interest is in the field of Cognitive Neuroscience of memory and more precisely in the characterization of the similarities, differences, and interactions between the semantic and episodic memory systems.

Alastair Smith
Research staff of Max-Planck-Institute for Psycholinguistics (Nijmegen, Netherlands); PhD (c) Max Planck Institute for Psycholinguistics; Masters by Research: Cognition and Computational Neuroscience University of Birmingham (United King); BSc, Mathematics, Computer Science & Psychology (Lancaster University, United King).

Falk Huettig
Associate Professor of Max-Planck-Institute for Psycholinguistics (Nijmegen, Netherlands); Research Fellow of Donders Institute for Brain, Cognition, and Behaviour (Nijmegen, Netherlands); Venia Legendi (Psychology), Habilitation, University of Münster (Germany); PhD in Psychology, University of York (England); MSc by Research (Psychology) and BSc Biological Sciences (Psychology), University of Edinburgh (Scotland); Visiting Professor of Centre for Neural and Cognitive Sciences, University of Hyderabad (India).

Susana Araújo
Cognitive Neuroscience Research Group, Department of Psychology & Centre for Molecular and Structural Biomedicine, CBME/IBB, LA, University of Algarve, Faro, Portugal.

Sara Pudas

Posdoctor at Department of Integrative Medical Biology, Umeå University (Sweden); PhD in Psychology of Stockholm University (Sweden); MSc in Cognitive Science of Umeå University, Unit of Psychiatry.

Nicola Canessa

Assistant professor of Vita-Salute University, Center for Cognitive Neuroscience —CCN— (Milano, Italy); Associate Professor, Cognitive Neuroscience of Institute for Advanced Studies (IUSS) (Pavia, Italy), Cognitive Neuroscience Unit, Division of Neuroscience, Ospedale San Raffaele; Ph.D. in Neuroscience (Department of Neuroscience, University of Parma, Italy); MSc. in Experimental Psychology and Neuroscience (Libera Università Vita-Salute San Raffaele. Italy).

Alessandra Dodich

Division of Neuroscience San Raffaele Scientific Institute (Milano, Italy); PhD (c) International Graduate School in Molecular Medicine, Center for Cognitive Neuroscience (Vita-Salute San Raffaele University, Italy); Laurea Specialistica Neuroscienze Cognitive (Libera Università Vita-Salute San Raffaele, Italy); BSc in Psychological, Cognitive and Psychobiological Sciences (Università degli Studi di Padova. Italy).

Chiara Crespi

Vita-Salute San Raffaele University (Milano, Italy); Cognitive Neuroscience of Institute for Advanced Studies (IUSS) (Pavia, Italy); PhD in Neuroscience and MSc. in Cognitive Neuroscience of Libera Università Vita-Salute San Raffaele (Italy); BSc in Psychology (Università degli Studi di Milano-Bicocca, Italy).

Stefano F. Cappa

Dean of Psychology, Vita-Salute San Raffaele University (Milan, Italy); Director of Neurology, San Raffaele Turro Hospital (Milan, Italy); Professor of Cognitive Neuroscience of Institute for Advanced Studies (IUSS, Pavia, Italy); PhD in Medicine and Surgery, cum laude, and Specialist in Neurology, cum laude, Università Statale (Milan, Italy).

Janna Glozman
Professor in the Psychology Department of Moscow State University and Scientific Director of the Center of Developmental Neuropsychology; PhD in Psychology, Lomonosov Moscow State University (Moscow, Russia); Linguistics from Moscow Linguistic University, and later graduated as well on memory troubles in local brain damages (supervised by A.R. Luria) at the Psychology Department of Moscow University; Member of the Russian Psychological Association, American Biographical Institute Research Board of Advisors, International Committee of the International Neuropsychiatric Association, Honorary Member of the Polish Neuropsychological Society.; Emerite Scientist of Moscow University; Decorated with the Prime of Vygotsky from the Portuguese Association “Lev Vygotsky in Education”, 2010. Medal of Chelpanov, 2014.

Tatiana Akhutina
Director Laboratory of neuropsychology, Department of Psychology, Lomonosov Moscow State University; PhD in Psychological sciences, Moscow Pedagogical State University.

Elena Karimulina
Assistant Professor Moscow State University of Psychology and Education (MSUPE), Department of Clinical Psychology and Psychology of Special Needs.

Natalia Zvereva
PhD in Psychology; Senior Research Fellow; Professor Department of Neuro and Pathopsychology, Faculty of Clinical and Special Psychology, Moscow State University of Psychology and Education; Senior Research Fellow, Department of Medical Psychology, Research Center of Mental Health, RAMS, Moscow, Russia.

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Preface

In the last decades, interest and development of investigations referred to *Neurosciences* and *Neuropsychology* has increased worldwide.

In the field of *Neurosciences*, the role of *Cognitive Neurosciences* has underlined the understanding of brain functioning. On the other hand, *Neuropsychology's* thematic streams such as *Cognitive Neuropsychology* and *Historical-Cultural Neuropsychology* have contributed to the study of human behavior and its connection with superior cognitive processes.

Cognitive Neuropsychology is a trend mostly used by American and European classical schools. *Historical-Cultural Neuropsychology* has its roots in the Russian neuropsychology school, from A.R Luria and L. Vigotsky's theoretical and methodological postures.

Nowadays it is difficult to find specialized material that integrates recent investigations made in the aforementioned areas. Which gives the work "*Neuroscience to neuropsychology. The study of the human brain*" an unique character.

This book arose from the idea of integrating works around *Neurosciences* and *Neuropsychology* in the same writing, allowing the reader to identify complementarity among current work topics. Nevertheless, the conception of such idea would have never been possible without the support of many professionals who are specialized in each of the fields presented.

This work is organized in two volumes, the first one written in Spanish and Portuguese, the second one in English, thereby maintaining the original language of the chapters received in every section. Important thematic editors supported this work´s development, finally organizing this work in three fields: *Cognitive Neuropsychology* (Volume I), *Historical-Cultural Neuropsychology* (Volume I, II) and *Cognitive Neuroscience* (Volume II).

In *Cognitive Neuropsychology*, Drs. José Góis Horácio and Naide Ferreira were invited. Both of them specialized in the field of cognitive neuropsychology and currently work at Egas Moniz hospital in Lisboa, Portugal. They not only have nationally contributed in the formation of neuropsychologists but also have supported the development of neuropsychology as a science.

Drs. Yulia Solovieva and Luis Quintanar from Benemérita University (Puebla, Mexico) supported *Historical-Cultural Neuropsychology* section. They teach in postgraduate degrees at the same university and many other postgraduate degrees all over South America. Both of them have over 20 published books in this field and have contributed actively in the diffusion of *Historical-Cultural Neuropsychology* nationally and internationally.

In *Cognitive Neurosciences* field, we considered Drs. Alexandra Reis and Luis Faísca as ideal people to coordinate this section. They are professors at Do Algarve University (Faro, Portugal). They also lead the Cognitive Neurosciences research group at the same university. Both of them have made important contributions to this field nationally and internationally.

We thank all of the thematic editors for having embraced this idea and for every important contribution in order to develop it jointly. This way, this work includes fresh, innovative investigations from authors in nine countries, such as: Colombia, Portugal, Mexico, Spain, Russia, Sweden, Holland, United Kingdom and Italy.

We also highlight the support provided by the editorial group of *Corporación Universitaria Reformada* (Barranquilla, Colombia) for their unconditional availability in the achievement and completion of the work.

We are confident that this work will be of great importance in the fields of neuroscience and neuropsychology. Likewise, we hope you enjoy reading it as much as we enjoyed its construction.

Daniela da Silva Marques

Section

1

Cognitive Neurosciences

Alexandra Isabel Dias Reis, Ph.D.
Luis Faísca, Ph.D.
Academic Editors

Rhythm in the brain: Is music special?

Susana Silva
Karl Magnus Petersson
São Luís Castro

Introduction

Whether music and language are processed using the same neural resources is an important question in cognitive neuroscience, since it taps into the architecture of human brain. It is also an important question for applied science, namely for transfer approaches that explore the benefits of musical practice to language skills (e.g., Besson, Chobert & Marie, 2011).

The state-of-the-art is mixed. While patient studies have mostly pointed to non-shared resources (Dalla Bella & Peretz, 1999; Peretz, 1993; Peretz & Coltheart, 2003), fMRI and EEG studies have found evidence of common substrates (Koelsch, Gunter, Wittfoth, & Sammler, 2005; Koelsch, Schmidt, & Kansok, 2002; Maess, Koelsch, Gunter, & Friederici, 2002; Patel, Gibson, Ratner, Besson, & Holcomb, 1998; Vuust, Wallentin, Mouridsen, Østergaard & Roepstorff, 2011), though there are exceptions (e.g., Fedorenko, McDermott, Norman-Haignere & Kanwisher, 2012). The investigation of resource overlap has focused on global structure (e.g., structural integrity in original vs. scrambled music-language materials) as well as on musical harmony related to linguistic syntax. The rhythmic subdomain, related to strictly temporal aspects, has remained comparatively unexplored (Fitch, 2013; Peretz, 2003).

Recent approaches suggest that rhythm, more than pitch, may be a key link between music and language (Hausen, Torppa, Salmela, Vainio & Särkämö, 2013), as well as a crucial dimension to understand language disorders such as dyslexia (Goswami, 2011). This is in line with Lehrdahl's (2003) proposal of shared resources for rhythm but not for pitch, but at odds with the possibility of a modular treatment of music rhythm (Peretz & Coltheart, 2003). There is one *a priori* reason to accept that music and speech rhythm may recruit different resources, and the reason is that the two domains have fundamentally different structures. Music rhythm is typically isochronous, while speech rhythm is typically not.

Music Rhythm, Isochrony and Hierarchy

Rhythm is a "dangerously polysemic" word (Fitch, 2013) requiring definition. Here we refer to *rhythms* (plural intended) as series of time intervals between events in a sequence, or the equivalent to the ordered onset asynchronies of those events. One rhythm is a particular sequence of time segments. Rhythms are infinitely diverse and they form the temporal *surface* of the sequential input from which structure may be extracted.

The underlying structure of music rhythms (Figure 1.1) is typically isochronous (Nettl, 2000), meaning that it is made of evenly-paced events. The *isochrony* of music rhythms appears at more than one level. At the lowest one, it describes the feeling of *pulse*, such that one claps or taps the foot to music. At higher levels, isochrony is linked to the perception of a salient pulse at regular (every n pulses, 1st, 3rd, 5th, 7th) or irregular (e.g., 1st, 3rd, 6th, 8th, 11th pulse) intervals. Because salient pulses drive dancers to lay their feet on the ground, they are referred to as *downbeats*, while non-salient pulses are *upbeats*. The intervals between downbeats are named *bars*. High-level isochrony describes the *meter* of one stimulus, which may persist even when downbeats are irregularly spaced. In the exemplified irregular meter, typical of Balkanic music, regular cycles of five beats (1st, 6th, 11th) superimpose on the irregular 2-3-2-3 sequence. Once pulses are framed by meter, they enter a hierarchical organization and are referred to as *beats* (Fitch, 2013).

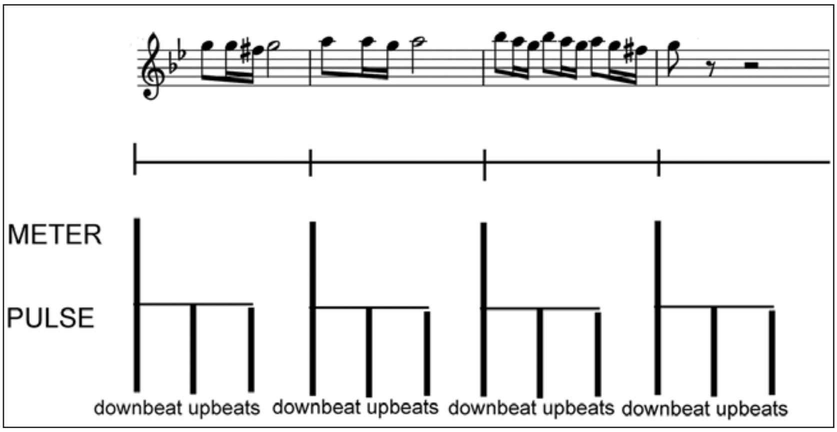


Figure 1.1. Melody with triple meter (3 beats per bar).

Source: The autors.

Although the isochronous time structure of a musical piece may be explicit (e.g., the bass drum in electronic "house music" style) and thus be part of the surface, it usually has to be inferred. Inferences rely on the conjoint organization of musical events (Fitch & Rosenfeld, 2007), meaning that new musical events tend to take place either at the pulse/bar onset, or at time points that form simple ratios with the pulse/bar duration. For example, the onset of a new sound at 1/2, 3/4, or 3/2 of a beat is frequent, but onsets at 1/7 or 22/21 are not. Chord changes, as well as rhythmic repetitions usually take place at the downbeat or at 1/2 bar in double (2 beats) or quadruple (4) meters.

The perception of pulse and meter require the ability to *infer structure* from the musical surface as well as a basic *timing* skill for perceiving or generating evenly-paced events. Patient studies indicate that timing skills may be spared when inference is impaired (Phillips-Silver et al., 2011). Both timing and inference allow the synchronization of movement to isochronous input, the three abilities combining into the *beat perception and synchronization* skill (Patel, Iversen, Bregman & Schulz, 2009; see Repp & Su, 2013, for a review on the related concept of sensorimotor synchronization). The beat perception and synchronization skill is not exclusive of humans. Some species seem able to synchronize to the pulse (Hasegawa, Okanoya, Hasegawa, & Seki, 2011, findings in budgerigar parrots), even when it has to be inferred from a musical context (Cook, Rouse, Wilson & Reichmuth, 2013, California sea lion; Patel et al., 2009, the Sulfur-Crested Cockatoo). Some features of BPS seem to be optimized in human synchronization, namely prediction, flexibility of tempo (the frequency of pulses) and cross-modality (Fitch, 2013, Patel, 2014).

Besides timing and inference, musical meter requires *hierarchical processing of isochrony*. Sequences are hierarchically structured when they can be represented as trees, the prominence of each event being determined by the tree level it belongs to, and not by serial order. Applied to musical meter, this means that metrically salient beats (the downbeats) occupy an additional, higher tree level compared to other beats. Downbeats may be seen as *heads* of trees, and bars as head-initial trees (Fitch, 2013). Typically, paradigms for studying the hierarchical processing of music rhythm place unexpected events at more than one level in the tree and compare responses across the two types of violations. For example, Geiser, Sandmann, Jäncke and Meyer (2010) placed accented tones either at the downbeat (higher-level in the tree) or an upbeat (lower-level), and compared the Mismatch Negativity (MMN) component of the electroencephalographic (EEG) sinal (Näätänen, Gaillard & Mäntysalo, 1978) across the two conditions. While musicians showed an increased MMN for upbeat accents, the down- vs. upbeat responses of non-musicians were indistinguishable, indicating reduced hierarchical processing in the latter. The paradigm developed by Honing and colleagues (see

Honing, 2012, for a review) manipulates the position of an omitted sound, such that omissions at weak metrical positions (upbeats) are compared to downbeat omissions ("loud rests") by means of the MMN response. Sensitivity to downbeat vs. upbeat levels was shown in adults without musical training (Ladinig, Honing, Háder & Winkler, 2009), as well as in newborns (Winkler, Háden, Ladinig, Sziller & Honing, 2009). Interestingly, this paradigm brought no evidence of hierarchical processing of rhythm in Rhesus monkeys (Honing, Merchant, Háden, Prado & Bartolo, 2012), although these non-human primates responded to omission and showed evidence of rhythmic grouping.

Hierarchical or not, isochrony affords to predict the temporal structure of events ("when something will happen"), and theoretical frameworks in cognitive science have acknowledged the importance of predictability in brain function. The framework of dynamic attending (Jones & Boltz, 1989) stresses how the temporal predictability of the input stems from temporal coherence, and shapes attentional modes. A future-oriented mode (attending to event endings) is favored by highly coherent inputs, and an analytical mode (attending to the local density of events) by less coherent ones (ibidem). Predictive coding (Friston, 2002) highlights top-down processing, and it stresses the continuous evaluation of the input's error term compared to predictions. In both views, lack of isochrony is relevant: it may determine a processing mode or increase the error term, with significant impact on brain activity.

In contrast to music rhythms, speech rhythms are not fundamentally isochronous (Patel, 2003). The early classification of languages as syllable-timed (e.g., French) or stress-timed (e.g., English) by linguists (see Dauer, 1983, for a review) suggested that an analogous of the pulse could be found in the intervals between syllables or between syllables carrying word-level stress. However, there is no evidence of isochrony in any of these cases (Roach, 1982). References to music *rhythm* and speech rhythm capture the fundamental differences between both systems and we will use them from now on in this sense.

In sum, music rhythm is isochronous and speech rhythm is not. Differences in the predictability of events across the two domains are expected, with possible impact on brain function. But do these differences really matter? Are they strong enough to support the claim of dedicated neural resources for processing music rhythm, meaning that at least some resources are not shared with language processing? In the first part of this chapter (Isochrony matters), the extent to which isochrony is relevant to the human brain will be assessed in three ways. First, isochrony is likely to be relevant if it has played an adaptive role throughout evolution. Current hypotheses suggest that it did, by allowing the synchronized movement of group members. Second, isochrony is relevant if brain signals respond to it in a significant manner, and if this can be related to a movement function. Third, isochrony is relevant if little or no experience is required for processing it, and if experience-independent skills can be related to movement. We also present the main findings from two of our studies, suggesting that structural isochrony may dissociate phrase perception in music from that in speech, and that the perception of music phrases may recruit dedicated resources. In the second part of this chapter we present the alternative view (Isochrony does not matter), stating that strict isochrony is not relevant to the brain, and music and speech rhythms recruit neural resources that are similar in essence.

Isochrony Matters

The function: isochrony affords cooperative action

Early hypotheses on the evolutionary role of beat perception and synchronization suggested it might be a by-product of emerging auditory-motor brain networks sustaining vocal learning (Patel, 2006; Patel et al., 2009). An alternative hypothesis proposed that beat perception and synchronization itself was adaptive because it facilitated cooperative action, vocal or not (Merker, Madison & Eckerdal, 2009), and it is in line with demonstrations of beat synchronization in non-vocal learning species (Cook et al., 2013). Laboratory studies support this view. Bowling, Herbst and Fitch (2013) asked participants to read text aloud with and without partners, and found higher levels of temporal regularity (evenly-paced events) in collective reading. This is consistent with the idea that isochrony of music rhythm is a response to the synchronization goals of a group.

The cooperative action hypothesis credits music rhythm (instead of, e.g., organized pitch) for facilitating movement in the context of musical behavior. If this is true, one might expect that motor responses are greater to isochrony than to any other musical property (e.g., melodic contour, harmony). Indeed, the experience of being physically driven by music is frequently reported by humans, and it is attributed to the beat. A recent study investigated this in the laboratory setting (Dalla Bella, Białuńska & Sowiński, 2013). Participants engaged in a synchronization task were distracted with music or with metric speech. The two kinds of distractors were thus matched for metric properties, while differing in music-specific pitch-related content. The two distractors were equally effective in disrupting performance, showing that music's superiority in driving movement is due to isochrony *per se*, and not to some other music-specific trait.

Brain substrates for isochronous input

Different brain areas for isochronous vs. non-isochronous input

The activation of motor-related areas of the brain during the perception of music rhythm (beat-based), but not during speech-like (nonbeat) rhythm (see Grahn, 2009, 2012, for a review) support the hypothesis of dedicated brain networks for isochronous rhythm. The basal ganglia and the supplementary motor area showed enhanced activation for perceived beat-based rhythms compared to nonbeat ones (Grahn and Brett, 2007). The basal ganglia seem to be *necessary for*, and not just activated in beat processing, since beat facilitates discrimination in healthy subjects, but not in Parkinson Disease patients (Grahn & Brett, 2009). The functional coupling between the basal ganglia and cortical motor areas is also higher for beat-based rhythms (Grahn & Rowe, 2009). The basal ganglia are thought to encode information about beat timing that facilitates cortical motor areas in precise control of movement timing, if movements are to be made in time with beats.

Similar to nonbeat (speech-like) stimuli failing to activate motor areas, reports of motor activations while listening to ecologically valid speech are not robust, and they seem to be restricted to conversational turn-taking (Scott, McGettigan & Eisner, 2009). Overall, these findings suggest that humans are hard-wired to process music rhythm with specific resources, serving the specific goal of driving synchronized movement.

Oscillatory responses to isochrony

Processing isochronous time seems to be well accounted for by the basic physics of neural system (Large, 2008; Large & Snyder, 2009). However, the transfer to non-isochronous time is not trivial, as we will see. The neural resonance theory proposes that the perception of pulse and meter involve the phase-locking of spontaneous brain oscillations to the temporal features of the ongoing periodic stimuli. Basic resonance entails locking to the pulse, and a high-order resonance accounts for meter perception. The theory was built to account for music rhythm. Approaches to non-periodic signals went as far as considering that continuous tempo tracking would be necessary to account for the occasional deviations from isochrony that are present in musical performances (Large, 2008). Therefore, the resonance theory did not try to account for the perception of non-isochronous time in speech rhythm.

Evidence in favor of the resonance approach includes neural activity that is sensitive to metrical structures (Large, 2008). Indirect evidence relies on the principle that the neuronal entrainment to the pulse/bar cycles is associated to cyclic levels of excitability in the entrained neuronal population, which in turn modulates the amplitude of event-related potentials that can be generated at different points (Nozaradan, Peretz, Missal & Mouraux, 2011). Therefore, ERPs to sound events at the pulse/downbeat onset (higher excitability of the neural population) should be enhanced compared to sound events in other events within the cycle. For example, Tierney and Kraus (2013a) compared the P1, N1 and Auditory Brainstem Responses (ABR) to sounds aligned with the pulse of ecologically valid music with the responses to shifted, unaligned, sounds, while subjects tapped to the music pulse. They observed enhanced ABR/P1 responses and decreased N1 for aligned stimuli. Direct evidence of neural resonance arises from features of the EEG signal that replicate, in real-time, the ongoing pulse/meter structure. Nozaradan et al. (2011) found that a beat stream of 2.4 Hz elicits high-amplitude oscillations in that frequency band, but not in 0.8, 1.2 or 1.6 Hz bands. Also, brainreading approaches based on the multivariate analyses of the continuous EEG signal showed successful identification of particular pieces of music (Schaefer, Farquhar, Blokland, Sadakata & Desain, 2011), including specific indices for violations of metrical expectations.

The neural resonance theory addressed auditory-motor coupling in its origins. Resonance was proposed to result from rhythmic bursts of high-frequency neural activity (beta and gamma oscillations), which would enable communication between neural areas such as auditory and motor cortices (Large, 2008; Large & Snyder, 2009). Further studies were consistent in showing the auditory-motor implications of resonance. Fujioka, Trainer, Large and Ross (2012) analyzed the variations in amplitude and coherence of beta oscillations (>20 Hz) in response to musical stimuli of different tempi. An enhanced response immediately before the pulse onset was observed, suggesting that beta oscillations, which are linked to sensorimotor coordination, maintain predictive coding and reflect auditory-motor coupling. In Tierney and Kraus's study (2013a, see also 2013b), tapping accuracy correlated with the size of the EEG responses to stimuli aligned with a musical context, suggesting that overlapping resources underlie both auditory and motor entrainment to music. In sum, the neurophysiological substrates for the perception of music rhythm seem to be domain-specific and, once again, linked to movement.

Independence from experience: development and expertise

Music rhythm seems to be special in the infant's brain, and links with movement are also present. Based on recent developmental findings, Honing (2012) suggested that the processing of music (isochronous) meter may be a fundamental cognitive mechanism, and several early pulse and meter-related abilities have been documented in the literature (see Stalinski & Schellenberg, 2009, for a review). Pulse-related skills include the ability to discriminate isochronous from non-isochronous sequences of tones, which has been observed in 2-month-old infants (Demany, McKenzie & Vurpillot, 1977). This finding is crucial to our point in that it suggests that humans may be hard-wired to process isochrony with specialized resources. Meter abilities, implying both isochrony and hierarchy, seem to be particularly strong. Newborns are sensitive to sound omissions at the downbeat (Winkler et al., 2009). At 7 months, they are able to discriminate between double (2 beats) and triple (3 beats) meters (Hannon & Johnson, 2005). The metrical context seems to play an important supportive role in infants' extraction of musical information. At 9 months, infants more readily detect rhythmic disruptions in strong meters compared to weak ones (Bergeson & Trehub, 2006). Direct comparisons between 6-month-old infants and adults showed that the retention of pitch information benefits from metrical strength in infants but not in adults (Trehub & Hannon, 2009). Altogether, this evidence supports the hypothesis that infants use metrical structure to bootstrap their acquisition of musical knowledge (Hannon & Johnson, 2005).

The amount of musical knowledge at early stages, including meter knowledge, inspired the hypothesis of a Music Acquisition Device (Levitin & Tirovolas, 2009) paralleling the Language Acquisition Device (LAD) proposed by Chomsky. Two additional phenomena in infants' perception of music rhythm strengthen the parallel: a universal matrix of contrasts and tuning. The idea of a *universal matrix of contrasts* states that early sensitivity is restricted to relevant variations for humans. Similar to language, where infants' broad sensitivity does not extend to arbitrary non-phonetic sound contrasts (Werker & Lalonde, 1988), infants do not process any kind of metric contrast.

For example, 5-month-old infants do not discriminate highly complex meters, not used in any culture (Hannon, Soley & Levine, 2011). *Tuning* is the sensitization to cultural-specific traits, like regular vs. irregular meters in Western vs. Balkanic culture respectively, and it is seems to be present at 12 months (Hannon & Trehub, 2005) or even earlier (Soley & Hannon, 2010). Although changes implied in the tuning process are particularly fast in the first year of life, 5-year-old children still show an advantage compared to 11-year-old ones in acquiring knowledge of unfamiliar metrical structures (Hannon, Vanden Bosch der Nederlanden & Tichko, 2012). Tuning (early) and acculturation (later) processes might be fostered by focused exposure to culture-specific musical traits (Gerry, Faux & Trainor, 2010). Conversely, familiarity with varied metrical structures enhances adults' sensitivity to the metrical organization of unfamiliar music (Kalender, Trehub & Schellenberg, 2013).

An aspect of infants' abilities which is also crucial to our point is the early link with movement. There is evidence that music is more powerful than speech in eliciting regular movements in infants (Zentner & Aerola, 2010). Conversely, externally-induced periodical bouncing shapes infants' preferences for certain metric structures (Phillips-Silver & Trainor, 2005).

Musical expertise: a case against the isochronous brain?

Evidence of processing advantages in musicians compared to non-musicians are somewhat contradictory to developmental findings, as they might imply that extensive experience would be required in order to make the brain sensitive to certain kinds of input ("soft-wiring"). Such evidence is available in respect to music rhythm.

Some findings are not strictly contradictory, since they point to refinement processes in musicians, linked to atypical and often language-like brain networks. Vuust et al. (2005) measured and source-analyzed the MMN response to subtle meter deviances in musicians and nonmusicians. Results indicated a left-lateralization of the MMN in musicians, contrasting with the right-lateralized response of laypersons. This suggests either a principle wherein significant features become left-lateralized or the integration of temporal processing in music into a "native-language network". The pattern was replicated in a later experiment (Vuust, Ostergaard, Pallesen, Bailey & Roepstorff, 2009), where strong metrical incongruity elicited MMN and P3a responses in both groups, the MMN being left-lateralized in musicians. The EEG of musicians also showed better discrimination of subtle violations.

Other findings indicate that expertise may be required to process relatively simple aspects of music rhythm, although the evidence is mixed. In favor of expertise-independence, Ladinig et al. (2009) showed a pre-attentive ability of meter processing (sensing "loud rests") in non-musicians. Geiser, Ziegler, Jancke and Meyer (2009) observed behavioral differences between musicians and laypersons in response to attended meter incongruities (change in the length of the bar), but no differences in the amplitude of ERPs, despite small changes in topography. This indicates that meter processing does not require long-term practice. However, a different experimental manipulation (placing accents either in upbeats or downbeats) revealed differences between the two groups in metric discrimination (Geiser et al., 2010). Importantly, laypersons showed no evidence of metrical cognition in this task, since their sensitivity to accented up- and downbeats was equivalent. Considering that newborns sense loud rests (Winkler et al., 2009) and infants discriminate between meter types (double vs. triple, Hannon & Johnson, 2005), the lack of sensitivity to metric cycles in adult non-musicians seems puzzling. Also, and differing from the expertise-independent activation of the motor cortex during beat perception (Grahn & Brett, 2007), activation of motor areas (supplementary motor area and middle-posterior cingulate cortex) during the perception of meter-related deviance (harmonic change in weak beats) seems to depend on long-term experience (James, Michel, Britz, Vuilleumier & Hauert, 2012). Confronted to the early link between the perception of music rhythm and movement (Zentner & Aerola, 2010), such findings again seem surprising.

One possibility is that such contrasting findings stem from methodological artefacts, since the tasks used to investigate infants and adult non-musicians differ substantially. However, a pattern seems to be present, in that non-musicians show weak abilities when hierarchical processing of isochronous time (meter) is involved, and not so much concerning pulse. Interestingly, a similar picture is found in non-human species, where pulse abilities are found, but hierarchical cognition seems to be absent (Fitch, 2013; Honing et al., 2012). One speculative possibility is that the hierarchical aspect (meter) dissociates from purely pulse-related abilities in the human brain. Pulse processing may serve a fundamental, movement-related function in evolution, while meter may be linked to language acquisition, possibly as a bootstrapping device. This would account for null findings in other species, and for the apparently increased abilities of infants compared to adult non-musicians.

Isochrony in phrase perception: is music special?

Structural similarities in the phrase structure of music and speech (e.g., boundary silence, pre-boundary lengthening) inspired the comparative investigation of EEG responses to phrase boundaries in music and speech (Knoesche et al., 2005; Nan, Knoesche & Friederici, 2006, 2009; Nan, Knösche, Zysset & Friederici, 2008; Neuhaus, Knoesche & Friederici, 2006). Findings of a similar EEG marker, the Closure Positive Shift, were interpreted as evidence that phrase structure processing is a cognitive function shared by music and language (Nan et al., 2009). In order to contribute to discussion on this interpretation, we focused on the structural aspects of music that do not seem to be shared with speech, that is, hierarchical isochronous structure. A well-known hypothesis in the musicological literature is that listeners use metric information to do phrase boundary prediction, and that a phrase ending is expected at every four bars. In two different studies, we investigated how this isochrony-related feature, the 4-bar structure, may shape phrase perception in music.

In a first study (Silva, Barbosa, Marques-Teixeira, Petersson & Castro, 2014), we used a violation paradigm to compare responses to a musical boundary pause with those to an omitted boundary (violation, Figure 1.2). Differences between the conditions, particularly those involving indices of expectancy violation, would indicate that listeners predict the phrase ending. We observed theta/beta increases in power, as well as an enhanced P2 in the violation condition, suggesting that a phrase boundary was indeed expected. Although the experiment did not test for bases of prediction other than the 4-bar length, the results were consistent with the musicological hypothesis.

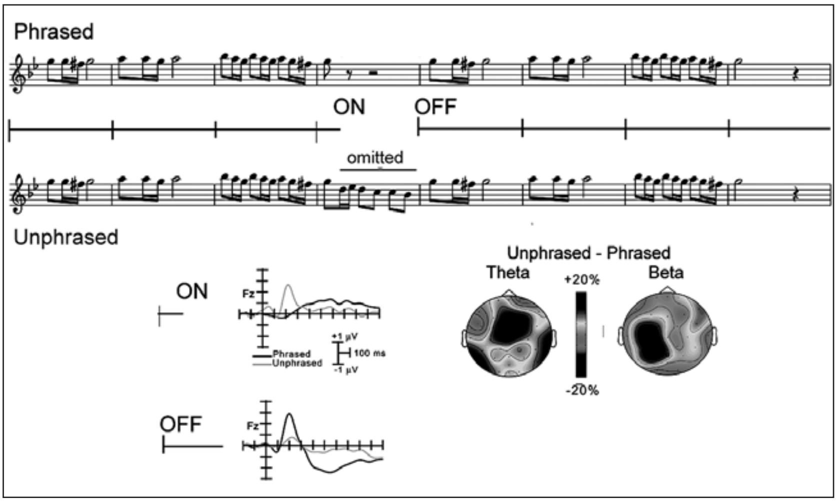


Figure 1.2. Example melodies and results from testing boundary prediction. In the unphrased condition, the boundary is omitted and filled with tones. These tones violate the expectation of a boundary pause. Comparisons between the onset of the pause and the onset of the filling tones (ON) showed increased theta and beta power for unphrased melodies, as well as an increased P2 component. At the offset of filling tones (OFF) the P2 is significantly decreased.

Source: Silva et al. (2014).

In a different study (Silva et al., under review), we compared responses to phrases containing either 4 fours bars (standard Western phrase), 3 bars, or an intruder segment (scrambled phrases). Intruder segments constitute violations of phrase structure. We wanted to test if a 3 bar phrase is perceived as a violation of the standard 4-bar phrase. Responses to standard 4-bar phrases differed from both 3-bar and scrambled phrases (Figure 1.3), suggesting that the metric length (number of bars) is a structural property that shapes phrase perception as much as structural integrity.

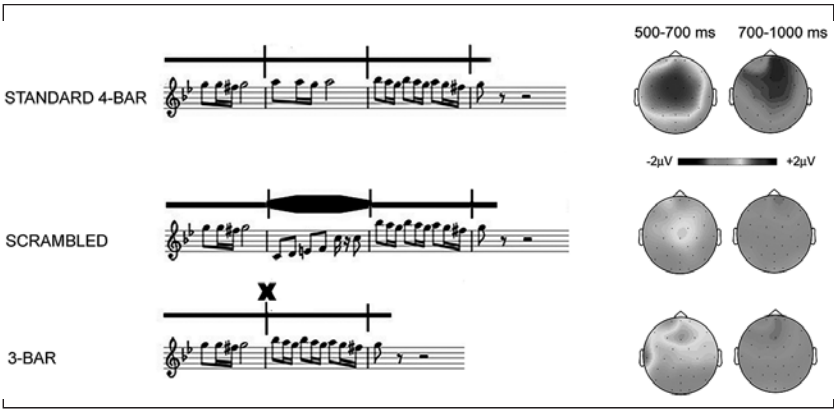



Figure 1.3. ERPs to the offset of different types of musical phrases. Four-bar phrases elicited larger amplitude responses than both scrambled and 3-bar phrases.

Source: Silva et al. (2014).

Both studies suggest that the hierarchical isochrony of the input modulates the perception of phrase structure in music. Because the processing of hierarchical isochrony seems to rely on specific brain networks, our studies provide indirect evidence that the amount of neural resource sharing in the perception of music and speech phrases may not be total, and that music may involve specific networks.

Isochrony does not Matter

An alternative approach to the relation between rhythm in music and in speech rhythm is viewing them as fundamentally similar, despite differences in isochrony. Some empirical findings support this view. For example, the perception of speech prosody correlates with rhythm, but not pitch-related abilities in music (Hausen et al., 2013). Participants were asked to judge deviances from isochrony in a music task, and to identify stress patterns in sequences of non-isochronous syllables differing in duration, pitch and intensity. The correlation suggests that judgments on the duration of both isochronous and non-isochronous events recruit common resources. We now review some current arguments for paralleling speech rhythm with language processing.

Music rhythm and language syntax

It has been suggested that music rhythm is akin to linguistic syntax, since both are hierarchically structured. The idea of hierarchical processing has been inspiring comparative research on linguistic syntax and musical (tonal) harmony for a number of years (Koelsch et al., 2002, 2005; Maess et al., 2002; Patel et al., 1998). Recently, Fitch (2013) proposed extending the parallel to rhythm, based on the argument that the multilevel structure of music rhythm constitutes “trees in time” (see introduction). Notwithstanding the potential of this approach, it steps over the fundamental question of whether music rhythm parallels *speech rhythm* in the brain.

Music rhythm and metrically regular speech

A direct approach to the relation between speech and music rhythm relies upon the possibility of *metrical regularity* in speech. Although speech is not isochronously structured, some utterances may be metrically regular, in the sense of comprising a regular distribution of stressed and unstressed syllables. A few studies have highlighted the role of metrical regularity in language comprehension. Rothermich, Schmidt-Kassow and Kotz (2012) found smaller N400 amplitudes to words in metrically regular sentence contexts (“‘Norbert ‘pflückte ‘letzten ‘Dienstag ‘Ginas ‘*Ro*sen und ‘Nelken.”, where ‘ denotes stressed syllables and italics the target syllable), compared to metrically irregular ones (“‘Norbert ‘pflückte ‘letzten ‘Dienstag ‘Ginas *Ro*’sen und ‘Nelken.”). This suggests that the possibility of predicting stress patterns (regular contexts) facilitates lexico-semantic integration, and that rhythmic regularity modulates language comprehension. By using a similar manipulation (congruent vs. incongruent word stress in a sentence context), Schmidt-Kassow and Kotz (2008) showed that meter interacts with syntax. Direct evidence of shared resources has been provided by Marie, Magne and Besson (2010), who found that musicians have an advantage over non-musicians in detecting metric violations in speech. The parallel is limited, since it applies only to instances of metrically predictable speech utterances. Nevertheless, it highlights a common mechanism, related to context-based prediction.

Music and speech rhythm as non-random signals

Although speech rhythm is not strictly isochronous, some approaches build on the assumption that it is not random (Peelle & Davis, 2012) and thus entails some predictability. Based on evidence of rhythmic difficulties in language-impaired populations (Corriveau & Goswami, 2009; Huss, Verney, Fosker, Mead & Goswami, 2011; Thomson & Goswami, 2008), Goswami (2011) has recently proposed the temporal sampling framework for developmental dyslexia. The approach suggests that the encoding of speech at different frequencies by neuroelectric oscillations may be impaired in dyslexic subjects. Speech frequencies in the delta (1.5-4 Hz), theta (4-10 Hz) and gamma (>20 Hz) range are thought to be crucial for encoding speech signals at the level of phrase or word stress, syllable and phoneme, respectively. Impairments in dyslexic subjects may be specifically related to the low delta and theta frequencies (ibidem), but there is also evidence that the problem may lie at the level of cross-frequency coupling, that is, the simultaneous encoding of syllabic (theta) and other types of information (Leong & Goswami, 2011). The approach was based on the multi-time resolution model of Poeppel and colleagues (Giraud & Poeppel, 2012), who proposed that brain oscillations *track* speech at different structural levels, by phase resetting of the corresponding frequencies.

Although the temporal sampling/multi-time resolution approach seems promising in terms of intervention (Thomson, Leong & Goswami, 2013), the exact underlying mechanisms remain untested (Protopapas, 2014), namely the extent to which non-isochrony may drive oscillatory entrainment. The multi-time resolution model proposes that neurons track the modulations in speech even when they are not fully periodic (Giraud & Poeppel, 2012), thus minimizing the relevance of strictly isochronous input. However, demonstrations of speech tracking by neural oscillations have relied on the increased phase similarity (coherence) of EEG trials locked to a common speech sentence, compared to the phase coherence of trials from different sentences (Luo, Liu & Poeppel, 2010; Luo & Poeppel, 2007; Zion Golumbic et al., 2013). The similarity between the structure of particular speech utterances and the corresponding oscillatory patterns has, to our knowledge, remained untested, as well as the mechanisms for continuous phase resetting required by non-isochronous input. In line with this, the experiments carried out by Goswami and colleagues have measured EEG and behavioral responses to speech either with metric speech (Leong & Goswami, 2014a; 2014b; Power, Mead, Barnes & Goswami, 2012), or abstract, modulated signals (Hämäläinen, Rupp, Soltész, Szücs & Goswami, 2012), and not with natural speech. Therefore, and to our knowledge, no direct evidence of entrainment to non-periodic speech sounds has yet been provided, at least in the same way that it has been done for music isochronous input (Nozaradan et al., 2011). A cyclic and not necessarily periodic structure may form the key link between music and language, but further evidence seems to be needed.

Conclusion

Several arguments lend music rhythm “a special place” in the human brain. Processing isochronous rhythms may have allowed cooperative movement throughout human evolution, and this may have shaped the human brain. The brain substrates for the perception of music rhythm relate to both perception and action, and they do not seem to be shared with language. Early rhythmic skills and the competences of adult non-musicians suggest that the processing of isochronous input does not require extended experience. Links between perception and movement seem again to exist. Other arguments suggest that music and speech rhythms may recruit the same resources, despite differences at the level of structural isochrony. The strongest among these is perhaps the argument that speech rhythm is a non-random, quasi-periodic signal, and not a non-periodic one. Approaches based on the entrainment of brain oscillations to speech signals may bridge the gap between neurophysiology and cognition, and contribute to explain the hierarchical component of speech perception. They also look promising in guiding clinical applications based on transfer effects, but clarifications seem to be required.

References

Bergeson, T. R., & Trehub, S. E. (2006). Infants perception of rhythmic patterns. *Music Perception*, *23* (4), 345-360. doi: 10.1525/mp.2006.23.4.345

Besson, M., Chobert, J. & Marie, C. (2011). Transfer of training between music and speech: common processing, attention, and memory. *Frontiers in Psychology*, *2*, *94*. doi: 10.3389/fpsyg.2011.00094

Bowling, D. L., Herbst, C. T., & Fitch, W. T. (2013). Social origins of rhythm? Synchrony and temporal regularity in human vocalization. *PLoS One*, *8* (11), e80402. doi: 10.1371/journal.pone.0080402.

Cook, P., Rouse, A., Wilson, M., & Reichmuth, C. (2013). A California sea lion (Zalophus californianus) can keep the beat: Motor entrainment to rhythmic auditory stimuli in a non vocal mimic. *Journal of Comparative Psychology*, *127* (4), 412–427. doi:10.1037/a0032345

Corriveau, K. H., & Goswami, U. (2009). Rhythmic motor entrainment in children with speech and language impairments: tapping to the beat. *Cortex*, *45* (1), 119–130. doi:10.1016/j.cortex.2007.09.008.

Dalla Bella, S., Białuńska, A., & Sowiński, J. (2013). Why movement is captured by music, but less by speech: role of temporal regularity. *PLoS ONE 8* (8), *e71945*. doi:10.1371/journal.pone.0071945

Dalla Bella, S., & Peretz, I. (1999). Music agnosias: selective impairments of music recognition after brain damage. *Journal of New Music Research*, *28* (3), 209–216. doi:10.1076/jnmr.28.3.209.3108

Dauer, R. M. (1983). Stress-timing and syllable-timing reanalyzed. *Journal of Phonetics*, *11* (1), 51–62.

Demany, L., McKenzie, B., & Vurpillot, E. (1977). Rhythm perception in early infancy. *Nature*, *266* (5604), 718-719. doi: 10.1038/266718a0

Fedorenko, E., McDermott, J. H., Norman-Haignere, S., & Kanwisher, N. (2012). Sensitivity to musical structure in the human brain. *Journal of Neurophysiology*, *108* (12), 3289–3300.

Fitch, W. T., & Rosenfeld, A. J. (2007). Perception and production of syncopated rhythms. *Music Perception*, *25* (1), 43-58. doi: 10.1525/mp.2007.25.1.43.

Fitch, W. T. (2013). Rhythmic cognition in humans and animals: distinguishing meter and pulse perception. *Frontiers in Systems Neuroscience. 7*, *68*. doi: 10.3389/fnsys.2013.00068.

Friston, K. (2002). Beyond phrenology: what can neuroimaging tell us about distributed circuitry? *Annual Review of Neuroscience*, *25* (1), 221-250. doi:10.1146/annurev.neuro.25.112701.142846.

Fujioka, T., Trainor, L. J., Large, E. W., & Ross, B. (2012). Internalized timing of isochronous sounds is represented in neuromagnetic beta oscillations. *The Journal of Neuroscience*, *32* (5), 1791-1802. doi: 10.1523/JNEUROSCI.4107-11.2012.

Geiser, E., Sandmann, P., Jäncke, L., & Meyer, M. (2010). Refinement of metre perception – training increases hierarchical metre processing. *European Journal of Neuroscience*, *32* (11), 1979–1985. doi:10.1111/j.1460-9568.2010.07462.x

Geiser, E., Ziegler, E., Jancke, L., & Meyer, M. (2009). Early electrophysiological correlates of meter and rhythm processing in music perception. *Cortex*, *45* (1), 93–102. doi:10.1016/j.cortex.2007.09.010

Gerry, D. W., Faux, A. L., & Trainor, L. J. (2010). Effects of Kindermusik training on infants' rhythmic enculturation. *Developmental Science*, *13* (3), 545–551. doi:10.1111/j.1467-7687.2009.00912.x

Giraud, A.-L., & Poeppel, D. (2012). Cortical oscillations and speech processing: emerging computational principles and operations. *Nature Neuroscience*, *15* (4), 511–517. doi:10.1038/nn.3063.

Goswami, U. (2011). A temporal sampling framework for developmental dyslexia. *Trends in Cognitive Sciences*, *15* (1), 3–10. doi:10.1016/j.tics.2010.10.001.

Grahn, J. A. (2009). The role of the basal ganglia in beat perception. *Annals of the New York Academy of Sciences*, *1169* (1), 35–45. doi:10.1111/j.1749-6632.2009.04553.x

Grahn, J. A. (2012). Neural mechanisms of rhythm perception: current findings and future perspectives. *Topics in Cognitive Science*, *4* (4), 585–606. doi:10.1111/j.1756-8765.2012.01213.x

Grahn, J. A., & Brett, M. (2007). Rhythm and beat perception in motor areas of the brain. *Journal of Cognitive Neuroscience*, *19* (5), 893–906. doi:10.1162/jocn.2007.19.5.893

Grahn, J. A., & Brett, M. (2009). Impairment of beat-based rhythm discrimination in Parkinson's disease. *Cortex*, *45* (1), 54–61. doi:10.1016/j.cortex.2008.01.005

Grahn, J. A. & Rowe, J. B. (2009). Feeling the beat: premotor and striatal interactions in musicians and nonmusicians during beat perception. *The Journal of Neuroscience*, *29* (23), 7540-7548. doi: 10.1523/JNEUROSCI.2018-08.2009

Hämäläinen, J. A., Rupp, A., Soltész, F., Szücs, D., & Goswami, U. (2012). Reduced phase locking to slow amplitude modulation in adults with dyslexia: An MEG study. *NeuroImage*, *59* (3), 2952–2961. doi:10.1016/j.neuroimage.2011.09.075

Hannon, E. E., & Johnson, S. P. (2005). Infants use meter to categorize rhythms and melodies: Implications for musical structure learning. *Cognitive Psychology*, *50* (4), 354–377. doi:10.1016/j.cogpsych.2004.09.003

Hannon, E. E., Soley, G., & Levine, R. S. (2011). Constraints on infants' musical rhythm perception: effects of interval ratio complexity and enculturation. *Developmental Science*, *14* (4), 865–872. doi:10.1111/j.1467-7687.2011.01036.x

Hannon, E. E., & Trehub, S. E. (2005). Tuning in to musical rhythms: infants learn more readily than adults. *Proceedings of the National Academy of Sciences of the United States of America*, *102* (35), 12639–12643. doi:10.1073/pnas.0504254102.

Hannon, E. E., Vanden Bosch der Nederlanden, C. M., & Tichko, P. (2012). Effects of perceptual experience on children's and adults' perception of unfamiliar rhythms. *Annals of the New York Academy of Sciences*, *1252* (1), 92–99. doi:10.1111/j.1749-6632.2012.06466.x

Hasegawa, A., Okanoya, K., Hasegawa, T., & Seki, Y. (2011). Rhythmic synchronization tapping to an audio-visual metronome in budgerigars. *Scientific Reports*, *1*. doi:10.1038/srep00120.

Hausen, M., Torppa, R., Salmela, V. R., Vainio, M., & Särkämö, T. (2013). Music and speech prosody: a common rhythm. Frontiers in Psychology, 4, 566. doi: 10.3389/fpsyg.2013.00566.

Honing, H. (2012). Without it no music: beat induction as a fundamental musical trait. *Annals of the New York Academy of Sciences*, *1252* (1), 85–91. doi:10.1111/j.1749-6632.2011.06402.x

Honing H., Merchant H., Háden G. P., Prado L., & Bartolo, R. (2012). Rhesus monkeys (*Macaca mulatta*) detect rhythmic groups in music, but not the beat. *PLoS ONE 7* (12), e51369. doi:10.1371/journal.pone.005136.9.

Huss, M., Verney, J. P., Fosker, T., Mead, N., & Goswami, U. (2011). Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology. *Cortex*, *47* (6), 674–689. doi:10.1016/j.cortex.2010.07.010.

James, C. E., Michel, C. M., Britz, J., Vuilleumier, P., & Hauert, C. -A. (2012). Rhythm evokes action: Early processing of metric deviances in expressive music by experts and laymen revealed by ERP source imaging. *Human Brain Mapping*, *33* (12), 2751–2767. doi:10.1002/hbm.21397.

Jones, M. R., & Boltz, M. (1989). Dynamic attending and responses to time. *Psychological Review*, *96* (3), 459–491. doi:10.1037/0033-295X.96.3.459.

Kalender, B., Trehub, S., & Schellenberg, E. G. (2013). Cross-cultural differences in meter perception. *Psychological Research*, *77* (2), 196–203. doi:10.1007/s00426-012-0427-y

Knoesche, T. R., Neuhaus, C., Haueisen, J., Alter, K., Maess, B., Witte, O. W., & Friederici, A. D. (2005). Perception of phrase structure in music. *Human Brain Mapping*, *24* (4), 259–273. doi:10.1002/hbm.20088.

Koelsch, S., Gunter, T. C., Wittfoth, M., & Sammler, D. (2005). Interaction between syntax processing in language and in music: an ERP study. *Journal of Cognitive Neuroscience*, *17* (10), 1565-1557. doi: 10.1162/089892905774597290.

Koelsch, S., Schmidt, B-H., & Kansok, J. (2002). Effects of musical expertise on the early right anterior negativity: An event-related brain potential study. *Psychophysiology*, *39* (5), 657–663. doi:10.1111/1469-8986.3950657

Ladinig, O., Honing, H., Háden, G., & Winkler, I. (2009). Probing attentive and preattentive emergent meter in adult listeners without extensive music training. *Music Perception*, *26* (4), 377-386. 26 (4), 377-386. doi: 10.1525/mp.2009.26.4.377.

Large, E.W. (2008). Resonating to musical rhythm: theory and experiment. In S. Grondin (Ed.), *The Psychology of Time* (pp. 189–231). United Kingdom: Emerald.

Large, E. W., & Snyder, J. S. (2009). Pulse and meter as neural resonance. *Annals of the New York Academy of Sciences*, *1169*, 46–57. doi:10.1111/j.1749-6632.2009.04550.x

Leong, V., & Goswami, U. (2014a). Assessment of rhythmic entrainment at multiple timescales in dyslexia: Evidence for disruption to syllable timing. *Hearing Research*, *308*, 141–161. doi:10.1016/j.heares.2013.07.015.

Leong, V. & Goswami, U. (2014b). Impaired extraction of speech rhythm from temporal modulation patterns in speech in developmental dyslexia. *Frontiers in Human Neuroscience*, *8*, *96*. doi: 10.3389/fnhum.2014.00096.

Lerdahl, F. (2003). The sounds of poetry viewed as music. In I. Peretz & E. Zatorre (Eds.). *The Cognitive Neuroscience of Music* (pp. 413-429). Oxford: Oxford University Press.

Levitin, D. J. & Tirovolas, A. K. (2009). Current Advances in the Cognitive Neuroscience of Music. *Annals of the New York Academy of Sciences*, *1156* (1), 211–231. doi:10.1111/j.1749-6632.2009.04417.x

Luo, H., Liu, Z. & Poeppel, D. (2010). Auditory cortex tracks both auditory and visual stimulus dynamics using low-frequency neuronal phase modulation. *PLoS Biology*, *8* (8), e1000445. doi:10.1371/journal.pbio.1000445

Luo, H., & Poeppel, D. (2007). Phase patterns of neuronal responses reliably discriminate speech in human auditory cortex. *Neuron*, *54* (6), 1001-1010. doi:10.1016/j.neuron.2007.06.004

Maess, B., Koelsch, S., Gunter, T. C., & Friederici, A. D. (2002). Musical syntax is processed in Broca's area: an MEG study. *Nature Neuroscience*, *4* (5), 540-545. doi: 10.1038/87502

Marie, C., Magne, C., & Besson, M. (2010). Musicians and the metric structure of words. *Journal of Cognitive Neuroscience*, *23* (2), 294–305. doi:10.1162/jocn.2010.21413

Merker, B. H., Madison, G. S., & Eckerdal, P. (2009). On the role and origin of isochrony in human rhythmic entrainment. *Cortex*, *45* (1), 4–17. doi: 10.1016/j.cortex.2008.06.011.

Näätänen, R., Gaillard, A. W. K., & Mäntysalo, S. (1978). Early selective-attention effect on evoked potential reinterpreted. *Acta Psychologica*, *42* (4), 313–329. doi:10.1016/0001-6918(78)90006-9

Nan, Y., Knoesche, T. R., & Friederici, A. D. (2006). The perception of musical phrase structure: a crosscultural ERP study. *Brain Research*, *1094* (1), 179–191. doi: 10.1016/j.brainres.2006.03.115

Nan, Y., Knoesche, T. R., & Friederci, A. D. (2009). Non-musicians' perception of phrase boundaries in music: A cross-cultural ERP study. *Biological Psychology*, *82* (1), 70–81. doi:10.1016/j.biopsycho.2009.06.002

Nan, Y., Knösche, T. R., Zysset, S., & Friederici, A. D. (2008). Cross-cultural music phrase processing: an fMRI study. *Human Brain Mapping*, *29* (3), 312–328. doi: 10.1002/hbm.20390

Näätänen, R., Gaillard, A. W. K., & Mäntysalo, S. (1978). Early selective-attention effect on evoked potential reinterpreted. *Acta Psychologica*, *42* (4), 313–329. doi:10.1016/0001-6918(78)90006-9

Nettl, B. (2000). An ethnomusicologist contemplates universals in musical sound and musical culture. In N.L. Wallin, B. Merker, &

S. Brown (Eds.). *The Origins of Music* (pp. 463-472). Cambridge, MA: MIT Press.

Neuhaus, C., Knoesche, T. R., & Friederici, A. D. (2006). Effects of musical expertise and boundary markers on phrase perception in music. *Journal of Cognitive Neuroscience*, *18* (3), 472–493.doi: 10.1162/jocn.2006.18.3.472

Nozaradan, S., Peretz, I., Missal, M. & Mouraux, A. (2011).Tagging the neuronal entrainment to beat and meter. *The Journal of Neuroscience*, *31* (28), 10234-10240. doi: 10.1523/JNEUROSCI.0411-11.2011.

Patel, A. D. (2003). Rhythm in language and music. *Annals of the New York Academy of Sciences*, *999* (1), 140–143. doi:10.1196/annals.1284.015

Patel, A. D. (2006). Musical rhythm, linguistic rhythm, and human evolution. *Music Perception*, *24* (1), 99-104. doi: 10.1525/mp.2006.24.1.99

Patel, A. D. (2014). The evolutionary biology of musical rhythm: was Darwin wrong? *PLoS Biology 12* (3), e1001821. doi:10.1371/journal.pbio.1001821

Patel, A. D., Gibson, E., Ratner, J., Besson, M., & Holcomb, P. J. (1998). Processing syntactic relations in language and music: an event-related potential study. *Journal of Cognitive Neuroscience*, *10* (6), 717–733. doi: 10.1162/089892998563121

Patel, A. D., Iversen, J. R., Bregman, M. R., & Schulz, I. (2009). Experimental evidence for synchronization to a musical beat in a nonhuman animal. *Current Biology*, *19* (10), 827–830. doi:10.1016/j.cub.2009.03.038.

Peelle, J. E. & Davis, M. H. (2012). Neural oscillations carry speech rhythm through to comprehension. *Frontiers in Psychology*, *3*, 320. doi: 10.3389/fpsyg.2012.00320.

Peretz, I. (1993). Auditory atonalia for melodies. *Cognitive Neuropsychology*, *10* (1), 21–56. doi:10.1080/02643299308253455

Peretz, I. (2003). Brain specialization for music: new evidence from congenital amusia. In I. Peretz & E. Zatorre (Eds.). *The Cognitive Neuroscience of Music* (pp. 192-203). Oxford: Oxford University.

Peretz, I., & Coltheart, M. (2003). Modularity of music processing. *Nature Neuroscience*, *6* (7), 688-691.doi: 10.1038/nn1083.

Phillips-Silver, J., & Trainor, L. J. (2005). Feeling the beat: movement influences infant rhythm perception. *Science*, *308* (5727), 1430–1430. doi:10.1126/science.1110922.

Phillips-Silver, J., Toiviainen, P., Gosselin, N., Piché, O., Nozaradan, S., Palmer, C. & Peretz, I. (2011). Born to dance but beat deaf: A new form of congenital amusia. *Neuropsychologia*, *49* (5), 961–969. doi:10.1016/j.neuropsychologia.2011.02.002.

Power, A. J., Mead, N., Barnes, L. & Goswami, U. (2012). Neural entrainment to rhythmically presented auditory, visual, and audio-visual speech in children. *Frontiers in Psychology*, *3*, 216. doi: 10.3389/fpsyg.2012.00216

Protopapas, A. (2014). From temporal processing to developmental language disorders: mind the gap. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *369*(1634). doi:10.1098/rstb.2013.0090

Repp, B., & Su, Y-H. (2013). Sensorimotor synchronization: A review of recent research (2006–2012). *Psychonomic Bulletin & Review*, *20* (3), 403–452. doi:10.3758/s13423-012-0371-2

Roach, P. (1982). On the distinction between 'stress-timed' and 'syllable-timed' languages. In D. Crystal (Ed.), *Linguistic controversies: essays in linguistic theory and practice in honour of F.R. Palmer* (pp. 73-79). London: Edward Arnold.

Rothermich, K., Schmidt-Kassow, M., & Kotz, S. A. (2012). Rhythm's gonna get you: Regular meter facilitates semantic sentence processing. *Neuropsychologia*, *50* (2), 232–244. doi:10.1016/j.neuropsychologia.2011.10.025.

Schaefer, R. S., Farquhar, J., Blokland, Y., Sadakata, M., & Desain, P. (2011). Name that tune: Decoding music from the listening brain. *Multivariate Decoding and Brain Reading*, *56* (2), 843–849. doi:10.1016/j.neuroimage.2010.05.084.

Schmidt-Kassow, M., & Kotz, S. A. (2008). Event-related brain potentials suggest a late interaction of meter and syntax in the P600. *Journal of Cognitive Neuroscience*, *21* (9), 1693–1708. doi:10.1162/jocn.2008.21153.

Scott, S. K., McGettigan, C., & Eisner, F. (2009). A little more conversation, a little less action–candidate roles for the motor cortex in speech perception. *Nature Reviews Neuroscience*, *10* (4), 295–302. doi:10.1038/nrn2603.

Silva, S., Branco, P., Barbosa, F., Marques-Teixeira, J., Petersson, K. M., & Castro, S. L. (under review). Musical Phrase Boundaries, Wrap-Up Effects and the Closure Positive Shift. *Brain research*.

Silva, S., Barbosa, F., Marques-Teixeira, J., Petersson, K. M., & Castro, S. L. (2014). You know when: Event-related potentials and theta/beta power indicate boundary prediction in music. *Journal of Integrative Neuroscience*, *13*, 1-16. doi:10.1142/S0219635214500022

Soley, G., & Hannon, E. E. (2010). Infants prefer the musical meter of their own culture: A cross-cultural comparison. *Developmental Psychology*, *46* (1), 286–292. doi:10.1037/a0017555

Stalinski, S. M., & Schellenberg, E. G. (2012). Music cognition: a developmental perspective. *Topics in Cognitive Science*, *4* (4), 485–497. doi:10.1111/j.1756-8765.2012.01217.x

Thomson, J. M., & Goswami, U. (2008). Rhythmic processing in children with developmental dyslexia: Auditory and motor rhythms link to reading and spelling. *Links and Interactions Between Language and Motor Systems in the Brain*, *102* (1–3), 120–129. doi:10.1016/j.jphysparis.2008.03.007.

Thomson, J., Leong, V., & Goswami, U. (2013). Auditory processing interventions and developmental dyslexia: a comparison of phonemic and rhythmic approaches. *Reading and Writing*, *26*(2), 139–161. doi:10.1007/s11145-012-9359-6.

Tierney, A., & Kraus, N. (2013a). Neural responses to sounds presented on and off the beat of ecologically valid music. *Frontiers in Systems Neuroscience*, *7*, *14*. doi: 10.3389/fnsys.2013.00014.

Tierney, A. & Kraus, N. (2013b). The ability to move to a beat is linked to the consistency of neural responses to sound. *The Journal of Neuroscience*, *33 (38)*, 14981-14988. doi: 10.1523/JNEUROSCI.0612-13.2013.

Trehub, S. E., & Hannon, E. E. (2009). Conventional rhythms enhance infants' and adults' perception of musical patterns. *Cortex*, *45*(1), 110–118. doi:10.1016/j.cortex.2008.05.012.

Vuust, P., Ostergaard, L., Pallesen, K. J., Bailey, C., & Roepstorff, A. (2009). Predictive coding of music – Brain responses to rhythmic incongruity. *Cortex*, *45* (1), 80–92. doi:10.1016/j.cortex.2008.05.014.

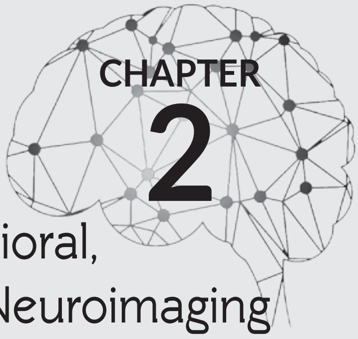
Vuust, P., Wallentin, M., Mouridsen, K., Østergaard, L., & Roepstorff, A. (2011). Tapping polyrhythms in music activates language areas. *Neuroscience Letters*, *494* (3), 211–216. doi:10.1016/j.neulet.2011.03.015.

Werker, J. F., & Lalonde, C. E. (1988). Cross-language speech perception: Initial capabilities and developmental change. *Developmental Psychology*, *24* (5), 672–683. doi:10.1037/0012-1649.24.5.672.

Winkler, I., Háden, G. P., Ladinig, O., Sziller, I., & Honing, H. (2009). Newborn infants detect the beat in music. *Proceedings of the National Academy of Sciences*, *106* (7), 2468–2471. doi:10.1073/pnas.0809035106.

Zentner, M., & Eerola, T. (2010). Rhythmic engagement with music in infancy. *Proceedings of the National Academy of Sciences*, *107*(13), 5768–5773. doi:10.1073/pnas.1000121107.

Zion Golumbic, E. M., Ding, N., Bickel, S., Lakatos, P., Schevon, C. A., McKhann, G. M., Goodman, R. R., Emerson, R., Mehta, A. D., Simon, J. Z., Poeppel, D., Schroeder, C. E. (2013). Mechanisms Underlying Selective Neuronal Tracking of Attended Speech at a "Cocktail Party". *Neuron*, *77* (5), 980–991. doi:10.1016/j.neuron.2012.12.037.



CHAPTER 2

Semantic memory: Behavioral, Electrophysiological and Neuroimaging approaches

Louis Renoult

Introduction

Semantic memory, also termed conceptual knowledge, is a form of declarative memory (Tulving, 1972, 1983; 2002). It is defined as general world knowledge, such as knowledge of facts, events, concepts, objects, and people. Semantic memory is generally considered to be shared among the members of a culture (but see Martinelli, Sperduti, & Piolino, 2012; Renoult, Davidson, Palombo, Moscovitch, & Levine, 2012 for recent reviews on personal forms of semantic memory). Historically, semantic memory has been tightly associated to studies of language comprehension and verbal learning. The current cognitive neuroscience approach typically recognizes this association (e.g., Patterson, 2007), while arguing that our ability to assign meaning to stimuli is not restricted or specific to language.

Within declarative memory, semantic memory is classically distinguished from episodic memory (see Table 2.1 for a comparison of their main characteristics). Episodic memory permits recollecting and re-experiencing personal past experiences within their specific spatio-temporal context (Tulving, 2002). For example, being able to vividly recollect and re-experience a specific incident when one forgot to pay at the restaurant would depend on episodic memory. In contrast, knowing what the word "restaurant" means and what people typically do in restaurants (i.e., sit down, order from the waiter, wait, eat and pay) depends on semantic memory. Contrary to episodic memory that is specific in time and place, knowledge stored in semantic memory is thus context-independent or abstracted over various contexts. Importantly, it is generally thought that episodic memory operations require the semantic memory system and may have evolved from it (Tulving, 2002).

This chapter is organized as follow. The first section concerns the behavioral and theoretical conceptualizations of semantic memory. The two following sections concern the neural bases of semantic memory and review event-related potentials (ERPs) and functional neuroimaging studies.

Table 2.1. Comparison of the main characteristics of semantic and episodic memory.

Episodic Memory	Semantic Memory
Memory for unique events (episodes)	Memory for facts and generic events (knowledge of the world)
Highly personal	Culturally shared or personal
Context specific (space, time)	Acontextual or generalized across contexts
Can be re-experienced (remember)	Not re-experienced (know)
Perceptually rich (experience-near)	Perceptually poor

Source: The autor.

Behavioral and Theoretical Conceptualizations of Semantic Memory

In this section, we will discuss how one typically infers that the meaning of a stimulus has been processed and how semantic representations are usually defined and conceptualized.

What is Semantic Processing?

Semantic processing consists in processing stimuli at the level of meaning. It is often contrasted to perceptual processing or processing of the physical characteristics of a stimulus (Tulving & Schacter, 1990). In the case of words, most models of semantic memory consider that word forms and their corresponding meaning representations are separated entities. Orthographic and phonological representations are stored in lexical memory while word meanings are stored in a separate but connected network in semantic memory (Anderson, 1983; Collins & Loftus, 1975; McClelland & Rumelhart, 1985). Words can thus be processed at the level of form or at the level of meaning (i.e., deep processing). One of the most-well known behavioral consequences of deep processing is that it leads to increased memory performance (reviewed in Craik, 2002). This phenomenon, which is also referred to as semantic elaboration, can involve evoking associations for different aspects of the study material or analyzing it in term of subcategories of knowledge. More generally, a number of experimental parameters can promote deep processing, notably the choice of tasks. In the following sections we will describe these parameters.

Semantic Tasks

Typical semantic tasks include semantic categorization, category verification, concreteness decision, decision on feature or dimension of stimuli and tasks in which participants read sentences for comprehension. These tasks can be considered as explicit semantic designs in the sense that participants are explicitly asked to process stimuli at the level of meaning. The use of these tasks is thus generally taken as evidence that stimuli have been processed deeply.

In the semantic categorization task, participants are presented with a prime word that is typically a category (e.g., fruit) and then perform a relatedness decision on a target word (e.g., apple). In the category (or sentence) verification task, participants have to verify or reject statements such as “a robin is a bird”. In feature-dimension decision tasks, participants are invited to compare a template stimulus to a reference feature or dimension (e.g., “Is it bigger than a tennis ball?”). Finally, in the concrete-abstract decision, they have to indicate whether a stimulus is concrete or abstract.

Non-Semantic Tasks

Non-semantic tasks can be divided into (1) designs that are used to study the implicit or automatic aspects of semantic processing, typically lexical decision and naming tasks, and (2) designs that promote processing at the level of word form or perceptual processing.

Lexical decision and naming tasks have constituted a major avenue of research on the automatic aspects of semantic processing. In these tasks, semantic processing is implicit in the sense that access to the meaning of words is not required for accurate performance. In the lexical decision task, a prime word is followed by a target word or pseudoword and participants have to decide whether the second stimulus is a word or not. In the naming task, the prime is followed by a target word that participants have to name. In both tasks, participants are faster when the target word (e.g., nurse) is semantically related to the prime word (e.g., doctor), an effect called semantic priming. In some cases, participants can become aware of the semantic relations between prime and target words. A number of parameters can be adjusted to favor automatic over explicit semantic processing: the proportion of prime and target pairs that are related, the time interval between the onset of the prime and the target (which is referred to as stimulus onset asynchrony or SOA) and the use of masked primes. The automatic aspects of semantic processing are typically studied with low proportion of related words, short SOAs and masked primes. These designs, in which conscious processes supposedly do not play any role in semantic processing, have been essential in demonstrating that words automatically activate their meaning (Neely & Kahan, 2001).

Other non-semantic tasks include letter case matching, phonological matching, letter search on prime or target words or morphological priming. These tasks are generally used to promote processing at the level of word form rather than at the level of meaning. When semantic effects (see below) are measured in such tasks, they are often reduced or suppressed.

Meaning Dimensions

Processing at the level of meaning can be based on several dimensions. The dimension that has received the most attention is categorical relations (e.g., fruit-apple). Other dimensions include functional relations (e.g., broom-sweep), script or schemata (e.g., restaurant-wine), synonyms (e.g., street-road) or antonyms (e.g., black-white) relations. All these meaning dimensions can result in semantic priming effects (Lucas, 2000). The same applies to stimuli that are related according to association norms. Although associative relations (e.g., mouse-cheese) are theoretically not semantic and would simply originate from a frequent co-occurrence of concepts in space and time (Fodor, 1983), it has been difficult to isolate pure semantic from pure associative relations (Hutchison, 2003; Lucas, 2000). As we have seen, semantic relations are not restricted to categorical relations and attempts to classify association types revealed that most associative relationships were also semantic (Hutchison, 2003).

Semantic Effects

Semantic effects are experimental measures of semantic processing. These include effects of semantic priming or congruity that we have previously mentioned but also effects of concreteness, semantic category or semantic richness. Effects of semantic priming and congruity are generally considered *contextual effects*, whereas concreteness, category or semantic richness are considered *structural effects* (see Kounios, 1996). The former are especially informative to investigate how concepts are related, while the latter would more directly reflect the structure of semantic representations. The presence of any of these effects in an experiment is taken as evidence that semantic processing has taken place.

The effects of semantic priming that we have described in the lexical decision and naming tasks are also observed in explicit semantic designs, such as semantic categorization tasks. However, in these latter tasks, they are referred to as effects of semantic congruity or relatedness, as they depend on an explicit assessment of semantic relations between prime and target words. Effects of semantic priming and congruity have been the most studied semantic effects (Hutchison, 2003; Lucas, 2000; Neely, 1991).

Concreteness constitutes a fundamental characteristic of a word. Concrete words, such as “dog”, are more directly associated with sensory experience and mental images and are easier to categorize than abstract words, such as “logic” (reviewed in Paivio, 1991). These differences result in a number of processing advantages for concrete compared to abstract words. Concrete words are generally responded to faster and better remembered when presented in sentences or in isolation (Paivio, 1991; Schwanenflugel, 1991).

Effects of semantic category have been well-studied in neurological patients and in neuroimaging studies but less systematically in behavioral studies. Longer RTs for artifactual categories than natural categories have often been reported (Debruille & Renoult, 2009; Kiefer, 2001; Paz-Caballero, Cuetos, & Dobarro, 2006; Price & Humphreys, 1989; Proverbio, Del Zotto, & Zani, 2007; Renoult & Debruille, 2011). These effects were often interpreted as reflecting an easier categorization of names of natural categories because of a greater overlap in their semantic features (e.g., Saffran & Scholl, 1999). However, in contrast to the effects of semantic priming or concreteness, absence of these behavioral differences in category processing are not necessarily taken to imply that category information has not been processed, especially when differences in brain activations are found (e.g., Kiefer, 2001).

Finally, effects of semantic richness concern how much information is evoked by concepts. Shorter reaction times have been observed for words with richer semantic representations. This includes words for which participants generate more semantic features (Grondin, Lupker, & McRae, 2009; Pexman, Holyk, & Monfils, 2003; Yap, Tan, Pexman, & Hargreaves, 2011), more semantic neighbors (Buchanan, Westbury, & Burgess, 2001; Siakaluk, Buchanan, & Westbury, 2003) or more associates (Buchanan et al., 2001).

Concepts and Semantic Representations

Stimuli that have semantic (or conceptual) representations, are stimuli that are meaningful and familiar (e.g., a picture of an animal) as opposed to meaningless or unfamiliar stimuli (e.g., an abstract geometrical drawing). The semantic representation of an object includes both information specific to that object, which defines it as a distinct entity (i.e., a specific animal), and information (or features) shared by other category members (Martin, 2001; Taylor, Devereux, & Tyler, 2011). Crucially, the activation of semantic representations depends on the meaning of the item and not on the physical format of its presentation. For instance, the semantic representation of a chair could be activated by the written word “chair”, the heard name “chair” or a picture of a chair. This mental representation allows recognizing various instances of the concept, reasoning about the concept and understanding complex combinations involving this concept (e.g., high chair) (Komatsu, 1992). In more general terms, semantic representations thus enable us to interpret the present environment based on past experiences: although I have never seen this particular tomato before (i.e., episodic information), I can infer that it is probably like other tomatoes I have eaten and therefore I know that it is edible and likely to taste good (Murphy, 2002).

Many of the current models of semantic memory stipulate that semantic representations are represented as a distributed network of elementary features or attributes (e.g., Devlin, Gonnerman, Andersen, & Seidenberg, 1998; Garrard, Ralph, Hodges, & Patterson, 2001; McRae, Cree, Seidenberg, & McNorgan, 2005; Taylor, Devereux, Acres, Randall, & Tyler, 2012; see Figure 2.1). Some of these features are highly distinctive of a specific concept (e.g., <eats nuts>, <does bury food>), other co-occur across category members (<has eyes>, <has legs>). Note that this perspective of a distributed network of semantic features differs from classic models (e.g., Collins & Loftus, 1975; Anderson, 1983) in which concepts are represented as holistic units or "nodes" (e.g., CAT) and nodes of similar meaning are connected in the network (e.g., CAT and DOG; Hutchison, 2003). Crucially, these models differ as to how concepts activate each other. According to distributed models, related concepts share many features and thus a prime facilitates the processing of a target word when there is sufficient overlap. In contrast, in holistic models, a mechanism of "automatic spreading of activation" is most often assumed: activation of the semantic representation of the prime would automatically spread to semantic associates, which may include the representation or node of the target.

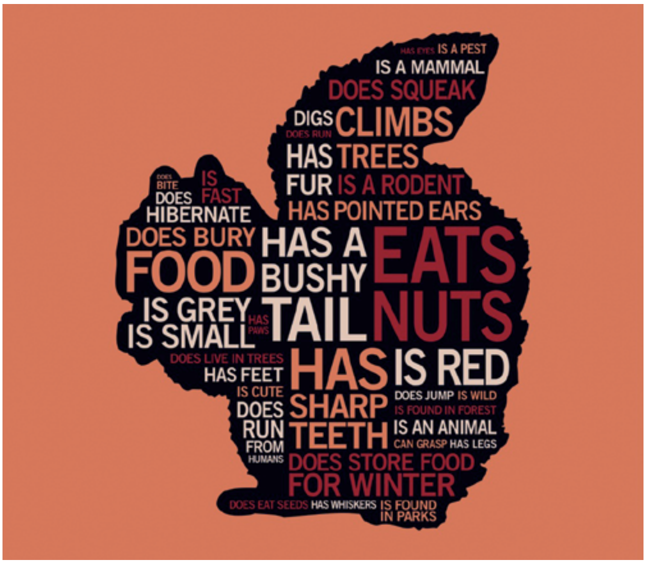


Figure 2.1. Hypothetical conceptual structure for squirrel. Semantic features of different degree of distinctiveness are represented, with greater distinctiveness represented by greater font size (illustration courtesy of Patrick Seymour).

Source: The autor.

Event-related Potentials (ERPs) Studies of Semantic Memory: The N400

Our knowledge of the organization of semantic representations in the brain has greatly benefited from the use of electrophysiological recordings in humans. One event-related potential (ERP) component in particular, the N400, has been shown to be sensitive to various aspects of semantic processing.

Main characteristics

The electroencephalogram (EEG) is a direct reflection of the electrical activity of the brain, as recorded from the human scalp. ERPs refer to voltage fluctuations in the ongoing EEG related to a stimulus, response or event of interest. They are typically obtained by averaging segments of the EEG, time-locked to the onset of the event (for recent reviews of the ERP methodology, see Handy, 2005; Kappenman & Luck, 2011; Luck, 2005).

The N400 ERP is a negative deflection which develops between 250 and 500 ms after stimulus onset (see Figure 2.2) and constitutes the brain's neural response to any potentially meaningful stimulus (Federmeier & Laszlo, 2009). The word "potentially" is important as, for instance, pronounceable and orthographically legal pseudowords (e.g., clock —> "cleck") also elicit N400. This ERP component has been recorded in response to various stimuli, such as visual and auditory words, drawings, photographs, faces, environmental sounds and odors (Kutas & Federmeier, 2011). In sentence processing, each word evokes an N400 (Van Petten & Kutas, 1990). This component has a broad scalp distribution, with maximum amplitudes at centro-parietal electrode sites (Curran, Tucker, Kutas, & Posner, 1993; Johnson & Hamm, 2000). It is often slightly greater over the right hemisphere, especially in right-handed participants having no left-handed family members (Van Petten & Luka, 2006).

The N400 has been shown to be sensitive to all the previously mentioned semantic dimensions and semantic effects. Its modulations have been described in a great number of tasks, the most typical being lexical decision, semantic categorization, sentence verification or concreteness decisions. In contrast, the N400 is typically not elicited in letter-case decision tasks or in tasks involving spelling errors, harmonic and melodic violations, violations of geometry, or grammatical violations that do not affect comprehension (Kutas, Van Petten, & Kluender, 2006).

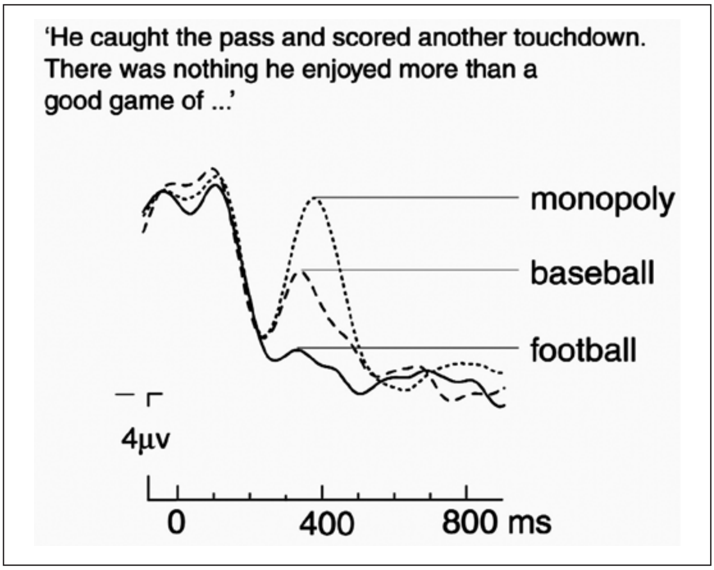


Figure 2.2. The N400. The amplitude of N400 is modulated by semantic expectancy and context but also by the structure of semantic memory. This is illustrated here by smaller N400 amplitude for within-category violations than between-category violations.

Source: adapted with permission from Kutas and Federmeier (2000).

The N400 and Meaning Dimensions

N400 effects of semantic congruity were observed in tasks involving all types of semantic relations, namely category (e.g., Heinze, Muente, & Kutas, 1998), functional relations (e.g., Bach, Gunter, Knoblich, Prinz, & Friederici, 2009), synonymy (e.g., Liu, Perfetti, & Hart, 2003), antonymy (e.g., Kutas & Iragui, 1998), schema (e.g., Chwilla & Kolk, 2005), world knowledge (e.g., Hagoort, Hald, Bastiaansen, & Petersson, 2004) and associative relations (e.g., Franklin, Dien, Neely, Huber, & Waterson, 2007). These findings thus indicate a systematic sensitivity of the N400 component to the processing of meaning.

N400 Effects

Effects of Semantic Priming and Congruity

Paralleling the behavioral literature, the effects of semantic priming and semantic congruity have been the most studied N400 effects. These effects consist of reduced N400 amplitudes for primed or congruous words compared to unprimed or incongruous words in a sentence (Kutas & Hillyard, 1980, 1984) or prime-target pairings (Bentin, McCarthy, & Wood, 1985). These effects are generally greater at centro-parietal electrode sites (maximum at CPz) and slightly greater over the right than over the left hemiscalp when words are presented visually (Kutas & Van Petten, 1994).

A number of studies have shown that N400 effects of semantic priming could be obtained with masked primes and very short SOAs (Deacon, Hewitt, Yang, & Nagata, 2000; Kiefer, 2002; Misra & Holcomb, 2003; Schnyer, Allen, & Forster, 1997) and therefore, that their occurrence does not require conscious processing. Likewise, N400 effects of semantic congruity have been observed in all sleep stages, that is, both in slow wave and REM sleep (Brualla, Romero, Serrano, & Valdizan, 1998; Ibanez, Lopez, & Cornejo, 2006; Perrin, Bastuji, & Garcia-Larrea, 2002). In contrast, other studies have reported greater N400 effects in conditions in which attention was explicitly focused on the processing of meaning compared to when conceptual processing was not task-relevant (Holcomb, 1988; Mitchell et al., 1991; West & Holcomb, 2000). Taken together, these studies suggest that the N400 can occur without consciousness, but that it can also be modulated by the allocation of attention.

Finally, N400 effects of semantic priming have also been described in cross-modal priming experiments, for instance with auditory primes and visual targets (Domalski, Smith, & Halgren, 1991) or visual words as primes and line drawings as targets (Ganis, Kutas, & Sereno, 1996). These results suggest that N400 processes may reflect the activity of a cross-modal semantic system. However, the presence of slightly but significantly different scalp distributions for each category of stimulus indicates that each modality may involve partly different neural generators (Kutas & Federmeier, 2000).

Effects of Semantic Expectancy

Although the N400 was first associated with semantic violations (Kutas & Hillyard, 1980), later work showed that violations were not critical to elicit an N400 (Kutas & Hillyard, 1984). The N400 has a broader sensitivity to semantic context (Lau, Phillips, & Poeppel, 2008). Its amplitude is inversely proportional to the expectancy of a stimulus (see Figure 2.2). In experiments using words as stimuli, expectancy can be determined by evaluating the percentage of participants that will use a particular word to complete a sentence. This percentage is called the “cloze probability”. Cloze probability and N400 amplitude are highly correlated (e.g., up to –0.8 in DeLong, Urbach, & Kutas, 2005, and –0.9 in Kutas and Hillyard, 1984). Thus, semantic expectancy appears to be the strongest modulator of N400 amplitude.

Effects of Concreteness

N400 amplitude is larger for concrete than for abstract words (Holcomb, Kounios, Anderson, & West, 1999; Kounios & Holcomb, 1994; West & Holcomb, 2000). Concreteness and imagery being highly correlated variables (e.g., r=.83 in Paivio, Yuille, & Madigan, 1968), this effect is generally considered analogous with the finding of greater N400 amplitude for highly imageable words compared to less imageable words (Nittono, Suehiro, & Hori, 2002; Swaab, Baynes, & Knight, 2002). Concrete words have sometimes been associated with a more frontal distribution than abstract words (Kounios & Holcomb, 1994), but the scalp distribution of the effect of concreteness has been quite variable, potentially reflecting the use of heterogeneous categories of stimuli across studies (Renoult, Brodeur, & Debruille, 2010).

Effects of Semantic Category

Within concrete words, different distributions of N400 amplitude on the scalp have been associated with words belonging to natural categories (such as animals) and artifactual categories (such as tools) (Debruille & Renoult, 2009; Kiefer, 2001, 2005; Paz-Caballero et al., 2006; Proverbio et al., 2007; Renoult & Debruille, 2011; Sim & Kiefer, 2005). In these studies, artifact categories were generally found to elicit greater N400 amplitudes over centro-parietal and occipito-temporal sites compared to natural categories. Conversely, natural categories were associated with greater N400 amplitudes than artifactual categories at frontal sites. Even though the spatial resolution of ERPs does not allow making precise inferences about the neural generators of these N400 effects, these results are clearly reminiscent of the neuroimaging findings discussed previously.

Effects of Semantic Richness

A number of recent studies have reported that N400 amplitude was modulated by the number of semantic features associated with meaningful stimuli (Amsel, 2011; Laszlo & Federmeier, 2010; Muller, Andoni Dunabeitia, & Carreiras, 2010; Rabovsky, Sommer, & Abdel Rahman, 2012; Taler, Kousaie, & Zunini, 2013). Experiments which investigated the learning of new concepts in adults showed graded N400 activity that was proportional to the amount of knowledge (Rahman & Sommer, 2008) or number of features (Gratton, Evans, & Federmeier, 2009) that had been acquired for those objects.

Taken together, the presence of N400 effects such as those of category, concreteness and semantic richness suggests that, in addition to being a sensitive index of the contextual modulations of semantic representations, this ERP component may also reflect the structure of these representations.

Lexical Effects

Finally, the N400 has also been shown to be modulated by a number of lexical effects. Words that are not frequently used in language elicit greater N400 amplitude compared to higher frequency words (Van Petten & Luka, 2006). This effect tends to disappear when words are placed in a supportive semantic context (Van Petten, 1993; Van Petten & Kutas, 1990) or repeated (Smith & Halgren, 1987; Young & Rugg, 1992), perhaps reflecting a different initial threshold of activation. Pseudowords were also found to evoke greater N400 amplitudes than actual words (Bentin, 1987; Chwilla, Brown, & Hagoort, 1995; Renoult, Wang, Mortimer, & Debruille, 2012). However, a pure lexical basis for this effect was questioned by studies showing that pseudowords that resemble real words could be associated with semantic effects, such as congruity (Deacon, Dynowska, Ritter, & Grose-Fifer, 2004) or concreteness (Kounios & Holcomb, 1994). In Deacon et al. (2004), pseudowords derived from related words elicited smaller N400 amplitudes than pseudowords derived from unrelated words. Similarly, Kounios and Holcomb (1994) reported that pseudowords derived from concrete words evoked greater N400 potentials than those derived from abstract words.

N400 Generators

Intracranial studies have described generators of the N400 in the anterior medial temporal lobe (Grunwald, Lehnertz, Heinze, Helmstaedter, & Elger, 1998; Nobre & McCarthy, 1995; Smith, Stapleton, & Halgren, 1986) but also in the vicinity of the superior sulcus of the lateral temporal lobe (Elger et al., 1997; Guillem, Nkaoua, Rougier, & Claverie, 1995; Halgren et al., 1994), in the posterior parietal cortex (Guillem et al., 1995; Guillem, Rougier, & Claverie, 1999; Halgren et al., 1994) or in the inferior frontal gyrus (Halgren et al., 1994). As these studies mostly investigate medial temporal structures, the importance of these brain regions for generating the N400 may have been overestimated (Engel, Moll, Fried, & Ojemann, 2005). However, their importance has also been noted using other techniques, such as high-density ERP recordings (Johnson & Hamm, 2000).

MEG studies investigating the sources of N400 scalp activity have been quite consistent in their description of generators in the vicinity of the left auditory cortex, that is, in the superior temporal gyrus (Halgren et al., 2002; Helenius, Salmelin, Service, & Connolly, 1998; Helenius et al., 2002; Service, Helenius, Maury, & Salmelin, 2007) or in the superior temporal sulcus (Elger et al., 1997; Halgren et al., 2002; Simos, Basile, & Papanicolaou, 1997). When bilateral sources were reported, right hemisphere generators were often active slightly after their left hemisphere homologues (Halgren et al., 2002; Helenius et al., 1998). fMRI studies using tasks that were previously associated with N400 effects reported generators in the anterior medial temporal lobe (P. Meyer, Mecklinger, & Friederici, 2010) and in the superior temporal gyrus (Matsumoto, Iidaka, Haneda, Okada, & Sadato, 2005). Finally, neuropsychological studies have reported that left temporal or temporo-parietal lesions produce significant reductions in N400 amplitude as well as comprehension deficits (Friederici, Hahne, & von Cramon, 1998; Hagoort, Brown, & Swaab, 1996; Swaab, Brown, & Hagoort, 1997).

Taken together these studies tend to show that left temporal, both in medial and lateral parts, as well as inferior parietal cortex are the greatest contributors to N400 activity. Inferior prefrontal sources have also been reported in a few studies (e.g., Halgren et al., 1994; Helenius et al., 1998). As we will see, this network corresponds precisely to the semantic convergence zones described in neuroimaging studies (Binder & Desai, 2011) and is compatible with a functional role of N400 in semantic integration or binding processes.

The N400: Binding Semantic Features in Coherent Conceptual Representations?

We have seen that the N400 may be a default response of the brain to the processing of semantic information: it is evoked by all meaning dimensions and semantic effects described in behavioral studies. The N400 thus constitutes a valuable index of semantic processing. Moreover, N400 scalp distribution varies with the category of stimuli being presented. As we will see, this is consistent with the idea of a distributed property-based network. In addition to its systematic sensitivity to the processing of meaning, investigators have observed that the N400 has a remarkable temporal stability. With the exception of a few studies that manipulated memory load, repetition or perceptual difficulty (Renoult, Wang, Calcagno, Prévost, & Debruille, 2012), the peak of N400 more or less always occur around 400ms after stimulus onset. As suggested by Federmeier and Laszlo (2009), timing may thus be key to understand how the semantic system binds together the distributed elementary features that constitute semantic representations. The N400 "striking temporal stability" may indicate that time is the gating factor for semantic processing (Federmeier & Laszlo, 2009; see also Kutas & Federmeier, 2010). Importantly, the view that the N400 reflects the binding or integration (Holcomb, 1993; van Berkum, Hagoort, & Brown, 1999) of semantic features into coherent semantic representations does not imply that no further semantic processing takes place after the N400 time window (around 250 to 500 ms after stimulus onset). Later semantic effects have been described and involved in the processing of meaning revision (Federmeier, Wlotko, De Ochoa-Dewald, & Kutas, 2007) or resolution of semantic ambiguity (Lee & Federmeier, 2006).

Functional Neuroimaging and the Structure of Concepts

In the following section, we will review the contribution of functional neuroimaging studies to the understanding of the structure of semantic memory. Two specific areas of research will be discussed. The first area has demonstrated how conceptual representations may be grounded in perception and action. The second has shown how different categories of knowledge may be segregated in different brain regions.

Brains regions most commonly associated with semantic processing

A Property based network

As stated by Patterson, Nestor, & Rogers (2007), "essentially all current theoretical positions about semantic memory share the view that much of the content of our semantic memory relates to perception and action, and is represented in brain regions that overlap with, or possibly even correspond to, the regions that are responsible for perceiving and acting." The idea that conceptual representations would be grounded in perception and action is not new however. The sensualist Philosophers, such as John Locke (1632-1704) or David Hume (1711-1776), stipulated that everything in the mind first passed through the senses or, in other words, that ideas originate in sensations. More recently, the famous neurologist John Hughlings Jackson (1835-1911) considered that "ideas of objects" are sensori-motor in nature (Jackson, 1884; see also York & Steinberg, 2011) and that, for example, a concept like "ball" would essentially be reduced to the impressions produced by the feel of its surface and the particular muscular adjustments required to pick it up.

In Cognitive Neuroscience, the view of a "grounded" or "embodied" conceptual system is most often associated with the idea that our conceptual representations are widely distributed in the brain and follow functional specialization of the cortex (Allport, 1985; Martin & Simmons, 2008; Paller, 2001; Patterson et al., 2007; Taylor et al., 2011; Thompson-Schill, 2003). In accordance with this view, the conceptual representations of objects would be as widespread as their respective attributes (i.e., shape, color, texture, size, sounds they make, function, etc., see Figure 2.3). Brain regions that are initially active when information is acquired would then be recruited when re-accessing the representation of the object (Saffran & Scholl, 1999). Importantly, once information is stored in semantic memory, the global representation of an object including all these distributed features will be accessed similarly by different means (i.e., recognition, denomination, reading, imagination) and the corresponding brain activations will be very similar (Martin, 2001).

Results from functional imaging studies are compatible with this perspective. A recent review of 38 studies examining modality-specific knowledge during language comprehension shows activation in or near areas usually associated with processing information from that modality (see Binder & Desai, 2011). For instance, retrieving knowledge about sound, touch and taste activates the corresponding auditory, somatosensory and gustatory cortical regions (Goldberg, Perfetti, & Schneider, 2006; Kellenbach, Brett, & Patterson, 2001). Similarly, reading action words related to movements of the face (e.g., smile), arm (throw), or leg (kick) results in somatotopic activations in motor and premotor cortices associated with movements of these body parts (Hauk, Johnsrude, & Pulvermuller, 2004). Another example is provided by a recent study by Desai, Binder, Conant, & Seidenberg (2010), in which participants listened to sentences describing actions, visual events or abstract events. Cortical areas associated with the planning and control of hand movements showed greater activation for sentences describing hand and arm actions, whereas visual association cortices were found to be activated by sentences describing visual events. Results of other studies using techniques with better time resolution, such as MEG and EEG, suggest that activation of sensory-motor areas occurs very quickly —as early as 200 ms after word presentation (e.g., Pulvermuller, Harle, & Hummel, 2001; Pulvermuller, Shtyrov, & Ilmoniemi, 2005), a time window corresponding to the onset of the N400— and thus that these activations likely do not take place after meaning has been extracted.

One has to note however, that this view of an embodied cognition, grounded in perception and action, may be restricted to concrete concepts. A number of studies have found that abstract stimuli activated large portions of the superior temporal lobe as well as inferior frontal regions, generally in the left hemisphere (Desai et al., 2010; Noppeney & Price, 2004; Sabsevitz, Medler, Seidenberg, & Binder, 2005; Wise et al., 2000). The results of these studies are consistent with the suggestion that processing of abstract concepts activates a verbal-lexical system for which the left hemisphere is dominant (Paivio, 1991). However, abstract concepts have been much less studied than concrete concepts (Crutch & Warrington, 2005) and their heterogeneity has thus certainly been much less appreciated.

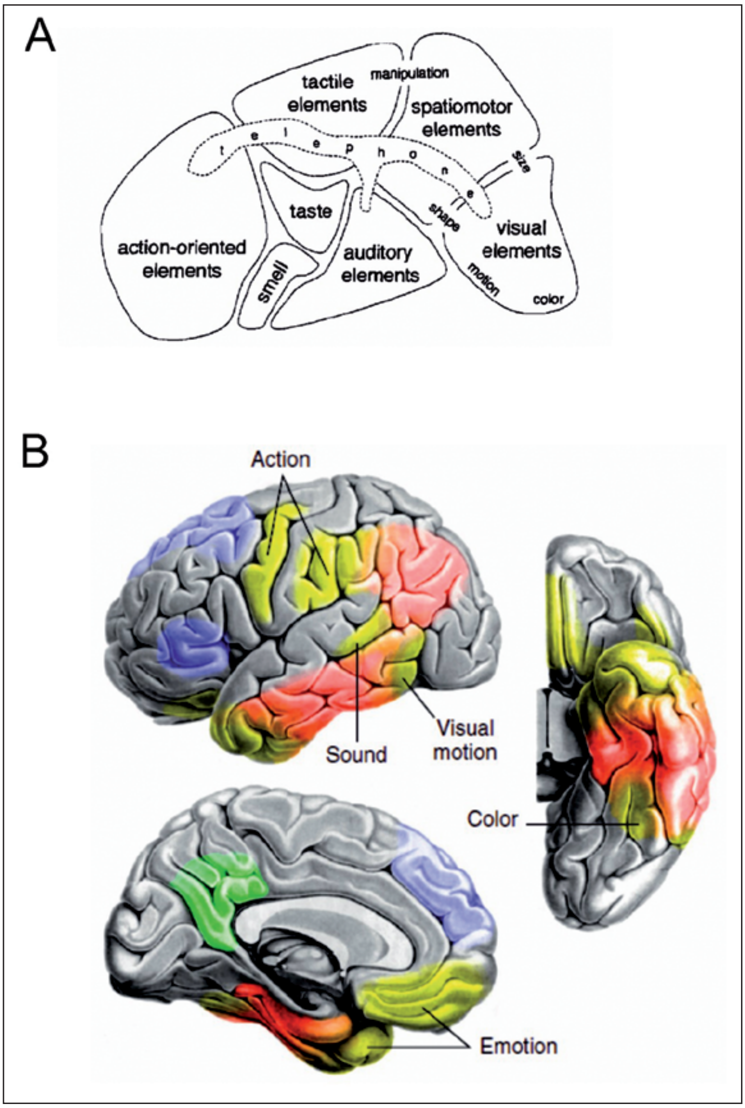


Figure 2.3: A property-based semantic network. This figure illustrates two schematic representations of distributed semantic networks that follow functional specialization of the cortex.

- **A.** A revised version of Allport's model (1985): object concepts are represented in a distributed network composed of sensory-motor attributes (reprinted with permission from Thompson-Schill, Kan and Oliver, 2001, in Cabeza, Roberto, and Alan Kingstone, eds., Handbook of Functional Neuroimaging of Cognition, second edition, Figure 6.1, p. 169, © 2006 Massachusetts Institute of Technology, by permission of The MIT Press).

B. Binder and Desai (2011) neuroanatomical model of semantic processing. Yellow: Modality-specific areas. Red: Convergence zones. Blue: Dorsomedial and inferior prefrontal cortices, involved in selection and control processes. Green: Posterior cingulate gyrus and Precuneus that are hypothesized by these authors to act at the interface between semantic processing and episodic encoding.

Source: reprinted with permission from Binder and Desai (2011).

Convergence zones: Representing or working with semantic knowledge?

Several authors have argued that sensory-motor aspects of conceptual knowledge are not sufficient to generalize across concepts that do not have similar features (Binder & Desai, 2011; Damasio, 1989a, 1989b; Patterson et al., 2007; Simmons & Barsalou, 2003; Taylor et al., 2011). Thus, a number of current views of semantic memory recognize that, in addition to property-based brain regions, associative or convergence zones would be involved in semantic processing. While the existence of convergence zones is not controversial, their precise function in semantic processing is still debated.

In Damasio's model (Damasio, 1989a; 1989b; Meyer & Damasio, 2009), convergence zones are "an attempt to solve the binding problem" (Damasio, 1989b), that is, an attempt at explaining how we are able to experience the world (and concepts in the present case) as a coherent whole, rather than a sum of disparate fragments processed in various cortical areas. Convergence zones are amodal cortical association areas that are responsible for the integration of sensory and motor features in perception (feed-forward projections) as well as for their reactivation in recall (feedback projections). They store the "combinatorial arrangements (binding codes)" of representations stored in early sensory and motor cortices, that is, a sort of "catalogue" for the reconstitution of fragments of experience (Damasio, 1989a). Crucially, this implies that these convergence zones are not storage sites (for multimodal representations). Instead they are only a repository of combinatorial codes that allow binding, reactivation and synchronization of disparate elementary sensory and motor features. In term of anatomical locations, Damasio proposes that convergence zones are diverse and located throughout the telencephalon: in association cortices (at multiple hierarchical levels, from posterior to anterior sites), limbic structures, as well as in the basal ganglia and cerebellum (Damasio, 1989a, 1989b). Importantly, Damasio does not restrict convergence zones to semantic memory in particular but to memory recall and recognition in general. The network that is described is thus less focal than the semantic convergence zones proposed in other models.

In the model of Patterson, Lambon Ralph and colleagues (Lambon Ralph, Sage, Jones, & Mayberry, 2010; Patterson et al., 2007; Rogers et al., 2004), a single semantic convergence zone is proposed. According to the "hub and spokes" model, various semantic features (or "spokes") would be bound through a shared amodal "hub" in the anterior temporal lobe (or temporal pole). Consistent with the model, lesions in this brain region in semantic dementia result in semantic impairment that is independent of the modality of reception (i.e., objects, pictures, words, various sensory modalities) and expression (i.e., naming, drawing or using an object). However, the role of the anterior temporal lobe as a semantic hub is still controversial with some investigators contending that a greater portion of the temporal lobe may serve as a convergence zone (Binder & Desai, 2011, see below), consistent with the observation that atrophy in the more posterior parts of the temporal lobe are also typically correlated with semantic deficits in semantic dementia (Mion et al., 2010; Williams, Nestor, & Hodges, 2005).

Binder and Desai (2011, see also Binder, Desai, Graves, & Conant, 2009) propose that the inferior parietal cortex, the middle and inferior parts of the temporal gyrus as well as the anterior part of the fusiform gyrus would act as convergence zones in semantic processing (see Figure 2.3B). According to these authors, these regions would be involved in general rather than modality specific semantic processing. The activity of brain regions coding for certain features or properties would thus converge and be integrated in these high-order brain regions. These convergence zones would thus be essential in abstracting and generalizing over multiple property-based information and extracting similarity between category exemplars. Crucially, this perspective differs from that of Damasio (1989a, 1989b) in that these convergence zones could serve in representational aspects of semantic memory in Binder's model (see also Simmons & Barsalou, 2003 for a similar perspective). Specifically, Binder and Desai (2011) speculate that the temporal lobe convergence zone would be involved in the semantic processing of concrete objects, while inferior parietal regions such as in the angular gyrus would be involved in conceptual combination (Binder et al., 2009) or in the representation of event concepts, that is, knowledge of events or scripts (Binder & Desai, 2011).

A crucial role of posterior temporal and inferior parietal regions in semantic processing is also proposed by Jefferies and colleagues (Jefferies, 2013; Jefferies & Lambon Ralph, 2006; Noonan, Jefferies, Garrard, Eshan, & Lambon Ralph, 2013) but with a different functional role. Based on patterns of impairments seen in aphasia, these authors propose that left posterior temporal, inferior parietal, as well as inferior frontal regions are involved in semantic control. By this appellation, they refer to the executive aspects of semantic processing such as selecting particular meanings among alternatives. This is illustrated by the finding that patients suffering from stroke aphasia following left tempoparietal and inferior prefrontal lesions access the meaning of items inconsistently and make associative errors, especially in tasks with greater executive demands.

This role of left inferior prefrontal cortex is semantic control is similar to the function attributed to this region by Thompson-Schill and colleagues (Thompson-Schill, 2003; Thompson-Schill, Bedny, & Goldberg, 2005). Inferior (or ventrolateral) prefrontal regions (including Brodmann's areas 44, 45 and 47), mostly on the left hemisphere, have been found to be activated during semantic processing by many neuroimaging studies. However, instead of a role in semantic retrieval or meaning access, Thompson-Schill and colleagues have proposed that this brain region would rather be necessary for selecting and retrieving relevant semantic information from competing alternatives (Thompson-Schill, 2003; Thompson-Schill et al., 2005; see also Bookheimer, 2002).

Effects of Semantic Category

Many neuroimaging studies of semantic memory have compared different classes of objects and observed selective activations. Well-known examples include the selectivity of a specific region of the fusiform gyrus to faces or that of a specific part of the parahippocampal cortex to places. Another well-studied example is the different neural representation of natural categories (such as animals) and artifactual categories (such as tools). Neuropsychological studies have shown that these categories could be doubly-dissociated in patients, even though selective semantic impairments for living things are more frequently observed than for non-living things (Taylor et al., 2011; Warrington & Shallice, 1984). A number of neuroimaging studies have shown that artifacts were associated with activation in frontal areas such as premotor areas, involved in action representation, and at the temporo-occipital junction including the posterior middle temporal gyrus, involved in motion perception (Chao, Haxby, & Martin, 1999; Chao & Martin, 2000; Chao, Weisberg, & Martin, 2002; Devlin et al., 2002; Devlin, Rushworth, & Matthews, 2005; Perani et al., 1999). In contrast, natural categories elicit more activation in visual associative areas (Martin, Wiggs, Ungerleider, & Haxby, 1996; Perani et al., 1999) and in the antero-medial temporal cortex, involved in features integration (Devlin et al., 2002; Moss, Rodd, Stamatakis, Bright, & Tyler, 2005). In addition, natural and artifact categories activate different parts of the fusiform gryus (the lateral part for natural categories and the medial part for artifacts; Chao et al., 1999; Chao et al., 2002; Devlin et al., 2005; Mechelli, Sartori, Orlandi, & Price, 2006).

The most popular interpretation of these category effects suggests that knowledge of natural and artifactual categories rely on a different weighting of various types of elementary features. According to the sensory-functional theory (Warrington & Shallice, 1984), natural categories would rely more on sensory (especially visual) features whereas functional/motor features would be crucial for artifactual categories, hence predicting a different reliance on brain regions processing these respective features. More recent instantiations of this view stipulate that different categories of objects (such as living and non-living items) are associated with different degree of association with various types of features, not only visual or functional, but also information about shape, motion, color, praxis, etc. (see Chen & Rogers, 2014), a perspective that is compatible with a property based network. Accordingly, selective category impairments occur when a lesion disrupts a set of properties that are essential for identifying or discriminating among category members (Martin & Simmons, 2008).

Certain authors have proposed that categories differ on semantic feature statistics (McRae, 2004; Taylor et al., 2011). For instance, in the Conceptual Structure Account (CSA; Taylor et al., 2011; Taylor, Moss, & Tyler, 2007; Tyler & Moss, 2001), two statistical characteristics of semantic features are often considered: distinctiveness (i.e., whether a feature is common to many: <has ears> or only a few concepts: <has a hump>) and co-occurrence in concepts (<has eyes> and <has tail> often co-occur, whereas <has legs> and <has stripes> infrequently co-occurr). Distinctive features are essential to differentiate a stimulus from similar exemplars, and the CSA model predicts that less correlated features will be more vulnerable to the effects of brain damage. Compared to nonliving things, living things have a smaller number of distinctive features and these features are less correlated with other features. This model thus explains well why the category of living things is much often impaired than that of nonliving things.

Finally, a different interpretation of category effects has been proposed by Caramazza and colleagues (reviewed in Mahon & Caramazza, 2009). These authors argued that, rather than being organized according to elementary features, the organization of conceptual knowledge may be "domain-specific". Categories that would have an evolutionary relevant history, such as living animate, living inanimate or tools would be segregated in different brain regions. In accordance with this hypothesis, a few studies reported evidence of an innate organization of conceptual categories, as demonstrated by the effects of early brain lesions (Farah & Rabinowitz, 2003) or category-related brain activations in congenitally blind individuals (Mahon, Anzellotti, Schwarzbach, Zampini, & Caramazza, 2009).

As noted by several investigators (e.g., Martin & Simmons, 2008; Simmons & Barsalou, 2003), these interpretations of category effects are not necessarily mutually exclusive and a domain-type categorical organization could be produced in the brain by a certain anatomical contiguity of property-based information, if these properties are essential for a given category and less for others.

Conclusions

We have reviewed current behavioral, electrophysiological and neuroimaging approaches used in the study of semantic memory. In the first section, we have seen that semantic memory could refer to a type of processing (semantic processing) and a type of representation (semantic representations). On the one hand, behavioral studies have described a number of variables that can be used to measure semantic processing in semantic tasks (i.e., explicit semantic processing) or non-semantic tasks (implicit semantic processing). Electrophysiological studies have reported systematic modulations of the N400 by these variables, both in implicit and explicit conditions. The N400 thus constitutes a valuable neural index of semantic processing. On the other hand, we have seen that most current models of semantic memory assume that semantic representations consist of a distributed network of elementary semantic features. Results of neuroimaging studies are compatible with this view and suggest that these features are distributed in the cortex according to functional specialization (e.g., visual knowledge in visual regions, auditory knowledge in auditory regions, etc.). Several current models of semantic memory assume that additional convergence zones serve to abstract and generalize across various semantic features. These semantic convergence zones may include anterior and posterior parts of the temporal lobe as well as inferior parietal regions. Though the exact function of these brain regions is still being debated, it is interesting to note that they largely overlap with the hypothesized generators of the N400, an observation that is compatible with the proposal that the N400 reflects the binding of elementary semantic features into coherent conceptual representations.

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References

Allport, D. A. (1985). Distributed memory, modular subsystems and dysphasia. In S. K. Newman & R. Epstein (Eds.), *Current perspectives in dysphasia*. (Edinburgh: Churchill Livingstone. ed., pp. 207-244).

Amsel, B. D. (2011). Tracking real-time neural activation of conceptual knowledge using single-trial event-related potentials. *Neuropsychologia*, *49*(5), 970-983. doi: 10.1016/j.neuropsychologia.2011.01.003.

Anderson, J. R. (1983). A Spreading Activation Theory of Memory. *Journal of Verbal Learning and Verbal Behavior*, *22*(3), 261-295. doi: Doi 10.1016/S0022-5371(83)90201-3.

Bach, P., Gunter, T. C., Knoblich, G., Prinz, W., & Friederici, A. D. (2009). N400-like negativities in action perception reflect the activation of two components of an action representation. *Social Neuroscience*, *4*(3), 212-232. doi: 10.1080/17470910802362546.

Bentin, S. (1987). Event-Related Potentials, Semantic Processes, and Expectancy Factors in Word Recognition. *Brain and language*, *31*(2), 308-327. doi: 10.1016/0093-934x(87)90077-0.

Bentin, S., McCarthy, G., & Wood, C. C. (1985). Event-related potentials, lexical decision and semantic priming. *Electroencephalography and clinical neurophysiology*, *60*(4), 343-355.

Binder, J. R., & Desai, R. H. (2011). The neurobiology of semantic memory. *Trends in cognitive sciences*, *15*(11), 527-536. doi: 10.1016/j.tics.2011.10.001

Binder, J. R., Desai, R. H., Graves, W. W., & Conant, L. L. (2009). Where Is the Semantic System? A Critical Review and Meta-Analysis of 120 Functional Neuroimaging Studies. *Cerebral Cortex*, *19*(12), 2767-2796. doi: 10.1093/cercor/bhp055.

Bookheimer, S. (2002). Functional MRI of language: new approaches to understanding the cortical organization of semantic processing. *Annu Rev Neurosci*, *25*, 151-188. doi: 10.1146/annurev.neuro.25.112701.142946.

Brualla, J., Romero, M. F., Serrano, M., & Valdizan, J. R. (1998). Auditory event-related potentials to semantic priming during sleep. *Electroencephalogr Clin Neurophysiol*, *108*(3), 283-290.

Buchanan, L., Westbury, C., & Burgess, C. (2001). Characterizing semantic space: Neighborhood effects in word recognition. *Psychonomic bulletin & review*, *8*(3), 531-544. doi: 10.3758/bf03196189.

Chao, L. L., Haxby, J. V., & Martin, A. (1999). Attribute-based neural substrates in temporal cortex for perceiving and knowing about objects. *Nat Neurosci*, *2*(10), 913-919. doi: 10.1038/13217.

Chao, L. L., & Martin, A. (2000). Representation of manipulable man-made objects in the dorsal stream. *NeuroImage*, *12*(4), 478-484. doi: 10.1006/nimg.2000.0635.

Chao, L. L., Weisberg, J., & Martin, A. (2002). Experience-dependent modulation of category-related cortical activity. *Cereb Cortex*, *12*(5), 545-551.

Chen, L., & Rogers, T. T. (2014). Revisiting domain-general accounts of category specificity in mind and brain. *WIREs Cognitive Science*, *5*, 327-344.

Chwilla, D. J., Brown, C. M., & Hagoort, P. (1995). The N400 as a Function of the Level of Processing. *Psychophysiology*, *32*(3), 274-285. doi: 10.1111/j.1469-8986.1995.tb02956.x

Chwilla, D. J., & Kolk, H. H. J. (2005). Accessing world knowledge: Evidence from N400 and reaction time priming. *Cognitive Brain Research*, *25*(3), 589-606. doi: 10.1016/j.cogbrainres.2005.08.011

Collins, A. M., & Loftus, E. F. (1975). Spreading Activation Theory of Semantic Processing. *Psychological review*, *82*(6), 407-428. doi: 10.1037/0033-295x.82.6.407.

Craik, F. I. M. (2002). Levels of processing: Past, present ... and future? *Memory*, *10*(5-6), 305-318. doi: Doi 10.1080/09658210244000135.

Crutch, S. J., & Warrington, E. K. (2005). Abstract and concrete concepts have structurally different representational frameworks. *Brain*, *128*(Journal Article), 615-627. doi: 10.1093/brain/awh349.

Curran, T., Tucker, D. M., Kutas, M., & Posner, M. I. (1993). Topography of the N400–Brain Electrical-Activity Reflecting Semantic Expectancy. *Electroencephalography and clinical neurophysiology*, *88*(3), 188-209. doi: 10.1016/0168-5597(93)90004-9.

Damasio, A. R. (1989a). The brain binds entities and events by multiregional activation from convergence zones. *Neural Comput.*, *1*(1), 123-132. doi: 10.1162/neco.1989.1.1.123.

Damasio, A. R. (1989b). Time-Locked Multiregional Retroactivation–a Systems-Level Proposal for the Neural Substrates of Recall and Recognition. *Cognition*, *33*(1-2), 25-62. doi: 10.1016/0010-0277(89)90005-x

Deacon, D., Dynowska, A., Ritter, W., & Grose-Fifer, J. (2004). Repetition and semantic priming of nonwords: Implications for theories of N400 and word recognition. *Psychophysiology*, *41*(1), 60-74. doi: Doi 10.1111/1469-8986.00120.

Deacon, D., Hewitt, S., Yang, C., & Nagata, M. (2000). Event-related potential indices of semantic priming using masked and unmasked words: evidence that the N400 does not reflect a post-lexical process. *Brain Res Cogn Brain Res*, *9*(2), 137-146.

Debruille, J. B., & Renoult, L. (2009). Effects of semantic matching and of semantic category on reaction time and N400 that resist numerous repetitions. *Neuropsychologia*, *47*(2), 506-517. doi: 10.1016/j.neuropsychologia.2008.10.007

DeLong, K. A., Urbach, T. P., & Kutas, M. (2005). Probabilistic word pre-activation during language comprehension inferred from electrical brain activity. *Nature neuroscience*, *8*(8), 1117-1121. doi: Doi 10.1038/Nn1504.

Desai, R. H., Binder, J. R., Conant, L. L., & Seidenberg, M. S. (2010). Activation of sensory-motor areas in sentence comprehension. *Cereb Cortex*, *20*(2), 468-478. doi: 10.1093/cercor/bhp115.

Devlin, J. T., Gonnerman, L. M., Andersen, E. S., & Seidenberg, M. S. (1998). Category-specific semantic deficits in focal and widespread brain damage: a computational account. *J Cogn Neurosci*, *10*(1), 77-94.

Devlin, J. T., Moore, C. J., Mummery, C. J., Gorno-Tempini, M. L., Phillips, J. A., Noppeney, U., . . . Price, C. J. (2002). Anatomic constraints on cognitive theories of category specificity. *NeuroImage*, *15*(3), 675-685. doi: 10.1006/nimg.2001.1002.

Devlin, J. T., Rushworth, M. F., & Matthews, P. M. (2005). Category-related activation for written words in the posterior fusiform is task specific. *Neuropsychologia*, *43*(1), 69-74. doi: 10.1016/j.neuropsychologia.2004.06.013.

Domalski, P., Smith, M. E., & Halgren, E. (1991). Cross-Modal Repetition Effects on the N4. *Psychological Science*, *2*(3), 173-178. doi: DOI 10.1111/j.1467-9280.1991.tb00126.x

Elger, C. E., Grunwald, T., Lehnertz, K., Kutas, M., Helmstaedter, C., Brockhaus, A., ... Heinze, H. J. (1997). Human temporal lobe potentials in verbal learning and memory processes. *Neuropsychologia*, *35*(5), 657-667. doi: 10.1016/s0028-3932(96)00110-8

Engel, A. K., Moll, C. K. E., Fried, I., & Ojemann, G. A. (2005). Invasive recordings from the human brain: Clinical insights and beyond. *Nature Reviews Neuroscience*, *6*(1), 35-47. doi: Doi 10.1038/Nrn1585.

Farah, M. J., & Rabinowitz, C. (2003). Genetic and environmental influences on the organisation of semantic memory in the brain:is “living things” an innate category? *Cogn Neuropsychol*, *20*(3), 401-408. doi: 10.1080/02643290244000293

Federmeier, K. D., & Laszlo, S. (2009). Time for Meaning: Electrophysiology Provides Insights into the Dynamics of Representation and

Processing in Semantic Memory. In B. H. Ross (Ed.), *Psychology of Learning and Motivation* (Burlington: Academic Press. ed., Vol. 51, pp. 1-44).

Federmeier, K. D., Wlotko, E. W., De Ochoa-Dewald, E., & Kutas, M. (2007). Multiple effects of sentential constraint on word processing. *Brain research*, *1146*, 75-84. doi: 10.1016/j.brainres.2006.06.101

Fodor, J. A. (1983). *The Modularity of mind : an essay on faculty psychology*. Cambridge, Mass.: MIT Press.

Franklin, M. S., Dien, J., Neely, J. H., Huber, E., & Waterson, L. D. (2007). Semantic priming modulates the N400, N300, and N400RP. *Clinical Neurophysiology*, *118*(5), 1053-1068. doi: 10.1016/j.clinph.2007.01.012.

Friederici, A. D., Hahne, A., & von Cramon, D. Y. (1998). First-pass versus second-pass parsing processes in a Wernicke's and a Broca's aphasic: Electrophysiological evidence for a double dissociation. *Brain and language*, *62*(3), 311-341. doi: 10.1006/brln.1997.1906.

Ganis, G., Kutas, M., & Sereno, M. I. (1996). The search for ''common sense'': An electrophysiological study of the comprehension of words and pictures in reading. *Journal of cognitive neuroscience*, *8*(2), 89-106. doi: DOI 10.1162/jocn.1996.8.2.89.

Garrard, P., Ralph, M. A., Hodges, J. R., & Patterson, K. (2001). Prototypicality, distinctiveness, and intercorrelation: Analyses of the semantic attributes of living and nonliving concepts. *Cogn Neuropsychol*, *18*(2), 125-174. doi: 10.1080/02643290125857.

Goldberg, R. F., Perfetti, C. A., & Schneider, W. (2006). Perceptual knowledge retrieval activates sensory brain regions. *J Neurosci*, *26*(18), 4917-4921. doi: 10.1523/JNEUROSCI.5389-05.2006.

Gratton, C., Evans, K. M., & Federmeier, K. D. (2009). See what I mean? An ERP study of the effect of background knowledge on novel object processing. *Mem Cognit*, *37*(3), 277-291. doi: 10.3758/MC.37.3.277.

Grondin, R., Lupker, S. J., & McRae, K. (2009). Shared features dominate semantic richness effects for concrete concepts. *Journal of Memory and Language*, *60*(1), 1-19. doi: 10.1016/j.jml.2008.09.001.

Grunwald, T., Lehnertz, K., Heinze, H. J., Helmstaedter, C., & Elger, C. E. (1998). Verbal novelty detection within the human hippocampus proper. *Proceedings of the National Academy of Sciences of the United States of America*, *95*(6), 3193-3197. doi: 10.1073/pnas.95.6.3193.

Guillem, F., Nkaoua, B., Rougier, A., & Claverie, B. (1995). Intracranial Topography of Event-Related Potentials (N400/p600) Elicited during a Continuous Recognition Memory Task. *Psychophysiology*, *32*(4), 382-392. doi: 10.1111/j.1469-8986.1995.tb01221.x

Guillem, F., Rougier, A., & Claverie, B. (1999). Short- and long-delay intracranial ERP repetition effects dissociate memory systems in the human brain. *Journal of cognitive neuroscience*, *11*(4), 437-458. doi: 10.1162/089892999563526.

Hagoort, P., Brown, C. M., & Swaab, T. Y. (1996). Lexical-semantic event-related potential effects in patients with left hemisphere lesions and aphasia, and patients with right hemisphere lesions without aphasia. *Brain*, *119*(Journal Article), 627-649. doi: 10.1093/brain/119.2.627.

Hagoort, P., Hald, L., Bastiaansen, M., & Petersson, K. M. (2004). Integration of word meaning and world knowledge in language comprehension. *Science*, *304*(5669), 438-441. doi: 10.1126/science.1095455.

Halgren, E., Baudena, P., Heit, G., Clarke, M., Marinkovic, K., & Chauvel, P. (1994). Spatiotemporal Stages in Face and Word-Processing .2. Depth-Recorded Potentials in the Human Frontal and Rolandic Cortices. *Journal of Physiology-Paris*, *88*(1), 51-80. doi: 10.1016/0928-4257(94)90093-0.

Halgren, E., Dhond, R. P., Christensen, N., Van Petten, C., Marinkovic, K., Lewine, J. D., & Dale, A. M. (2002). N400-like magnetoencephalography responses modulated by semantic context, word frequency, and lexical class in sentences. *NeuroImage*, *17*(3), 1101-1116. doi: 10.1006/nimg.2002.1268.

Handy, T. C. (2005). *Event-related potentials: a methods handbook*. Camridge, Mass.: MIT Press.

Hauk, O., Johnsrude, I., & Pulvermuller, F. (2004). Somatotopic representation of action words in human motor and premotor cortex. *Neuron*, *41*(2), 301-307.

Heinze, H. J., Muente, T. F., & Kutas, M. (1998). Context effects in a category verification task as assessed by event-related brain potential (ERP) measures. *Biological psychology*, *47*(2), 121-135. doi: 10.1016/s0301-0511(97)00024-0.

Helenius, P., Salmelin, R., Service, E., & Connolly, J. F. (1998). Distinct time courses of word and context comprehension in the left temporal cortex. *Brain*, *121*(Journal Article), 1133-1142. doi: 10.1093/brain/121.6.1133.

Helenius, P., Salmelin, R., Service, E., Connolly, J. F., Leinonen, S., & Lyytinen, H. (2002). Cortical activation during spoken-word segmentation in nonreading-impaired and dyslexic adults. *Journal of Neuroscience*, *22*(7), 2936-2944.

Holcomb, P. J. (1988). Automatic and Attentional Processing–an Event-Related Brain Potential Analysis of Semantic Priming. *Brain and language*, *35*(1), 66-85. doi: 10.1016/0093-934x(88)90101-0.

Holcomb, P. J. (1993). Semantic Priming and Stimulus Degradation–Implications for the Role of the N400 in Language Processing. *Psychophysiology*, *30*(1), 47-61.

Holcomb, P. J., Kounios, J., Anderson, J. E., & West, W. C. (1999). Dual-coding, context-availability, and concreteness effects in sentence comprehension: An electrophysiological investigation. *Journal of Experimental Psychology-Learning Memory and Cognition*, *25*(3), 721-742. doi: 10.1037/0278-7393.25.3.721.

Hutchison, K. A. (2003). Is semantic priming due to association strength or feature overlap? A microanalytic review. *Psychonomic bulletin & review*, *10*(4), 785-813. doi: 10.3758/bf03196544.

Ibanez, A., Lopez, V., & Cornejo, C. (2006). ERPs and contextual semantic discrimination: Degrees of congruence in wakefulness and sleep. *Brain and language*, *98*(3), 264-275. doi: DOI 10.1016/j.bandl.2006.05.005.

Jackson, J. H. (1884). The Croonian Lectures on Evolution and Dissolution of the Nervous System. *Br Med J*, *1*(1215), 703-707.

Jefferies, E. (2013). The neural basis of semantic cognition: converging evidence from neuropsychology, neuroimaging and TMS. *Cortex*, *49*(3), 611-625. doi: 10.1016/j.cortex.2012.10.008.

Jefferies, E., & Lambon Ralph, M. A. (2006). Semantic impairment in stroke aphasia versus semantic dementia: a case-series comparison. *Brain*, *129*(Pt 8), 2132-2147. doi: 10.1093/brain/awl153.

Johnson, B. W., & Hamm, J. P. (2000). High-density mapping in an N400 paradigm: evidence for bilateral temporal lobe generators. *Clinical Neurophysiology*, *111*(3), 532-545. doi: 10.1016/s1388-2457(99)00270-9.

Kappenman, E., & Luck, S. J. (2011). *The Oxford Handbook of Event-Related Potential Components.* (Oxford University Press. ed.).

Kellenbach, M. L., Brett, M., & Patterson, K. (2001). Large, colorful, or noisy? Attribute- and modality-specific activations during retrieval of perceptual attribute knowledge. *Cogn Affect Behav Neurosci*, *1*(3), 207-221.

Kiefer, M. (2001). Perceptual and semantic sources of category-specific effects: Event-related potentials during picture and word categorization. *Memory & cognition*, *29*(1), 100-116. doi: 10.3758/bf03195745.

Kiefer, M. (2002). The N400 is modulated by unconsciously perceived masked words: further evidence for an automatic spreading activation account of N400 priming effects. *Cognitive Brain Research*, *13*(1), 27-39. doi: 10.1016/s0926-6410(01)00085-4.

Kiefer, M. (2005). Repetition-priming modulates category-related effects on event-related potentials: Further evidence for multiple cortical semantic systems. *Journal of cognitive neuroscience*, *17*(2), 199-211. doi: 10.1162/0898929053124938.

Komatsu, L. K. (1992). Recent Views of Conceptual Structure. *Psychological bulletin*, *112*(3), 500-526. doi: 10.1037//0033-2909.112.3.500.

Kounios, J. (1996). On the continuity of thought and the representation of knowledge: Electrophysiological and behavioral time-course measures reveal levels of structure in semantic memory. *Psychonomic bulletin & review*, *3*(3), 265-286. doi: 10.3758/bf03210752.

Kounios, J., & Holcomb, P. J. (1994). Concreteness Effects in Semantic Processing–Erp Evidence Supporting Dual-Coding Theory. *Journal of Experimental Psychology-Learning Memory and Cognition*, *20*(4), 804-823. doi: 10.1037/0278-7393.20.4.804.

Kutas, M., & Federmeier, K. D. (2000). Electrophysiology reveals semantic memory use in language comprehension. *Trends in cognitive sciences*, *4*(12), 463-470. doi: 10.1016/s1364-6613(00)01560-6.

Kutas, M., & Federmeier, K. D. (2011). Thirty years and counting: finding meaning in the N400 component of the event-related brain potential (ERP). *ANNUAL REVIEW OF PSYCHOLOGY*, *62*(Journal Article), 621-647. doi: 10.1146/annurev.psych.093008.131123.

Kutas, M., & Hillyard, S. A. (1980). Reading Senseless Sentences–Brain Potentials Reflect Semantic Incongruity. *Science*, *207*(4427), 203-205. doi: 10.1126/science.7350657.

Kutas, M., & Hillyard, S. A. (1984). Brain Potentials during Reading Reflect Word Expectancy and Semantic Association. *Nature*, *307*(5947), 161-163. doi: 10.1038/307161a0.

Kutas, M., & Iragui, V. (1998). The N400 in a semantic categorization task across 6 decades. *Evoked Potentials-Electroencephalography and Clinical Neurophysiology*, *108*(5), 456-471. doi: 10.1016/s0168-5597(98)00023-9.

Kutas, M., & Van Petten, C. (1994). Psycholinguistics electrified: Event-related brain potential investigations. *Handbook of Psycholinguistics*. (San Diego, CA: Academic. ed., pp. 83-143).

Kutas, M., Van Petten, C. K., & Kluender, R. (2006). Psycholinguistics Electrified II (1994-2005). In J. T. Matthew & A. G. Morton (Eds.), *Handbook of Psycholinguistics (Second Edition)* (pp. 659-724). London: Academic Press.

Lambon Ralph, M. A., Sage, K., Jones, R. W., & Mayberry, E. J. (2010). Coherent concepts are computed in the anterior temporal lobes. *Proc Natl Acad Sci U S A*, *107*(6), 2717-2722. doi: 10.1073/pnas.0907307107.

Laszlo, S., & Federmeier, K. D. (2010). The N400 as a snapshot of interactive processing: Evidence from regression analyses of orthographic neighbor and lexical associate effects. *Psychophysiology*. doi: 10.1111/j.1469-8986.2010.01058.x

Lau, E. F., Phillips, C., & Poeppel, D. (2008). A cortical network for semantics: (de)constructing the N400. *Nature Reviews Neuroscience*, *9*(12), 920-933. doi: 10.1038/nrn2532.

Lee, C. L., & Federmeier, K. D. (2006). To mind the mind: an event-related potential study of word class and semantic ambiguity. *Brain Res*, *1081*(1), 191-202. doi: 10.1016/j.brainres.2006.01.058.

Liu, Y., Perfetti, C. A., & Hart, L. (2003). ERP evidence for the time course of graphic, phonological, and semantic information in Chinese meaning and pronunciation decisions. *Journal of Experimental Psychology-Learning Memory and Cognition*, *29*(6), 1231-1247. doi: 10.1037/0278-7393.29.6.1231.

Lucas, M. (2000). Semantic priming without association: A meta-analytic review. *Psychonomic bulletin & review*, *7*(4), 618-630. doi: 10.3758/bf03212999.

Luck, S. J. (2005). *An introduction to the event-related potential technique*. Cambridge, Mass. [u.a.]: MIT Press.

Mahon, B. Z., Anzellotti, S., Schwarzbach, J., Zampini, M., & Caramazza, A. (2009). Category-specific organization in the human brain does not require visual experience. *Neuron*, *63*(3), 397-405. doi: 10.1016/j.neuron.2009.07.012.

Mahon, B. Z., & Caramazza, A. (2009). Concepts and categories: a cognitive neuropsychological perspective. *Annu Rev Psychol*, *60*, 27-51. doi: 10.1146/annurev.psych.60.110707.163532.

Martin, A. (2001). Functional neuroimaging of semantic memory. In R. Cabeza & A. Kingstone (Eds.), *Handbook of Functional NeuroImaging of Cognition* (pp. 153-186): Cambridge: MIT Press.

Martin, A., & Simmons, W. K. (2008). 3.07–Structural Basis of Semantic Memory. In H. B. Editor-in-Chief: John (Ed.), *Learning and Memory: A Comprehensive Reference* (pp. 113-130). Oxford: Academic Press.

Martin, A., Wiggs, C. L., Ungerleider, L. G., & Haxby, J. V. (1996). Neural correlates of category-specific knowledge. *Nature*, *379*(6566), 649-652. doi: 10.1038/379649a0.

Martinelli, P., Sperduti, M., & Piolino, P. (2012). Neural substrates of the self-memory system: New insights from a meta-analysis. *Hum Brain Mapp*. doi: 10.1002/hbm.22008.

Matsumoto, A., Iidaka, T., Haneda, K., Okada, T., & Sadato, N. (2005). Linking semantic priming effect in functional MRI and event-related potentials. *NeuroImage*, *24*(3), 624-634. doi: 10.1016/j.neuroimage.2004.09.008.

McClelland, J. L., & Rumelhart, D. E. (1985). Distributed Memory and the Representation of General and Specific Information. *Journal of Experimental Psychology-General*, *114*(2), 159-188. doi: Doi 10.1037//0096-3445.114.2.159.

McRae, K. (2004). Semantic memory: Some insights from feature-based connectionist attractor networks. *Psychology of Learning and Motivation: Advances in Research and Theory, Vol 45*, *45*, 41-86. doi: Doi 10.1016/S0079-7421(03)45002-0.

McRae, K., Cree, G. S., Seidenberg, M. S., & McNorgan, C. (2005). Semantic feature production norms for a large set of living and nonliving things. *Behavior Research Methods*, *37*(4), 547-559. doi: 10.3758/bf03192726.

Mechelli, A., Sartori, G., Orlandi, P., & Price, C. J. (2006). Semantic relevance explains category effects in medial fusiform gyri. *NeuroImage*, *30*(3), 992-1002. doi: 10.1016/j.neuroimage.2005.10.017.

Meyer, K., & Damasio, A. (2009). Convergence and divergence in a neural architecture for recognition and memory. *Trends in Neuroscience*, *32*(7), 376-382. doi: 10.1016/j.tins.2009.04.002.

Meyer, P., Mecklinger, A., & Friederici, A. D. (2010). On the Processing of Semantic Aspects of Experience in the Anterior Medial Temporal Lobe: An Event-related fMRI Study. *Journal of cognitive neuroscience*, *22*(3), 590-601. doi: DOI 10.1162/jocn.2009.21199.

Mion, M., Patterson, K., Acosta-Cabronero, J., Pengas, G., Izquierdo-Garcia, D., Hong, Y. T., . . . Nestor, P. J. (2010). What the left and right anterior fusiform gyri tell us about semantic memory. *Brain*, *133*(11), 3256-3268. doi: 10.1093/brain/awq272.

Misra, M., & Holcomb, P. J. (2003). Event-related potential indices of masked repetition priming. *Psychophysiology*, *40*(1), 115-130.

Mitchell, P. F., Andrews, S., Fox, A. M., Catts, S. V., Ward, P. B., & McConaghy, N. (1991). Active and Passive Attention in Schizophrenia–an Erp Study of Information-Processing in a Linguistic Task. *Biological psychology*, *32*(2-3), 101-124. doi: 10.1016/0301-0511(91)90004-z

Moss, H. E., Rodd, J. M., Stamatakis, E. A., Bright, P., & Tyler, L. K. (2005). Anteromedial temporal cortex supports fine-grained differentiation among objects. *Cereb Cortex*, *15*(5), 616-627. doi: 10.1093/cercor/bhh163.

Muller, O., Andoni Dunabeitia, J., & Carreiras, M. (2010). Orthographic and associative neighborhood density effects: What is shared, what is different? *Psychophysiology*, *47*(3), 455-466. doi: 10.1111/j.1469-8986.2009.00960.x

Murphy, G. L. (2002). *The big book of concepts*. Cambridge, Mass.: MIT Press.

Neely, J. H. (1991). Semantic priming effects in visual word recognition: A selective review of current findings and theories. In

D. Besner & G. W. Humphreys (Eds.), *Basic processes in reading: Visual word recognition.* (Hillsdale, NJ: Erlbaum ed., pp. 264-336).

Neely, J. H., & Kahan, T. A. (2001). Is semantic activation automatic? A critical re-evaluation. *Nature of Remembering*, 69-93. doi: Doi 10.1037/10394-005.

Nittono, H., Suehiro, M., & Hori, T. (2002). Word imageability and N400 in an incidental memory paradigm. *International Journal of Psychophysiology, 44*(3), 219-229. doi: 10.1016/s0167-8760(02)00002-8.

Nobre, A. C., & McCarthy, G. (1995). Language-Related Field Potentials in the Anterior-Medial Temporal-Lobe .2. Effects of Word Type and Semantic Priming. *Journal of Neuroscience, 15*(2), 1090-1098.

Noonan, K. A., Jefferies, E., Garrard, P., Eshan, S., & Lambon Ralph, M. A. (2013). Demonstrating the qualitative differences between semantic aphasia and semantic dementia: a novel exploration of nonverbal semantic processing. *Behav Neurol, 26*(1-2), 7-20. doi: 10.3233/BEN-2012-110200.

Noppeney, U., & Price, C. J. (2004). Retrieval of abstract semantics. *NeuroImage, 22*(1), 164-170. doi: 10.1016/j.neuroimage.2003.12.010.

Paivio, A. (1991). Dual coding theory: Retrospect and current status. *Canadian Journal of Psychology/Revue canadienne de psychologie, 45*(3), 255-287. doi: 10.1037/h0084295.

Paivio, A., Yuille, J. C., & Madigan, S. A. (1968). Concreteness Imagery and Meaningfulness Values for 925 Nouns. *Journal of experimental psychology, 76*(1p2), 1-&. doi: Doi 10.1037/H0025327.

Paller, K. A. (2001). Neurocognitive foundations of human memory. *Psychology of Learning and Motivation: Advances in Research and Theory, Vol 40, 40*, 121-145.

Patterson, K. (2007). The reign of typicality in semantic memory. *Philosophical Transactions of the Royal Society B-Biological Sciences, 362*(1481), 813-821. doi: 10.1098/rstb.2007.2090.

Patterson, K., Nestor, P. J., & Rogers, T. T. (2007). Where do you know what you know? The representation of semantic knowledge in the human brain. *Nat Rev Neurosci*, *8*(12), 976-987. doi: 10.1038/nrn2277.

Paz-Caballero, D., Cuetos, F., & Dobarro, A. (2006). Electrophysiological evidence for a natural/artifactual dissociation. *Brain research*, *1067*(1), 189-200. doi: 10.1016/j.brainres.2005.10.046.

Perani, D., Schnur, T., Tettamanti, M., Gorno-Tempini, M., Cappa, S. F., & Fazio, F. (1999). Word and picture matching: a PET study of semantic category effects. *Neuropsychologia*, *37*(3), 293-306.

Perrin, F., Bastuji, H., & Garcia-Larrea, L. (2002). Detection of verbal discordances during sleep. *Neuroreport*, *13*(10), 1345-1349. doi: Doi 10.1097/00001756-200207190-00026.

Pexman, P. M., Holyk, G. G., & Monfils, M. H. (2003). Number-of-features effects and semantic processing. *Memory & cognition*, *31*(6), 842-855. doi: 10.3758/bf03196439.

Price, C. J., & Humphreys, G. W. (1989). The Effects of Surface Detail on Object Categorization and Naming. *Quarterly Journal of Experimental Psychology Section A-Human Experimental Psychology*, *41*(4), 797-828.

Proverbio, A. M., Del Zotto, M., & Zani, A. (2007). The emergence of semantic categorization in early visual processing: ERP indices of animal vs. artifact recognition. *BMC neuroscience*, *8*(Journal Article), 24. doi: 10.1186/1471-2202-8-24.

Pulvermuller, F., Harle, M., & Hummel, F. (2001). Walking or talking? Behavioral and neurophysiological correlates of action verb processing. *Brain Lang*, *78*(2), 143-168. doi: 10.1006/brln.2000.2390.

Pulvermuller, F., Shtyrov, Y., & Ilmoniemi, R. (2005). Brain signatures of meaning access in action word recognition. *J Cogn Neurosci*, *17*(6), 884-892. doi: 10.1162/0898929054021111.

Rabovsky, M., Sommer, W., & Abdel Rahman, R. (2012). The time course of semantic richness effects in visual word recognition. *Frontiers in Human Neuroscience*, *6*(Journal Article), 11. doi: 10.3389/fnhum.2012.00011.

Rahman, R. A., & Sommer, W. (2008). Seeing what we know and understand: how knowledge shapes perception. *Psychon Bull Rev, 15*(6), 1055-1063. doi: 10.3758/PBR.15.6.1055.

Renoult, L., Brodeur, M. B., & Debruille, J. B. (2010). Semantic processing of highly repeated concepts presented in single-word trials: Electrophysiological and behavioral correlates. *Biological psychology, 84*(2), 206-220. doi: 10.1016/j.biopsycho.2010.01.014.

Renoult, L., Davidson, P. S. R., Palombo, D. J., Moscovitch, M., & Levine, B. (2012). Personal Semantics: At the crossroads of semantic and episodic memory. *Trends in cognitive sciences*, *16*(11).

Renoult, L., & Debruille, J. B. (2011). N400-like Potentials and Reaction Times Index Semantic Relations between Highly Repeated Individual Words. *Journal of cognitive neuroscience*, *23*(4), 905-922. doi: 10.1162/jocn.2009.21410.

Renoult, L., Wang, X., Calcagno, V., Prévost, M., & Debruille, J. B. (2012). From N400 to N300: Variations in the timing of semantic processing with repetition. *NeuroImage*, *61*(1), 206-215. doi: 10.1016/j.neuroimage.2012.02.069.

Renoult, L., Wang, X., Mortimer, J., & Debruille, J. B. (2012). Explicit semantic tasks are necessary to study semantic priming effects with high rates of repetition. *Clinical Neurophysiology*, *123*(4), 741-754. doi: 10.1016/j.clinph.2011.08.025.

Rogers, T. T., Lambon Ralph, M. A., Garrard, P., Bozeat, S., McClelland, J. L., Hodges, J. R., & Patterson, K. (2004). Structure and deterioration of semantic memory: a neuropsychological and computational investigation. *Psychol Rev*, *111*(1), 205-235. doi: 10.1037/0033-295X.111.1.205.

Sabsevitz, D. S., Medler, D. A., Seidenberg, M., & Binder, J. R. (2005). Modulation of the semantic system by word imageability. *NeuroImage*, *27*(1), 188-200. doi: 10.1016/j.neuroimage.2005.04.012.

Saffran, E. M., & Scholl, A. (1999). Clues to the functional and neural architecture of word meaning. In C. M. Brown & P. Hagoort (Eds.), *The neurocognition of language.* (pp. 241-272). Oxford England ; New York: Oxford University Press.

Schnyer, D. M., Allen, J. J., & Forster, K. I. (1997). Event-related brain potential examination of implicit memory processes: masked and unmasked repetition priming. *Neuropsychology*, *11*(2), 243-260.

Schwanenflugel, P. J. (1991). Why are Abstract Concepts Hard to Understand? In P. J. Swanenflugel (Ed.), *The psychology of word meanings*. (Hillsdale, NJ, England: Lawrence Erlbaum Associates. ed., pp. 223-250).

Service, E., Helenius, P., Maury, S., & Salmelin, R. (2007). Localization of syntactic and semantic brain responses using magnetoencephalography. *Journal of cognitive neuroscience*, *19*(7), 1193-1205. doi: 10.1162/jocn.2007.19.7.1193.

Siakaluk, P. D., Buchanan, L., & Westbury, C. (2003). The effect of semantic distance in yes/no and go/no-go semantic categorization tasks. *Memory & cognition*, *31*(1), 100-113. doi: Doi 10.3758/Bf03196086.

Sim, E. J., & Kiefer, M. (2005). Category-related brain activity to natural categories is associated with the retrieval of visual features: Evidence from repetition effects during visual and functional judgments. *Cognitive Brain Research*, *24*(2), 260-273. doi: 10.1016/j.cogbrainres.2005.02.006.

Simmons, W. K., & Barsalou, L. W. (2003). The similarity-in-topography principle: reconciling theories of conceptual deficits. *Cogn Neuropsychol*, *20*(3), 451-486. doi: 10.1080/02643290342000032.

Simos, P. G., Basile, L. F. H., & Papanicolaou, A. C. (1997). Source localization of the N400 response in a sentence-reading paradigm using evoked magnetic fields and magnetic resonance imaging. *Brain research*, *762*(1-2), 29-39. doi: 10.1016/s0006-8993(97)00349-1.

Smith, M. E., & Halgren, E. (1987). Event-related potentials during lexical decision: effects of repetition, word frequency, pronounceability, and concreteness. *Electroencephalography and clinical neurophysiology.Supplement*, *40*(Journal Article), 417-421.

Smith, M. E., Stapleton, J. M., & Halgren, E. (1986). Human Medial Temporal-Lobe Potentials-Evoked in Memory and Language

Tasks. *Electroencephalography and clinical neurophysiology*, *63*(2), 145-159. doi: 10.1016/0013-4694(86)90008-8.

Swaab, T., Brown, C., & Hagoort, P. (1997). Spoken sentence comprehension in aphasia: Event-related potential evidence for a lexical integration deficit. *Journal of cognitive neuroscience*, *9*(1), 39-66. doi: DOI 10.1162/jocn.1997.9.1.39.

Swaab, T. Y., Baynes, K., & Knight, R. T. (2002). Separable effects of priming and imageability on word processing: an ERP study. *Cognitive Brain Research*, *15*(1), 99-103. doi: 10.1016/s0926-6410(02)00219-7.

Taler, V., Kousaie, S., & Zunini, R. L. (2013). ERP measures of semantic richness: the case of multiple senses. *Frontiers in Human Neuroscience*, *7*. doi: Artn 5.

Doi 10.3389/Fnhum.2013.00005.

Taylor, K. I., Devereux, B. J., Acres, K., Randall, B., & Tyler, L. K. (2012). Contrasting effects of feature-based statistics on the categorisation and basic-level identification of visual objects. *Cognition*, *122*(3), 363-374. doi: 10.1016/j.cognition.2011.11.001.

Taylor, K. I., Devereux, B. J., & Tyler, L. K. (2011). Conceptual structure: Towards an integrated neurocognitive account. *Language and Cognitive Processes*, *26*(9), 1368-1401. doi: Doi 10.1080/01690965.2011.568227.

Taylor, K. I., Moss, H. E., & Tyler, L. K. (2007). The Conceptual Structure Account: A cognitive model of semantic memory and its neural instantiation. In J. Hart & M. Kraut (Eds.), *The Neural Basis of Semantic Memory* (pp. 265-301). Cambridge: Cambridge University Press.

Thompson-Schill, S. L. (2003). Neuroimaging studies of semantic memory: inferring "how" from "where". *Neuropsychologia*, *41*(3), 280-292. doi: 10.1016/s0028-3932(02)00161-6.

Thompson-Schill, S. L., Bedny, M., & Goldberg, R. F. (2005). The frontal lobes and the regulation of mental activity. *Curr Opin Neurobiol*, *15*(2), 219-224. doi: 10.1016/j.conb.2005.03.006.

Tulving, E. (1972). Episodic and Semantic Memory. *Organization of memory.* (pp. 381-403). New York: Academic Press.

Tulving, E. (1983). *Elements of episodic memory*. Oxford: Clarendon Press ; New York : Oxford University Press.

Tulving, E. (2002). Episodic memory: From mind to brain. *ANNUAL REVIEW OF PSYCHOLOGY*, *53*(Journal Article), 1-25. doi: 10.1146/annurev.psych.53.100901.135114.

Tulving, E., & Schacter, D. L. (1990). Priming and Human-Memory Systems. *Science*, *247*(4940), 301-306.

Tyler, L. K., & Moss, H. E. (2001). Towards a distributed account of conceptual knowledge. *Trends Cogn Sci*, *5*(6), 244-252.

van Berkum, J. J. A., Hagoort, P., & Brown, C. M. (1999). Semantic integration in sentences and discourse: Evidence from the N400. *Journal of cognitive neuroscience*, *11*(6), 657-671.

Van Petten, C. (1993). A Comparison of Lexical and Sentence-Level Context Effects in Event-Related Potentials. *Language and Cognitive Processes*, *8*(4), 485-531. doi: Doi 10.1080/01690969308407586.

Van Petten, C., & Kutas, M. (1990). Interactions between sentence context and word frequency in event-related brain potentials. *Mem Cognit*, *18*(4), 380-393.

Van Petten, C., & Luka, B. J. (2006). Neural localization of semantic context effects in electromagnetic and hemodynamic studies. *Brain and language*, *97*(3), 279-293. doi: 10.1016/j.bandl.2005.11.003.

Warrington, E. K., & Shallice, T. (1984). Category Specific Semantic Impairments. *Brain*, *107*(SEP), 829-854. doi: 10.1093/brain/107.3.829.

West, W. C., & Holcomb, P. J. (2000). Imaginal, semantic, and surface-level processing of concrete and abstract words: An electrophysiological investigation. *Journal of cognitive neuroscience*, *12*(6), 1024-1037. doi: 10.1162/08989290051137558.

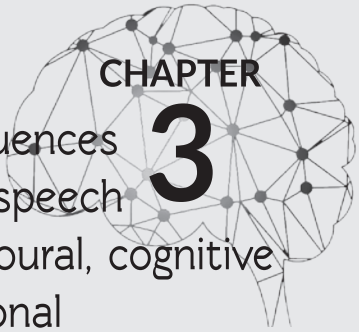
Williams, G. B., Nestor, P. J., & Hodges, J. R. (2005). Neural correlates of semantic and behavioural deficits in frontotemporal dementia. *NeuroImage*, *24*(4), 1042-1051. doi: 10.1016/j.neuroimage.2004.10.023.

Wise, R. J., Howard, D., Mummery, C. J., Fletcher, P., Leff, A., Buchel, C., & Scott, S. K. (2000). Noun imageability and the temporal lobes. *Neuropsychologia*, *38*(7), 985-994.

Yap, M. J., Tan, S. E., Pexman, P. M., & Hargreaves, I. S. (2011). Is more always better? Effects of semantic richness on lexical decision, speeded pronunciation, and semantic classification. *Psychonomic bulletin & review*, *18*(4), 742-750. doi: 10.3758/s13423-011-0092-y

York, G. K., 3rd, & Steinberg, D. A. (2011). Hughlings Jackson's neurological ideas. *Brain*, *134*(Pt 10), 3106-3113. doi: 10.1093/brain/awr219.

Young, M. P., & Rugg, M. D. (1992). Word-Frequency and Multiple Repetition as Determinants of the Modulation of Event-Related Potentials in a Semantic Classification Task. *Psychophysiology*, *29*(6), 664-676.



CHAPTER 3

Towards a comprehensive understanding of the consequences of literacy training for online speech processing: Integrating behavioural, cognitive neuroscience, and computational approaches

Alastair Smith
Falk Huettig

Introduction

Although the process in which you are now engaged may proceed rapidly and largely automatically, the computational complexity of the reading process is great, reflected in the years of effortful learning required for an individual to become a proficient reader. Reading requires the ability to map from structured visual representations (orthography) to pre-existing semantic and phonological information. The social and financial implications of acquiring this ability for the individual are profound, illiterate individuals earn 30-42% less than their literate counterparts (Martinez & Fernandez, 2010), have a lower life expectancy and experience greater social exclusion (UNESCO, 2006). In recent years an increasing body of empirical evidence has emerged to suggest that the impact of literacy at the level of the individual may also extend to qualitatively alter cognitive processing more broadly.

Within this paper we will first briefly describe current understanding of how over the course of literacy training the brain adapts to accommodate the neural apparatus necessary to support efficient reading. We will then provide a brief overview of the implications of this acquisition process for aspects of neural and cognitive processing beyond the language domain, before focusing on a developing body of studies that examine the extent to which literacy impacts on online speech processing. Reading requires the complex interaction of systems that process information across multiple modalities. Understanding how changes within one aspect of the system may impact on processing in another is not trivial, we argue therefore that only through developing computational models at varying levels of abstraction can we gain traction on such issues. We aim, through use of this topic as a case study, to highlight the added value a computational modelling approach can offer when attempting to understand the complex relationship between neural and behavioural findings, and for a meaningful understanding of the underlying system.

Isolating the Neural Apparatus of the Reading System: What Brain Imaging Methods can (and cannot) tell us

Orthographic systems differ in the extent to which they encode a language's phonological or semantic structure (see Comrie, 2013). For example shallow alphabetic systems such as Finnish or Serbian occupy one extreme of the transparency spectrum, in such systems single graphemes perfectly correspond to individual speech sounds. At the opposite end of the spectrum lye logographic systems such as Mandarin Chinese, referred to as opaque systems, in which correspondence between orthography and phonology is only at the level of the morpheme. Mandarin is also an example of a system in which sub-lexical semantic structure can be found within the orthography, with components of the orthographic system (radicals) providing information regarding the semantic category of a word. Even though orthographic systems vary in the degree to which they encode a language's phonological or semantic structure, brain imaging data suggests that populations that vary across these dimensions possess reading systems whose neural architecture spans largely the same key brain regions (e.g. Nakamura et al., 2012).

The brain imaging literature suggests that through viewing orthographic codes proficient readers are able to activate the same left lateralized language processing networks that respond to speech (Devauchelle, Oppenheim, Rizzi, Dehaene, & Pallier, 2008) and that this network is largely established by two months of age (Dehaene-Lambertz et al., 2010).

Dehaene et al., (2010) used fMRI to examine brain responses to written and spoken language in both literate and illiterate populations. They compared the BOLD response in these two populations as they viewed simple written sentences or listened to spoken language. Both literates and illiterates activated a large left lateralised network associated with language processing during the speech processing task: left posterior, middle, and anterior superior temporal sulcus; left temporal pole; left and right premotor cortex; left inferior frontal gyrus; and left supplementary motor area. However, only the literate group activated this same network when viewing written sentences. Comparisons of performance on spoken sentences versus written sentences in literates also showed that on both tasks frontal regions were equally activated however overlapping temporal regions displayed greater activation to spoken words.

One region activated by written words but not speech greatly affected by exposure to literacy training was an area of the left ventral occipito-temporal cortex, often referred to as the Visual Word Form Area (VWFA). This region has received particular attention within the literature describing the neural architecture of the reading system due to the consistency with which it is activated across languages and orthographies when processing written words (e.g. Chinese: Fu et al., 2002; French & Finnish: Vigneau et al., 2005; German: Reinholz & Pollmann, 2005). Although, interpretation of the precise role of the VWFA and its level of modularity are disputed (see Price & Devlin, 2003), there is common agreement that this region plays an important role in reading, potentially as an interface between bottom up generic visual information and top down influences of phonological and semantic processing (Price, 2012). Posterior areas of the occipito-temporal cortex have been associated more with visual feature extraction while anterior regions with lexico-semantic processing at the word level, with such a gradient reported both for alphabetic (e.g. Woollams et al., 2011) and logographic literates (Chan et al., 2009).

Such specialization makes sense when examining the regions' connectivity and functional properties prior to literacy training. Studies examining the functional role of this region prior to literacy indicate that it is involved in processing complex visual objects and face recognition, with a preference for high resolution shapes presented in the fovea. In fact the right occipito-temporal cortex maintains this role following literacy training. However, unlike the region in the right hemisphere the same region in the left hemisphere is close to and tightly connected to cortical regions involved in processing spoken language, therefore as Dehaene and Cohen, (2007) argue, the left occipito-temporal regions functional role is 'recycled' in order to facilitate the mapping between orthographic script and semantic and phonological information. This 'neuronal recycling hypothesis', in which cultural factors drive invasion and reuse of evolutionary older brain circuits due to their structural properties, is supported by evidence that shows a reduction in activation of the VWFA to non-word categories once it is exposed to literacy training (Turkeltaub et al., 2003; Ventura et al., 2013). On this basis it is also less surprising that the region is so consistently activated across orthographic systems (although see Cao, Lee, et al., 2010) given that all major writing systems construct orthographic representations from very similar inventories of elementary line configurations (Changizi et al., 2006).

Note that the visual word form area is a single component of a larger reading system. To date neuroimaging evidence suggests that the reading process potentially involves two distinct paths (e.g. Jobard et al., 2003; Richardson et al., 2011). A ventral path which facilitates activation of semantic information via orthography [e.g. Jobard et al., 2003: left anterior ventral occipito-temporal cortex, posterior part of middle temporal gyrus and triangular part of inferior frontal gyrus; Richardson et al., 2011: inferior occipital to ventral occipito-temporal to anterior superior temporal sulcus] and a dorsal path which facilitates activation of phonological information via orthography [e.g. Jobard et al., 2003: left lateralized superior temporal areas, supramarginal gyrus, and opercular part of inferior frontal gyrus; Richardson et al., 2011: inferior occipital to posterior superior temporal sulcus or ventral occipito-temporal to posterior superior temporal sulcus].

A common assumption within the literature is that such organisation will result in differences in the distribution of labour across the two paths determined by the orthographic transparency of a given language or the lexicality of the item processed. Studies comparing activation during reading between populations that differ in the transparency of the language in which they are literate have observed such distinctions. For example in two PET studies, Paulesu et al., (2000) reported stronger activation in ventral regions of English literates compared to Italian literates. This is predicted on the basis that the deeper English orthography possesses a larger number of irregular mappings between orthography and phonology; therefore there is greater dependence on the ventral path to provide semantic information to assist in cases of irregular grapheme to phoneme mappings. Within subject comparisons have shown a similar ventral bias for deeper orthographies. Again using PET, Kiyosawa et al., (1995) compared cerebral blood flow within participants when processing either Kanji, an orthographic form of Japanese in which correspondence between orthography and phonology exists only at the level of the morpheme, or kana an alternative written form of Japanese in which correspondence exists at the syllabic level. Comparisons showed a ventral connection bias when reading in kanji yet a dorsal connection bias when reading in kana. Also fitting with this characterisation of the two pathways is developmental data showing a progression as a result of increased proficiency in reading, displayed by English literates, from an initial dorsal bias in processing to later ventral dominance (Pugh et al., 2001; Shaywitz et al., 2002). Pugh et al., (2000; 2001) argues that the ventral path is used largely for fast fluent reading in proficient readers and the dorsal path is only required for slow analytic conversion from orthography to phonology, hence, over the course of literacy training, children progress towards ventral dominance. Some researchers have even suggested that such a dorsal path is only required for non-word reading (Levy 2008; 2009). However, recent studies such as Richardson et al., (2011) indicate a more complex involvement of the dorsal path. Their data showed involvement of the dorsal path at both early and late stages of processing, they interpret this as evidence for mapping between orthography and phonology within this path at multiple grain sizes.

A large body of evidence has also been provided by studies which contrast activation during word Vs. pseudoword reading and irregular vs regular word reading. Both sets of studies generally agree that a common neural network is activated by both words (regular and irregular) and pseudowords, however pseudowords appear to generate greater activation particularly in the left posterior or inferior frontal cortex (for review see Price 2012), while greater activation in left anterior ventral occipito-temporal cortex has been observed for irregular words over regular words (Herbster et al., 1997).

Analysis of structural connectivity measures examined between illiterates and literates have also contributed to this debate. Two earlier studies exposed an increase in white matter for literates compared to illiterates within the corpus callosum (Castro-Caldas et al., 1999; Petersson et al., 2007), with no differences in grey matter observed (Petersson et al., 2007). A later study by Carreiras et al., (2009) also found increased white matter in the splenium of the corpus callosum in late literates compared to illiterates, and that this measure of increased structural connectivity was reflected in increased inter-hemispheric functional activity between left and right angular gyri. However, in addition to white matter changes they also observed increased grey matter intensity in bilateral angular, dorsal occipital, middle temporal, left supramarginal and superior temporal gyri. These increases in grey matter support arguments for early literacy training resulting in greater changes to the dorsal (grapheme -> phoneme) path. This fits with earlier studies that suggested greater dependence on this route during early stages of literacy training. However, the latest study to examine changes to structural connectivity between illiterates and late literates has demonstrated that through using a more sensitive approach (diffusion tensor imaging tractography, DTI) it may also be possible to observe changes in regions associated with orthographic to semantic mapping (de Schotten et al., 2012). De Schotten et al., (2012) observed that late literates displayed increased levels of structural connectivity in the temporo-parietal portion of the left arcuate fasciculus and that the microstructure of this region correlated with reading performance. This structure has been argued to be important not only in grapheme-phoneme conversion (van Atteveldt et al., 2004; Simos et al., 2002) but has also been linked to orthographic-semantic mapping as it also projects to the angular gyrus (Vigneau et al., 2006).

A recent review of the imaging data on this topic Price (2012) concluded that it remains unclear to what extent pathways overlap and dissociate within the reading system. The large body of evidence we have describing the neural structure of the reading system comes largely from three contrasts transparent Vs. non-transparent, word Vs. pseudo-word and literate Vs. illiterate. Each of these is to some extent compromised in the clarity of the picture it is able to provide. Contrasts between orthographic systems are often confounded by task differences, non-word vs word contrasts by the fact that words and non-words differ across multiple dimensions that are difficult to control. Moreover, illiterate vs literate contrasts are often unable to control for factors such as exposure to formal schooling or pre-existing cognitive deficits. It seems therefore that precise understanding of the mechanisms connecting modulation of activity in sub-networks of the broader reading system by factors such as transparency, frequency and lexicality lies currently beyond the scope of current brain imaging methods alone.

The effects of literacy on cognitive processing: A multidisciplinary approach

The behavioural consequences of developing and incorporating the neural systems required to support proficient reading into pre-existing neural structures has generated numerous papers and intense debate (see Huettig & Mishra, 2014; Petersson, Ingvar & Reis, 2009; Morais & Kolinsky, 2001). There have been many behavioural consequences ascribed to literacy training, beyond standard literacy skills. However, due to the inherent complexities of isolating the effects of literacy from other factors such as increased exposure to formal schooling or pre-existing cognitive deficits many remain controversial. Some less controversial examples include the following effects that largely relate to aspects of visual processing. Firstly, there is evidence demonstrating differences in visual object processing. Literates are faster and produce fewer errors than illiterates in naming 2D objects, while performance on naming 3D objects appears to be unaffected (Reid et al., 2001). Similarly, literates display an advantage when naming black and white images for both line drawings and photos, whereas no advantage is observed for colour images (Reis et al., 2006). However, literates unlike illiterates appear to loose mirror invariance, with literates shown to perform slower than illiterates on same-different tasks for letter strings, false fonts and pictures regardless of their orientation (Pegado et al., 2014). The structure of visual search has also been shown to alter as a consequence of literacy training. Compared to illiterates, literate's functional visual field is extended from fovea to para-fovea areas and their visual scan pattern displays asymmetries aligned to the reading direction of their given language (Olivers et al., 2014). Literates (in left-to-right writing systems) have also been observed to detect and touch targets faster on the left compared to the right of the visual field, whereas no preference is observed in illiterates (Bramão et al., 2007). However, within this paper we focus on potentially the most controversial issue to result from this literature, the extent to which literacy affects online speech processing. Does literacy acquisition lead to a qualitative difference in the manner in which speech is processed online?

Behavioural evidence for literacy effects on speech processing

There remains considerable debate as to the extent phonological processing is affected by literacy training. A major contributor to this debate has been studies of phonological awareness. Phonological awareness tasks require an individual to explicitly manipulate the phonological structure of a word (e.g. phoneme deletion task: produce the word “coat” without the sound “c”; should produce the word “oat”). Performance on such tasks has been shown to improve dramatically once exposed to literacy training and also provides a good predictor of reading acquisition rates and developmental dyslexia (Snowling, 2000; Hulme 2002). The greatest improvements in performance have been observed for manipulation of finer grained phonological structure at the phonemic level with performance largely at chance prior to literacy training (Alcock et al., 2010; De Jong & Van der Leij; Hulme, Snowling & Caravolas, & Carroll, 2005; Treiman & Zukowski, 1991). One potential explanation for these observed improvements is provided by the ‘lexical restructuring hypothesis’ (Fowler, 1991; Metsala & Walley, 1998), which argues that as the vocabulary expands words become increasingly well-defined phonologically to allow differentiation between words within a more densely populated lexicon. However, such a hypothesis is challenged by a number of studies that show similarly poor performance on phonemic awareness tasks in illiterate adults (Adrian, Alegria & Morais, 1995; Loureiro, Willadino Braga, Souze, Queiroz & Dellatolas, 2004; Morais, Cary, Alegria & Bertelson, 1979; Scliar-Cabral, Morais, Nepomuceno, & Kolinsky, 1997) and increases in phonemic awareness in adult late-literates (individuals exposed to literacy training later in life), both populations are therefore less likely to display such developmental effects (Morais, Bertelson, Cary & Alegria, 1986). Further although the greatest impact of literacy training appears to be on fine level phonological structure, studies have also reported increased performance on tasks tapping coarser grain units (Syllable Detection: Morais, Content, Cary Mehler & Seguli, 1989; Rhyme Awareness: Adrian et al., 1995; Morais et al., 1986; Phonological Length: Kolinsky, Cart & Morais, 1987). Together this evidence favours arguments suggesting that at least explicit awareness of phonemic structure is greatly enhanced by exposure to literacy training beyond a level achieved purely through experience of spoken language.

However, the question remains, to what extent does performance on explicit phonological awareness tasks reflect online phonological processing. Evidence to inform our understanding of this issue is scarce and ambiguous. Pseudo-word repetition tasks have been used to shed light on this issue on the basis that to perform the task effectively participants must store rich phonological representations of the pseudo-word in order to reproduce them accurately at a later point in time. Performance on pseudo word tasks has been shown to improve with literacy training while word repetition is often unaffected (e.g. Reis & Castro-Caldas, 1997). Illiterates have also displayed worse categorical perception in speech tasks than literates, with literates displaying sharper boundary perception for ba-da contrasts (Serniclaes et al., 2005). An effect that was also shown to correlate with reading ability (Hoonhort et al., 2011). This data is far from conclusive, being consistent with either qualitative or simply quantitative changes to phonological processing as a consequence of literacy training.

Psycholinguistic grain size theory (Ziegler & Goswami, 2005) however, argues for a qualitative effect of literacy on phonological processing. This theoretical model argues that exposure to the written form of words effects phonological processing such that the level of processing reflects the systematic relationships that exist between orthographic units and phonological units of the given language. Therefore individuals trained on alphabetic languages should exhibit fine grained phoneme level processing as there is tight correspondence between individual graphemes and phonemes within the orthographic system. Conversely, the theory also predicts that logographic systems, in which correspondence only exists at the level of the morpheme, should lead to processing at a correspondingly coarser grain-size that does not penetrate to the phonemic level. Therefore, logographic literates should behave similarly to illiterates in tasks that probe phoneme level processing.

The work described earlier on the link between literacy and changes to phonological processing was conducted entirely on alphabetic (pre)literates and largely fits with this theoretical model. There are however a few studies that test the models prediction for the effects that should be observed in logographic literates. However, as both English and pinyin (a phonetic-symbol system for representation of Chinese Mandarin) increase in their prevalence it is becoming increasingly difficult to isolate populations exposed purely to logographic literacy training. An early study by de Gelder and Vroomen (1992) examined performance of three populations on a categorical perception task similar to that administered by Serniclaes et al., (2005). They tested the ability of a group of Dutch (alphabetic) literates, a group of Chinese (logographic) literates and a group of bi-scriptal (Chinese & Dutch) literates to distinguish between /ba/ and /da/ drawn from a 9 step continuum. They observed that both alphabetic and bi-scriptal literates displayed sharper boundary precision than logographic literates. Supporting the hypothesis that training on orthographic systems that encode phoneme level structure leads to more fine grained phonological processing. Further supporting evidence is provided by Cheung and Chen (2004). They compared performance of Cantonese-Chinese literates who had either only learned logographic characters for reading or had also been exposed to training in alphabetic pinyin. They observed that only the group exposed to both alphabetic and logographic literacy training displayed evidence of phoneme level processing in both sound matching and primed shadowing tasks.

However, such findings have been challenged by recent data (Kidd et al., 2014) that suggests logographic literates are able to display sensitivity to phonemic structure without prior exposure to phoneme level sound script correspondence when probed with speech gating and non-word repetition tasks. Therefore this debate remains open, one reason being that it is difficult to establish the type of behaviour that should or should not be observed should processing qualitatively differ. For example, should an individual display sub-syllabic errors on nonword repetition tasks by replacing the onset of a syllable, it is not possible to distinguish whether this is due to replacing simply the onset or the entire syllable that simply shares its vowel. Similarly, on speech gating tasks, is earlier classification of a word necessarily evidence of finer grained processing, or could behaviour simply reflect an ability to activate coarser grain units given less input?

Does granularity of phonological processing affect language-mediated eye gaze?

A data set that potentially offers insight regarding the granularity of phonological processing operating in literates and illiterates was provided by Huettig, Singh and Mishra (2011). They compared the eye gaze of low literate and high literate groups as they heard spoken words while simultaneously viewing visual scenes. On experimental trials the scenes presented contained multiple objects one of which shared its phonological onset with the spoken word (e.g. hearing "beaker", while viewing a scene containing a beaver). They observed that while high literates gaze was tightly time locked to the unfolding speech signal, quickly looking towards items sharing their phonological onset while the speech signal overlapped and then quickly moving their gaze away once the speech signal mismatched, low literates only looked marginally more at phonologically overlapping objects than unrelated items. Further, their gaze only displayed such a bias in later time windows, therefore unlike literates, illiterates gaze was not tightly time locked to the momentary onset overlap. In this experiment both groups are presented with identical visual and auditory stimuli, however some aspect of the manner in which this information is processed differs expressed in the output of the system, their eye gaze.

Could this difference in eye gaze reflect differences between populations in the granularity of phonological processing? This was the question examined in Smith, Monaghan & Huettig (2014a). Within a computational neural network model of language mediated eye gaze they manipulated the granularity of phonological processing and then compared the resulting gaze behaviour when the model was exposed to conditions replicating those participants experienced in Huettig, Singh and Mishra (2011).

The model used within the study utilized a recurrent neural network architecture derived from the hub-and-spoke models of semantic processing that have previously successfully modelled neuropsychological data sets (see Smith, Monaghan & Huettig, 2014b). Such models have proved successful in connecting neural and behavioural data as they provide a framework that captures many of the key processing characteristics of neural populations while simultaneously operating at a level of abstraction that is both tractable and understandable (see McClelland & Rodgers, 2014). Within such a framework behaviour is modelled as the emergent property of interaction between many simpler elements that pass activation between one another through weighted connections. This low level structure is assumed to reflect neurons and synapses, however in order to maintain tractability models are not implemented at the single neuron level. Instead many details of the real system are abstracted away with networks designed to capture the behaviour of larger connected groups of neuronal populations.

The emergent behaviour of such models develops through application of a learning algorithm that slowly alters weights within the network such that the network learns to perform a specific function defined by constraints imposed by the learning environment, for example a sequence of events within or across modalities. This relatively simple framework captures complex properties of neural systems (see McClelland & Rogers, 2014). For example, representations become patterns of activation distributed across multiple units within the system; processing is interactive and dynamic such that is evolves over time; learning and long term memory are captured through changes to connection weights; all of which is dependent on the statistical structure of the environment. These fundamental properties of neural systems, for example the interactive nature of processing both within and across modalities, make such systems incredibly difficult to predict. We know from the neuroscience literature that human and animal neocortex is massively interactive, not only with top down feedback from high level processing regions but also with cross modal connections between primary perceptual processing regions (see Ghazanfar & Schroeder, 2006; Lewokowicz & Ghazafar, 2009). In order to tease apart theoretical models of complex interactive systems such as those outlined in the previous review of the reading system we need to ensure that assumed predictions used to compare contrasting models are well motivated. Due to the level of complexity within such systems in order to generate well motivated predictions explicit implementation in computational models is necessary (e.g. Dilkina et al., 2008).

The network used to model language mediated eye gaze in Smith, Monaghan & Huettig (2014) implemented a parsimonious solution to how the various modalities known to be involved were connected. It consisted of a visual processing layer that allowed visual information from up to 4 locations in the visual field to be inputted. A phonological layer allowed the network to receive a phonological input that varied over time. There was also a semantic layer that allowed the model to learn semantic relationships between items. Finally, an eye layer enabled the model to provide an output measure indicating the probability of fixating a given location in the visual field. All modalities (visible layers) were connected via a central resource (hidden layer). The model was trained to map from visual and phonological representations to semantic representations and to gaze towards a target when its phonological or semantic representation was active. Critically the representations on which the network was trained aimed to capture the distinct structural features of each modality (e.g. phonological representations unfolded over time). Using such componential phonological representations in which a word was represented as a sequence of phonemes, the model has been shown to replicate a broad range of word level properties of language mediated visual attention (see Smith, Monaghan & Huettig, 2013) displayed by literate populations. The model demonstrated that the complex time course dynamics reported in such studies was an emergent property of such a network simply trained on these cross modal mappings.

To test whether differences in the granularity of phonological processing could offer explanation for the pattern of behaviour reported in Huettig, Singh and Mishra, (2011) the same architecture was implemented and trained on one of three levels of phonological representations. Fine-grained representations aimed to simulate processing at the phoneme level. Fine grained representations words were created by randomly sampling from a phoneme inventory, such that each word was a unique sequence of six phonemes. Moderate grain representations consisted of two components per word, analogous to syllable level processing. While course grained representations were simulated with a single component encoding each word. Defining representations in this way had consequences for the structure of phonological overlap between onset competitors and targets. Importantly, although at the word level all competitor and target shared 1/3 of phonetic features, fine grained competitors shared all features within their initial two components, moderate grained competitors shared 2/3 of features in their initial component, while coarse grained competitors shared 1/3 of features within the single component that encoded the given word.

Predictions of the behavioural consequences for language mediated eye gaze of this explicit description of the effects of literacy on phonological processing were extracted by training networks on one of the three forms of phonological representation and then exposing networks to the same conditions used in Huettig, Singh and Mishra, (2011). Networks trained on fine and moderate grain phonological representations fixated phonological onset competitors in a manner similar to that of high literates in that gaze was drawn towards such items shortly after word onset and then gaze quickly moved away from such items once the speech signal mismatched. Networks trained on coarse grained representations on the other hand only fixated phonological competitors marginally more than unrelated items and the period of increased fixation was not closely time locked to the onset of the speech signal. This data demonstrates that finer grained phonological processing as a consequence of literacy training may underlie differences between high and low literates reported in Huettig, Singh & Mishra (2011), and therefore such data provides further support for the predictions of Psycholinguistic Grain Size Theory. However, the modelling work also constrains such predictions in that to replicate the behaviour observed phonological representations needed to be very coarse grained.

Implementing a theory explicitly in a computational model as described not only allows us to test its compatibility to existing data sets but also generate new predictions that can be tested empirically. For example, the given implementation of coarse grain representations does not contain sufficiently rich encoding of the temporal structure of phonological representations for a system to distinguish between onset or rhyme overlap. Therefore the current implementation predicts that should illiterates possess such coarse grained representations then their gaze should be equally drawn towards phonological onset and phonological rhyme competitors. We know from previous studies that alphabetic literates do not display this behaviour, instead consistent with the fine grain models behaviour (Smith, Monaghan and Huettig, 2011) alphabetic literates display earlier and stronger phonological onset effects compared to phonological rhyme effects in the visual world paradigm (Allopenna et al., 1998). However, we do not yet know whether illiterates display such sensitivity to the location of overlap. Such data will allow us to further refine our theoretical model of the effects of literacy on phonological processing.

Neuroscience evidence for literacy effects on speech processing

Although many behavioural studies have demonstrated effects of orthographic knowledge on speech processing in laboratory settings (for review see Ziegler et al., 2008), the extent to which effects are strategic, post lexical or instead reflect effects of literacy during every day on-line speech processing remains a hotly disputed issue. Many such studies have relied upon orthographic consistency effects to demonstrate the influence of orthographic knowledge during spoken word processing. A study by Cutler, Trieman and van Ooijen (2010) however demonstrated within a phoneme deletion task that orthographic consistency effects could be modulated (and ultimately eliminated) by increasing or decreasing the saliency of spelling through increasing or decreasing the number of irregularly spelt words within the stimuli. Similarly, Yoncheva et al., (2013) showed that the presence or absence of orthographic consistency effects in ERP data could depend on task goals. Within their study participants heard spoken words and were required to either make rhyme judgements or judgements based on the melodic structure of the word. Only when attention was drawn towards the phonological structure of words in the rhyme judgement task did they observe within the ERP data orthographic consistency effects.

However, such challenges have been countered. Pattamadilok et al., (2008) demonstrated that consistency effects can also be observed on tasks that did not explicitly demand attention to sub-syllabic structure by observing orthographic consistency effects in ERPs during a semantic categorisation task. A further two studies have demonstrated that such orthographic effects can be observed in ERP data when performing tasks in which participants are not required to attend to the spoken input. Pattamadilok et al., (2014) demonstrated that orthographic congruency effects were present in Miss-match negativity ERP responses when participants were told to attend to a silent video while simultaneously hearing rhyming words that varied in their orthographic congruency but they were explicitly told to ignore. While Perre et al., (2011) demonstrated that consistency effects appeared in ERP data when participants were tasked with detecting noise bursts in go-no go trials that were interspersed with spoken words that varied in their orthographic consistency.

A second challenge is to demonstrate that effects observed reflect pre-lexical processing rather being later post lexical effects. Pattamadilok et al., (2011) used ERP measures to show that orthographic effects recorded in rhyme judgement tasks differed from those extracted from lexical decision or semantic tasks. They observed effects in periods 300-350ms post word onset during lexico-semantic tasks (replicating effects observed in Pattamadilok et al., 2008) yet effects emerged in 175-250ms and 375-750ms time windows during rhyme judgement tasks. Perre et al., (2008) reported similar effects using a lexical decision task, with congruency effects present in the ERP data at around 320ms post word onset, preceding word offset (approx.. 600ms). Within their stimuli they also manipulated the location of the inconsistent orthographic unit which also appeared in their ERP data, with ERP differences emerging around 200ms after the onset of the orthographically inconsistent unit. Such evidence supports arguments suggesting that pre-lexical effects of orthography can occur during spoken word processing.

Such pre-lexical effects are consistent with interactive theories suggesting orthographic knowledge affects core spoken word recognition. However, interactive theories differ in the mechanisms through which this influence is exerted. One possibility is that orthographic representations are activated online during spoken word processing. Such a position has been argued to lead to delayed effects as time is required for the speech signal to proceed to orthographic processing regions before orthographic knowledge can begin to exert an affect. Also, this position predicts activation of information in orthographic processing regions during spoken word processing. An alternative hypothesis is that literacy training, learning to map between orthographic and phonological representations, leads to a restructuring of phonological processing regions. Therefore effects on speech are likely to be observed early and in regions associated with phonological processing. A third possibility is that both phonological processing regions become restructured and orthographic representations are activated online during spoken word recognition.

Petersson et al. (2007) examined this issue by testing literate and illiterate groups on word and pseudo word repetition tasks. They found that while the illiterate group differed in the network interactions across tasks literates displayed the same network interactions on both tasks. Both groups appeared to use the same mechanisms on the word repetition task, however differences between groups appeared only on the pseudoword repetition task. The authors interpreted these findings in support of the hypothesis that the auditory-verbal language network is modified as a consequence of literacy training. Data from fMRI studies exists supporting both online activation and simultaneous phonological restructuring and online orthographic activation. Monzalvo & Dehaene-Lambertz, (2013) examined the BOLD response of children aged 6-9 years while listening to native or foreign spoken sentences. Children who had received a year's literacy training displayed increased activation in regions associated with phonological processing (posterior superior temporal region) while those who had received 4 years literacy training displayed increased activation in phonological processing regions in addition to top down activation of the left inferior temporal cortex and regions including the VWFA when listening to their native language. This suggests that both mechanisms are involved during spoken word processing although greater proficiency is required before orthographic representations are routinely activated during online speech processing. A study contrasting activation during spoken word processing in illiterate and literate adults using fMRI also reported evidence for both phonological restructuring and online orthographic activation (Dehaene et al., 2010). Within the study they observed activation of the VWFA when literates but not illiterates processed spoken words. They also observed a near doubling of activity of the planum temporale in literates compared to illiterates in response to spoken words and pseudo words. The planum temporale is located close to primary auditory cortex, and has been linked to the acquisition of sensitivity to phonemes and phonological rules specific to an individual's mother tongue. Therefore, the authors argue, such observed changes as a consequence of literacy are likely to reflect how literacy changes the phonological code.

fMRI however lacks temporal resolution and is compromised in its ability to describe the rapid sequencing of events in the first few hundred milliseconds as spoken words unfold and are processed. Electroencephalography on the other hand provides a temporally rich measure offering important insight to the temporal structure of events during spoken word processing. Consistent with the time course of orthographic consistency effects observed in ERP studies referenced earlier in this section Perre et al., (2009) observed such effects as participants performed a lexical decision task approximately 330ms post word onset. Using standardized low resolution electromagnetic tomography to predict the generators of the observed effects, they were able to localize the orthographic consistency effect observed to the region left BA40, a region classically associated with phonological processing. There was no evidence however for effects generated in posterior cortical areas associated with orthographic processing such as the VWFA. Further supporting this account of the effects of literacy during spoken word processing is evidence from Pattamadilok et al., 2010 in which TMS was used to modulate activation in either phonological processing regions (left supremarginal gyrus) or orthographic processing regions (left ventral occipito-temproal cortex) while participants performed a lexical decision task in which orthographic consistency was modulated. They found that the orthographic consistency advantage was removed by stimulation of the phonologically associated brain region, while there was no effect observed when orthographic processing regions were stimulated. Together, this evidence suggests that exposure to training on alphabetic languages is likely to affect the structure of phonological processing regions involved in online speech processing. A further effect of online activation of orthographic representations may also commonly be experienced during spoken word processing although such effects are likely to be experienced at later stages of processing.

Such theoretical models make strong assumptions about the effects of learning orthographic mappings and contrasts in the effects that should be observed given alternative restructuring versus online orthographic activation models. Phonological restructuring models are also largely motivated by the Psycholinguistic Grain Size theory and are therefore constrained (for example) by the importance placed on the granularity of correspondence between phonology and orthography. Computational models provide a means of examining the assumptions underlying these theoretical models and generate well motivated predictions that follow from them. For example were phonological restructuring to underlie the differences observed between high and low literate groups then we know from the modelling conducted in Smith, Monaghan & Huettig (2014) that substantial qualitative changes to the structure of phonological representations is required for this to be a valid explanation for this behaviour as only very coarse grained phonological processing is required to eliminate the time locked effect as observed in low literates.

Examining the plausibility of phonological restructuring using computational models

Harm and Seidenberg (1999) examines how learning to map from orthographic representations to phonological representations in English alters the structure of phonological processing in a simple neural network model of reading. The model consists of a phonological attractor network that is trained to sustain phonological representations of monosyllabic English works over time. This phonological attractor is used as a model of illiterate speech processing. They extend the model to include an orthographic layer that passes activation through a set of hidden units to the phonological layer of the phonological attractor. This larger 'literate' model is in addition trained to map from orthographic representations of English monosyllabic words to their phonological form. Once both categories of network were trained Harm and Seidenberg (1999) probed the phonological attractor of each network to examine how literacy training impacted on phonological processing. They observed that the literate networks were better than illiterate networks in restoring phonetic features and entire phonemes when corrupted by noise. When comparing the connection weights within the network they observed that the literate network had developed as a consequence of literacy training stronger connections between units processing the same phoneme segment than weights connecting between phoneme segments. They concluded that this was evidence for the literate network developing stronger phoneme level attractors, and therefore that literacy training led to more fine grained processing in the literate model. This modelling work provides strong support for the phonological restructuring hypothesis and psycholinguistic grain size theory by providing an explicit description for how learning to map between orthographic and phonological representations that include fine grained correspondence between representations across modalities leads to changes in the granularity of processing in line with the granularity encoded in the orthography.

In a recent study by Smith, Monaghan and Huettig (2014c) the same model was used to examine the extent to which the nature of the restructuring observed is dependent on the transparency of the orthographic system on which the network is trained. This directly tests both the assumption within both Harm and Seidenberg (1999) and Psycholinguistic Grain Size theory that the nature of the correspondence between orthography and phonology drives the nature of the emergent effects of literacy on phonological processing. Smith, Monaghan and Huettig (2014c) trained two categories of network. Both categories of network shared the same architecture as the literate model in Harm and Seidenberg, (1999), however, whereas one was trained on the same English orthographic to phonological mappings used in the earlier study (Transparent networks), a second category of network was trained on the same representations but with the mappings randomised (Opaque networks). This meant that the structure of representations in each modality was controlled however in this latter case correspondence between orthography and phonology only existed at the word level. Thus this second condition replicated training on non-transparent orthographic systems.

Once trained both categories of network were tested on their ability to restore single phonetic features and entire phonemes corrupted by noise. Results showed that transparent networks were better at restoring both corrupted phonetic features and phonemes than opaque networks. However, the authors also examined the legality of the larger linguistic units formed by the restored phoneme segments. This analysis showed that opaque models were more likely to restore a phoneme to form a legal (present in the training set) onset or coda than transparent networks. This pattern of behaviour is consistent with the argument that the nature of correspondence between orthography and phonology defines the impact of literacy training on phonological processing. Transparent models trained on an orthographic system in which correspondence existed at the phoneme level developed behaviour consistent with a phoneme level bias in processing. Whereas, networks trained on a system in which correspondence existed at the word level developed behaviour consistent with a bias toward a coarser grained level of phonological processing.

The modelling work provides an explicit implementation of the grain size hypothesis in order to generate well motivated predictions regarding how differences in transparency should impact on phonological processing. There is already data in the literature that suggests such predictions may be accurate. For example, Shu et al., (2008) demonstrate that Chinese literates display increased phonemic awareness only when exposed to training on pinyin (see also Brennan et al. 2013; Cao et al. 2011; Cheung et al. 2001; Ho & Bryant, 1997; Huang & Hanley et al, 1995, 1997; McBride-Chang et al. 2004; Read et al. 1986). The model provides well motivated predictions for how logographic and alphabetic literates should differ in their sensitivity to noisy speech that can be tested in new empirical studies. The results of which can be used to constrain models of the effects of literacy on phonological processing.

The level of restructuring captured explicitly in this work however is not sufficient to generate the qualitative difference in phonological processing needed to generate the representational differences implemented in Smith, Monaghan and Huettig (2014). However, there are very few computational studies that have explored the implications of orthographic training on phonological processing and those that do make questionable assumptions regarding the nature of phonological processing prior to literacy training. In the most influential implemented cognitive models of reading (e.g. Harm & Seidenberg, 1999, 2004; Coltheart, Rastle, Perry, Langdon & Ziegler 2001; Houghton & Zorzi, 2003) the phonological representations on which the models are trained assume a phonological input in which phonemic structure is clearly defined. In which phonemes are represented as discrete units within the input and variation within types is minimal and independent of their context within a word. We know however that features of the speech signal such as co-articulation, elision and reductions can frequently irradiate phoneme boundaries. Therefore, the assumption that prior to literacy training phonological representations include detailed phoneme level structure seems questionable particularly when viewed in light of the substantial body of evidence suggesting that phonological representations are likely to be coarse grained prior to literacy training. This remains one of the many areas in which computational modelling may prove insightful. Should a model be trained to classify noisy speech input at the word level? what is the structure of phonological representation to emerge? Examining such an issue is not only important to ensure that we have comprehensive models of spoken word processing that not only describe processing within alphabetic literates but also in illiterate and non-aphabetic literate populations. But also understanding these emergent representations may allow us to explore how the structure of such representations is related to rates of literacy acquisition. For example the literature currently demonstrates strong links between an individual's phonological processing abilities and later reading performance, with dyslexia linked to problems in this area (e.g. Blau et al., 2009; 2010; Descroches et al., 2010). Constructing an explicit model of this connection will allow us to probe potential factors that may generate representations that lead to problems in acquisition and also develop training programs to reduce the impact on learning.

This description of problems with existing computational models highlights a further important interpretation problem for computational models. It is important that computational models are viewed as important methodological tools rather than full descriptions of the true underlying form. Each model should aim to provide a means of rigorously testing the implications of a specific theoretical perspective. They should therefore aim to offer an existence proof but also a means of testing the implications of a particular perspective and a means of generating well motivated predictions. Predictions that without implementation are often impossible to generate accurately when working with such complex systems. Should predictions or behaviour of the model not fit with behavioural data then such information is still informative, offering information with which to motivate new models of alternative theories that subsequently can be used to generate predictions that can be tested empirically. This process should ultimately guide us towards well-grounded models that provide increasingly detailed explicit descriptions of the underlying system, bringing closer the connection between our behavioural and neural observations. Computational models provide a means of connecting across these two literatures. Without such models it is easy for disciplines to be internally coherent yet not connected. Computational models provide cognitive science with its 'McDowells', ensuring our theoretical models within cognitive neuroscience or cognitive psychology do not fly off "frictionless, spinning into the void" (McDowell, 1996).

References

Adrián, J. A., Alegria, J., & Morais, J. (1995). Metaphonological abilities of Spanish illiterate adults. *International Journal of Psychology*, *30(3)*, 329–351.

Alcock, K. J., Ngorosho, D., Deus, C., & Jukes, M. C. H. (2010). We don't have language at our house: Disentangling the relationship between phonological awareness, schooling, and literacy. *British Journal of Educational Psychology, 80(1)*, 55–76.

Blau, V., Reithler, J., van Atteveldt, N., Seitz, J., Gerretsen, P., Goebel, R., & Blomert, L. (2010). Deviant processing of letters and speech sounds as proximate cause of reading failure: a functional magnetic resonance imaging study of dyslexic children. *Brain*, *133(3)*, 868-879.

Blau, V., van Atteveldt, N., Ekkebus, M., Goebel, R., & Blomert, L. (2009). Reduced neural integration of letters and speech sounds links phonological and reading deficits in adult dyslexia. *Current Biology*, *19(6)*, 503-508.

Bramão, I., Mendonça, A., Faísca, L., Ingvar, M., Petersson, K. M., & Reis, A. (2007). The impact of reading and writing skills on a visuo-motor integration task: A comparison between illiterate and literate subjects. *Journal of the International Neuropsychological Society*, *13(2)*, 359-364.

Brennan, C., Cao, F., Pedroarena?Leal, N., McNorgan, C., & Booth, J. R. (2013). Reading acquisition reorganizes the phonological awareness network only in alphabetic writing systems. *Human brain mapping*, *34(12)*, 3354-3368.

Cao, F., Khalid, K., Lee, R., Brennan, C., Yang, Y., Li, K., Bolger, D. J., & Booth, J. R. (2011). Development of brain networks involved in spoken word processing of Mandarin Chinese. *NeuroImage, 57(3)*, 750-759.

Cao, F., Lee, R., Shu, H., Yang, Y., Xu, G., Li, K., & Booth, J. R. (2010). Cultural constraints on brain development: Evidence from a developmental study of visual word processing in Mandarin Chinese. *Cerebral Cortex, 20(5)*, 1223-1233.

Carreiras, M., Seghier, M. L., Baquero, S., Estévez, A., Lozano, A., Devlin, J. T., & Price, C. J. (2009). An anatomical signature for literacy. *Nature, 461(7266)*, 983-986.

Caldas, A., Miranda, P. C., Carmo, I., Reis, A., Leote, F., Ribeiro, C., & Soares, E. (1999). Influence of learning to read and write on the morphology of the corpus callosum. *European Journal of Neurology, 6(1)*, 23-28.

Chan, S.T., Tang, S.W., Tang, K.W., Lee, W.K., Lo, S.S., Kwong, K.K., (2009). Hierarchical coding of characters in the ventral and dorsal visual streams of Chinese language processing. *Neuroimage 48*, 423–435.

Changizi, M. A., Zhang, Q., Ye, H., & Shimojo, S. (2006). The structures of letters and symbols throughout human history are selected to match those found in objects in natural scenes. *The American Naturalist, 167(5)*, E117-E139.

Cheung, H., & Chen, H. C. (2004). Early orthographic experience modifies both phonological awareness and on-line speech processing. *Language and Cognitive Processes, 19(1)*, 1-28.

Cheung, H., Chen, H. C., Lai, C. Y., Wong, O. C., & Hills, M. (2001). The development of phonological awareness: Effects of spoken language experience and orthography. *Cognition, 81(3)*, 227-241.

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: a dual route cascaded model of visual word recognition and reading aloud. *Psychological review, 108(1)*, 204-256.

Comrie, B. (2005). Writing Systems. In Haspelmath, M., Dryer, M. S., Gil, D., & Comrie, B., (Eds.) *The World Atlas of Language Structures* (pp. 568-572). Oxford, England: Oxford University Press.

Cutler, A., Treiman, R., & van Ooijen, B. (2010). Strategic deployment of orthographic knowledge in phoneme detection. *Language and Speech*, *53(3)*, 307–320.

de Jong, P. F., & van der Leij, A. (2003). Developmental changes in the manifestation of a phonological deficit in dyslexic children learning to read a regular orthography. *Journal of Educational Psychology*, *95(1)*, 22–40.

De Schotten, M. T., Cohen, L., Amemiya, E., Braga, L. W., & Dehaene, S. (2014). Learning to read improves the structure of the arcuate fasciculus. *Cerebral Cortex*, *24(4)*, 989-995.

Dehaene, S., Cohen, L., (2007). Cultural recycling of cortical maps. *Neuron*, *56(2)*, 384–398.

Dehaene, S., Pegado, F., Braga, L. W., Ventura, P., Nunes Filho, G., Jobert, A., Dehaene-Lambertz, G., Kolinsky, R., Morais, J., & Cohen, L. (2010). How learning to read changes the cortical networks for vision and language. *Science*, *330(6009)*, 1359-1364.

Dehaene-Lambertz, G., Montavont, A., Jobert, A., Allirol, L., Dubois, J., Hertz-Pannier, L., & Dehaene, S. (2010). Language or music, mother or Mozart? Structural and environmental influences on infants' language networks. *Brain and Language*, *114(2)*, 53–65.

Desroches, A. S., Cone, N. E., Bolger, D. J., Bitan, T., Burman, D. D., & Booth, J. R. (2010). Children with reading difficulties show differences in brain regions associated with orthographic processing during spoken language processing. *Brain research*, *1356*, 73-84.

Devauchelle, A. D., Oppenheim, C., Rizzi, L., Dehaene, S., & Pallier, C. (2009). Sentence syntax and content in the human temporal lobe: an fMRI adaptation study in auditory and visual modalities. *Journal of Cognitive Neuroscience*, *21(5)*, 1000-1012.

Dilkina, K., McClelland, J. L., & Plaut, D. C. (2008). A single-system account of semantic and lexical deficits in five semantic dementia patients. *Cognitive Neuropsychology*, *25(2)*, 136-164.

Fowler, A. (1991) How early phonological development might set the stage for phoneme awareness. In Brady, S. & Shankweiler,

D. (Eds), *Phonological Processes in Literacy*, (pp. 97–117). Hillsdale, New Jersey: Erlbaum.

Fu, S., Chen, Y., Smith, S., Iversen, S., & Matthews, P. M. (2002). Effects of word form on brain processing of written Chinese. *NeuroImage*, *17(3)*, 1538-1548.

Gelder, B. D., & Vroomen, J. (1992). Auditory and visual speech perception in alphabetic and non-alphabetic Chinese-Dutch bilinguals. *Advances in psychology*, *83*, 413-426.

Ghazanfar, A. A., & Schroeder, C. E. (2006). Is neocortex essentially multisensory? *Trends in Cognitive Science*, *10*, 278–285.

Harm, M. W., & Seidenberg, M. S. (1999). Phonology, reading acquisition, and dyslexia: insights from connectionist models. *Psychological review*, *106(3)*, 491-528.

Harm, M. W., & Seidenberg, M. S. (2004). Computing the meanings of words in reading: cooperative division of labor between visual and phonological processes. *Psychological review*, *111(3)*, 662.

Herbster, A.N., Mintun, M.A., Nebes, R.D., Becker, J.T., (1997). Regional cerebral blood flow during word and nonword reading. *Human Brain Mapping*. *5(2)*, 84–92.

Ho, C. S. H., & Bryant, P. (1997). Development of phonological awareness of Chinese children in Hong Kong. *Journal of Psycholinguistic Research*, *26(1)*, 109-126.

Hoonhorst, I., Medina, V., Colin, C., Markessis, E., Radeau, M., Deltenre, P., & Serniclaes, W.,(2011). Categorical perception of voicing, colors and facial expressions: A developmental study. *Speech Communication*, *53(3)*, 417–430.

Houghton, G., & Zorzi, M. (2003). Normal and impaired spelling in a connectionist dual-route architecture. *Cognitive Neuropsychology*, *20(2)*, 115-162.

Huang, H. S., & Hanley, J. R. (1997). A longitudinal study of phonological awareness, visual skills, and Chinese reading acquisition among first-graders in Taiwan. *International Journal of Behavioral Development*, *20(2)*, 249-268.

Huettig, F., & Mishra, R. K. (2014). How literacy acquisition affects the illiterate mind–A critical examination of theories and evidence. *Language and Linguistics Compass*, *8(10)*, 401-427.

Huettig, F., Singh, N., & Mishra, R. K. (2011). Language-mediated visual orienting behavior in low and high literates. *Frontiers in Psychology*, *2*, 285.

Hulme, C., Hatcher, P. J., Nation, K., Brown, A., Adams, J., & Stuart, G. (2002). Phoneme awareness is a better predictor of early reading skill than onset-rime awareness. *Journal of experimental child psychology*, *82(1)*, 2-28.

Hulme, C., Snowling, M., Caravolas, M., & Carroll, J. (2005). Phonological skills are (probably) one cause of success in learning to read: A comment on Castles and Coltheart. *Scientific Studies of Reading*, *9(4)*, 351–365.

Jobard, G., Crivello, F., Tzourio-Mazoyer, N., (2003). Evaluation of the dual route theory of reading: a metanalysis of 35 neuroimaging studies. *Neuroimage 20*, 693–712.

Kidd, J. C., Shum, K. K. M., Ho, C. S. H., & Au, T. K. F. (2014). Phonological Representations and Early Literacy in Chinese. *Scientific Studies of Reading*, *ahead of print*, 1-25.

Kiyosawa, M., Itoh, M., Nakagawa, Y., Kobayashi, N., Tamai, M., (1995). Effect of kanji and kana reading on cerebral blood flow patterns measured by PET. *Japanese journal of ophthalmology*. *39(2)*, 198–205.

Kolinsky, R., Cary, L., & Morais, J. (1987). Awareness of words as phonological entities: The role of literacy. *Applied Psycholinguistics*, *8(3)*, 223–232.

Levy, J., Pernet, C., Treserras, S., Boulanouar, K., Aubry, F., Demonet, J.F., & Celsis, P., (2009). Testing for the dual-route cascade reading model in the brain: an fMRI effective connectivity account of an efficient reading style. *PLoS One 4*, e6675.

Levy, J., Pernet, C., Treserras, S., Boulanouar, K., Berry, I., Aubry, F., Demonet, J.F., & Celsis, P., (2008). Piecemeal recruitment of left-lateralized brain areas during reading: a spatio-functional account. *Neuroimage 43*, 581–591.

Lewkowicz, D. J., & Ghazanfar, A. A. (2009). The emergence of multisensory systems through perceptual narrowing. *Trends in Cognitive Sciences*, *13(11)*, 470–478

Loureiro, C. D. S., Willadino Braga, L., Souza, L. D. N., Queiroz, E., & Dellatolas, G. (2004). Degree of illiteracy and phonological and metaphonological skills in unschooled adults. *Brain and Language*, *89(3)*, 499–502.

Martinez, R & Fernandez, P. (2010). *The Social and Economic Impact of Illiteracy: Analytical Model and Pilot Study*. Paris, France: UNESCO.

McBride-Chang, C., Bialystok, E., Chong, K. K., & Li, Y. (2004). Levels of phonological awareness in three cultures. *Journal of Experimental Child Psychology*, *89(2)*, 93-111.

McDowell, J. (1996). *Mind and world*. Cambridge, Massachusetts: Harvard University Press.

Metsala, J.L. & Walley, A.C. (1998) Spoken vocabulary growth and the segmental restructuring of lexical representations: precursors to phonemic awareness and early reading ability. In Metsala, J.L. and Ehri, L.C. (Eds), *Word Recognition in Beginning Literacy*, (pp. 89–120). Hillsdale, NJ: Erlbaum.

Monzalvo, K., & Dehaene-Lambertz, G. (2013). How reading acquisition changes children's spoken language network. *Brain and language*, *127(3)*, 356-365.

Morais, J., & Kolinsky, R. (2001). The literate mind and the universal human mind. In Dupoux, E., (Ed.), *Language, brain and cognitive development: Essays in Honor of Jacques Mehler (pp.* 463-480). Cambridge, Massachusetts: MIT.

Morais, J., Bertelson, P., Cary, L., & Alegria, J. (1986). Literacy training and speech segmentation. *Cognition*, *24(1)*, 45–64.

Morais, J., Cary, L., Alegria, J., & Bertelson, P. (1979). Does awareness of speech as a sequence of phones arise spontaneously? *Cognition*, *7(4)*, 323–331.

Morais, J., Content, A., Cary, L., Mehler, J., & Segui, J. (1989). Syllabic segmentation and literacy. *Language and Cognitive Processes*, *4(1)*, 57–67.

Nakamura, K., Kuo, W. J., Pegado, F., Cohen, L., Tzeng, O. J., & Dehaene, S. (2012). Universal brain systems for recognizing word shapes and handwriting gestures during reading. *Proceedings of the National Academy of Sciences*, *109(50)*, 20762-20767.

Olivers, C. N. L., Huettig, F., Singh, J. P., & Mishra, R. K. (2014). The influence of literacy on visual search. *Visual Cognition.*, *21*, 74-101.

Pattamadilok, C., Knierim, I. N., Duncan, K. J. K., & Devlin, J. T. (2010). How does learning to read affect speech perception?. *The Journal of Neuroscience*, *30(25)*, 8435-8444.

Pattamadilok, C., Morais, J., Colin, C., & Kolinsky, R. (2014). Unattentive speech processing is influenced by orthographic knowledge: Evidence from mismatch negativity. *Brain and language*, *137*, 103-111.

Pattamadilok, C., Perre, L., & Ziegler, J. C. (2011). Beyond rhyme or reason: ERPs reveal task-specific activation of orthography on spoken language. *Brain and Language*, *116(3)*, 116–124.

Pattamadilok, C., Perre, L., Dufau, S., & Ziegler, J. C. (2008). On-line orthographic influences on spoken language in a semantic task. *Journal of Cognitive Neuroscience*, *21(1)*, 169–179.

Paulesu, E., McCrory, E., Fazio, F., Menoncello, L., Brunswick, N., Cappa, S.F., Cotelli, M., Cossu, G., Corte, F., Lorusso, M., Pesenti, S., Gallagher, A., Perani, D., Price, C., Frith, C.D., & Frith, U., (2000). A cultural effect on brain function. *Nature Neuroscience*, *3(1)*, 91–96.

Pegado, F., Nakamura, K., Braga, L. W., Ventura, P., Nunes Filho, G., Pallier, C., Jobert, A., Morais, J., Cohen, L., Kolinsky, R., & Dehaene, S. (2014). Literacy breaks mirror invariance for visual stimuli: A behavioral study with adult illiterates. *Journal of Experimental Psychology: General*, *143(2)*, 887-894.

Perre, L., & Ziegler, J. C. (2008). On-line activation of orthography in spoken word recognition. *Brain Research*, *1188*, 132–138.

Perre, L., Bertrand, D., & Ziegler, J. (2011). Literacy affects spoken language in a nonlinguistic task: An erp study. *Frontiers in Psychology*, *2*, 1–8.

Perre, L., Pattamadilok, C., Montant, M., & Ziegler, J. C. (2009). Orthographic effects in spoken language: On-line activation or phonological restructuring? *Brain Research*, *1275*, 73–80.

Petersson, K. M., Ingvar, M., & Reis, A. (2009). Language and literacy from a cognitive neuroscience perspective. In D. Olsen, & N. Torrance (Eds.), *Cambridge handbook of literacy* (pp. 152-181). Cambridge, England: Cambridge University Press.

Petersson, K. M., Silva, C., Castro-Caldas, A., Ingvar, M., & Reis, A. (2007). Literacy: a cultural influence on functional left–right differences in the inferior parietal cortex. *European Journal of Neuroscience*, *26(3)*, 791-799.

Price, C. J. (2012). A review and synthesis of the first 20 years of PET and fMRI studies of heard speech, spoken language and reading. *Neuroimage*, *62(2)*, 816-847.

Price, C.J., Devlin, J.T., (2003). The myth of the visual word form area. *Neuroimage 19*, 473–481.

Pugh, K.R., Mencl, W.E., Jenner, A.R., Katz, L., Frost, S.J., Lee, J.R., Shaywitz, S.E., Shaywitz, B.A., (2000). Functional neuroimaging studies of reading and reading disability (developmental dyslexia). *Mental retardation and developmental disabilities research reviews*, *6(3)*, 207–213.

Pugh, K.R., Mencl, W.E., Jenner, A.R., Katz, L., Frost, S.J., Lee, J.R., Shaywitz, S.E., & Shaywitz, B.A., (2001). Neurobiological studies of reading and reading disability. *Journal of communication disorders. 34(6)*, 479–492.

Read, C., Yun-Fei, Z., Hong-Yin, N., & Bao-Qing, D. (1986). The ability to manipulate speech sounds depends on knowing alphabetic writing. *Cognition*, *24(1)*, 31-44.

Reinholz, J., & Pollmann, S., (2005). Differential activation of object-selective visual areas by passive viewing of pictures and words. *Cognitive brain research. 24(3)*, 702–714.

Reis, A., Faísca, L., Ingvar, M., & Petersson, K. M. (2006). Color makes a difference: Two-dimensional object naming in literate and illiterate subjects. *Brain and Cognition*, *60(1)*, 49-54.

Reis, A., Petersson, K. M., Castro-Caldas, A., & Ingvar, M. (2001). Formal schooling influences two-but not three-dimensional naming skills. *Brain and cognition*, *47(3)*, 397-411.

Richardson, F.M., Seghier, M.L., Leff, A.P., Thomas, M.S., & Price, C.J. (2011). Multiple routes from occipital to temporal cortices during reading. *Journal of Neuroscience*, *31(22)*, 8239–8247.

Rogers, T. T., & McClelland, J. L. (2014). Parallel distributed processing at 25: Further explorations in the microstructure of cognition. *Cognitive science*, *38(6)*, 1024-1077.

Scliar-Cabral, L., Morais, J., Nepomuceno, L., & Kolinsky, R. (1997). The awareness of phonemes: So close-so far away. *International Journal of Psycholinguistics*, *13*, 211–240.

Serniclaes, W., Ventura, P., Morais, J., & Kolinsky, R. (2005). Categorical perception of speech sounds in illiterate adults. *Cognition*, *98(2)*, B35–B44.

Shu, H., Peng, H., & McBride?Chang, C. (2008). Phonological awareness in young Chinese children. *Developmental Science*, *11(1)*, 171-181.

Simos PG, Breier JI, Fletcher JM, Foorman BR, Castillo EM, & Papanicolaou AC. (2002). Brain mechanisms for reading words and pseudowords: an integrated approach. *Cerebral Cortex*, *12(3)*, 297–305.

Smith, A., Monaghan, P., & Huettig, F. (2013). An amodal shared resource model of language-mediated visual attention. *Frontiers in Psychology*, *4*, 528.

Smith, A., Monaghan, P., & Huettig, F. (2014a). Literacy effects on language and vision: Emergent effects from an amodal shared resource (ASR) computational model. *Cognitive Psychology*, *75*, 28-54.

Smith, A., Monaghan, P., & Huettig, F. (2014b). Modelling language – vision interactions in the hub and spoke framework. In J. Mayor, & P. Gomez (Eds.), Computational Models of Cognitive Processes: *Proceedings of the 13th Neural Computation and Psychology Workshop (NCPW13)*. (pp. 3-16). Singapore: World Scientific Publishing.

Smith, A., Monaghan, P., & Huettig, F. (2014c). Examining strains and symptoms of the 'Literacy Virus': The effects of orthographic transparency on phonological processing in a connectionist model of reading. In P. Bello, M. Guarini, M. McShane, & B. Scassellati (Eds.), *Proceedings of the 36th Annual Meeting of the Cognitive Science Society (CogSci 2014)*. Austin, Texas: Cognitive Science Society.

Snowling, M., Bishop, D. V. M., & Stothard, S. E. (2000). Is preschool language impairment a risk factor for dyslexia in adolescence?. *Journal of Child Psychology and Psychiatry, 41(05),* 587-600.

Treiman, R., & Zukowski, A. (1991). Levels of phonological awareness. In S. A. Brady & D. P. Shankweiler (Eds.), *Phonological processes in literacy: A tribute to Isabelle Y. Liberman* (pp. 67–83). Oxford, England: Routledge.

Turkeltaub, P.E., Gareau, L., Flowers, D.L., Zeffiro, T.A., and Eden, G.F. (2003). Development of neural mechanisms for reading. *Nature neuroscience*, *6(7)*, 767–773.

UNESCO, (2006), Why Literacy Matters. In UNESCO (Ed.), *Education for All. Literacy for Life* (pp. 135-145). Paris, France: UNESCO Publishing.

van Atteveldt N, Formisano E, Goebel R, Blomert L. (2004). Integration of letters and speech sounds in the human brain. *Neuron. 43(2)*, 271–282.

Ventura, P., Fernandes, T., Cohen, L., Morais, J., Kolinsky, R., & Dehaene, S. (2013). Literacy acquisition reduces the influence of automatic holistic processing of faces and houses. *Neuroscience letters*, *554*, 105-109.

Vigneau M, Beaucousin V, Herve P, Duffau H, Crivello F, Houde O, Mazoyer B, & Tzourio-Mazoyer N. (2006). Meta-analyzing left hemisphere language areas: phonology, semantics, and sentence processing. *Neuroimage*, *30*(4),1414–1432.

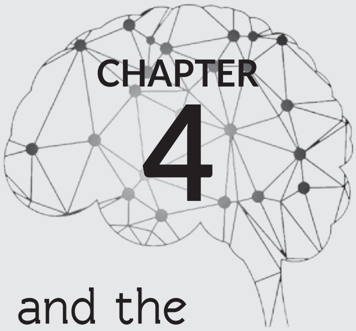
Vigneau, M., Jobard, G., Mazoyer, B., & Tzourio-Mazoyer, N., (2005). Word and non-word reading: what role for the Visual Word Form Area? *Neuroimage*, *27(3)*, 694–705.

Woollams, A.M., Silani, G., Okada, K., Patterson, K., & Price, C.J., (2011). Word or word-like? Dissociating orthographic typicality from lexicality in the left occipito-temporal cortex. *Journal of cognitive neuroscience*, *23(4)*, 992–1002.

Yoncheva, Y. N., Maurer, U., Zevin, J. D., & McCandliss, B. D. (2013). Effects of rhyme and spelling patterns on auditory word ERPs depend on selective attention to phonology. *Brain and language*, *124(3)*, 238-243.

Ziegler, J. C., & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin*, *131(1)*, 3–29.

Ziegler, J. C., Petrova, A., & Ferrand, L. (2008). Feedback consistency effects in visual and auditory word recognition: where do we stand after more than a decade?. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34(3)*, 643-661.



CHAPTER 4

Brain sensitivity to words and the "word recognition potential"

Susana Araújo, Alexanda Reis
Luís Faísca & Karl Magnus Petersson

Introduction

Experimental work concerned with how literate humans recognize printed words converges on the idea that skillful reading must rely on the development of some form of perceptual expertise for letters and group of letters. A functional/structural reorganization of the visual system has been proposed as a possible explanation for this perceptual expertise. In particular, a region of the left ventral occipitotemporal cortex, the putative visual word form area (VWFA), has attracted the attention of the scientific community in recent years. It has been proposed that this region is functionally associated with orthographic processing and coding. We first review some studies that support the role of this region in automatic visual word recognition. Electrophysiological evidence has also identified a key correlate for print processing, the N170 component. Given this component's robust response to orthographic stimulation in the course of learning to read, and given that it may provide a neural marker of a reading disability, N170 specialization is the main focus of this chapter.

Visual Word Recognition: An Incredibly Fast Skill

Reading is arguably the most complex cognitive skill formally acquired by humans. Yet under normal conditions skilled readers can process written text almost effortlessly and at a remarkable speed. It has been estimated that word-specific information is processed within the first 200 ms of stimulus presentation. Fast visual word processing ability implies that fluent readers must develop a rapid and efficient visual word-form recognition system, which enables a direct translation from visual-orthographic codes into pronunciations (phonology) and word meaning (semantics) (Dehaene, 2010). As a first stage of the reading process, before higher-level linguistic properties are accessed, readers must process the elementary visual features of a word's constituent letters and associate those letter identities with positional information – this is referred to as orthographic processing. The dominant theories of reading consider orthographic processing as primarily an extension of already established linguistic skills in the domain of spoken language processing. This conclusion is based on the grounds that learning to read in the context of an alphabetic script is facilitated by the individual letters/letter clusters (graphemes) being associated with elementary sounds of the language (phonemes) in order to recover a phonological representation of the word being read (Ziegler & Goswami, 2005). Yet, in a recent study Grainger and colleagues challenged the hypothesis that prior linguistic knowledge is a necessary prerequisite in order to achieve orthographic processing by showing that nonhuman primates can actually learn this skill (Grainger, Dufau, Montant, Ziegler, & Fagot, 2010). Hence, it thus seems that orthographic processing may, at least partly, be constrained by general principles of visual object processing shared by monkeys and humans.

Another broad theoretical consensus in studies of skilled reading is that readers seem to develop visual pattern memories of familiar words (i.e., an orthographic *lexicon* with a representation of the whole word form) which are important in rapidly recognizing a printed word; indeed, skilled readers recognize words by mapping, via some form of letter-level code, visual features onto whole-word orthographic representations. This lexicon can be viewed as a mental dictionary containing entries of all the words a reader knows. According to this idea, visual word recognition, in a sense of transforming print to meaning, is then conceptualized in terms of "lexical access" or "lexical selection" (Dehaene, 2010). Indeed, since the 1970's the influential dual-route conception of reading already incorporated this assumption in suggesting that the pronunciation of a printed word could be computed by searching long-term memories for stored information about words (lexical access) or, in the case of unfamiliar words, by an alternative way consisting of applying a series of letter-sound correspondence rules (for a review, see Coltheart, 2007).

Yet an older debate in reading research regards the temporal flow of information in the lexical system, that is, whether word recognition is achieved by a hierarchy of processing stages that occur in a strictly feedforward manner *versus* whether higher-level linguistic representations such as phonological structure can exert a top-down influence on early visual orthographic processing (for an overview, see Lupker, 2007). Temporally modular feedforward models assume hierarchically-organized processing stages, where printed words are identified principally on the basis of orthographic information with other representations such as semantics and phonology activated subsequently. Whether or not these non-visual orthographic representations are accessed before orthographic access is complete, they never feed back to influence the orthographic computation.

According to interactive activation models, however, the reading system is rather interactive and allows feedback from higher-level linguistic information to visual orthographic representations relatively early (McClelland & Rumelhart, 1981). One major problem that the first approach faces is explaining why there often seems to be observable effects of "higher-level information" on "lower-level processing," which is already possible under an interactive perspective. Here the word-superiority effect is a classical example: skilled readers identify letters (lower-level information) better when they appear in a real word than when appear in a chain of random letters such as nonwords (Reicher, 1969). A proposed explanation for this phenomenon is that because familiar words have an entry in the mental lexicon, processing of letters within words (unlike letters in meaningless chains) profits from lexical top-down influences and such letters are then better perceived. In other words, higher-level representations shape early visual word recognition through top-down feedback from lexical knowledge to perceptual stages. In a recent review, Carreiras and colleagues also concluded that behavioral, neuroimaging, and electrophysiological evidence obtained so far is more consistent with interactive accounts for the temporal flow of information in the reading system (Carreiras, Armstrong, Perea, & Frost, 2014).

Like that of the interactive activation model (McClelland & Rumelhart, 1981), many modelers have found the idea of interactivity attractive. For example, the basic interactive activation system is used to describe the first part of the "lexical route" in the dual-route cascaded model, which is one of the most influential computational models for explaining the underlying processes involved in single word reading (Castles, Bates, Coltheart, Luciano, & Martin, 2006; Coltheart, 2007; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). According to this model, there are two independent mechanisms for accessing meaning from print: (1) by directly mapping the whole-word orthographic configuration ("orthographic input lexicon") to word phonology in the phonological output lexicon, which in turn activates the word's phonemes for speech or (2) using a nonlexical route which connects the letter-level representations directly to the phoneme system (i.e., a phonological decoding procedure based on grapheme-to-phoneme correspondence rules; it operates in a left-to-right fashion). Finally, there is a semantic system that indirectly connects the orthographic input lexicon with the phonological output lexicon. This system, through feedback operations, would provide a means of explaining, for example, the typical semantic priming effects observed in experimental studies (target words that are preceded by a related semantic context word – prime – are responded to faster than targets that are not, such as “dog-cat” *versus* “dog-nurse”).

But certainly there must be something more than lexical factors to explain the ease and rapidity with which we perceive print. Because reading is first and foremost a visual activity, a major focus in recent reading research has been on the role of visual processing in pre-literate children (e.g., Yamada et al., 2011), in young “beginning” and adult “proficient” readers (e.g., Brem et al., 2009; Spironelli & Angrilli, 2009). One argument that has been discussed in the literature is that skilled visual word recognition resides in our ability to elaborate *abstract* word representations (irrespective of letter size, case and font; Cohen & Dehaene, 2004; McCandliss, Cohen, & Dehaene, 2003). However, other researchers have argued against this view, suggesting that the reason why visual recognition of frequently encountered words is so fast and easy pertains to the formation of multiple representations of the same visual word pattern at lower levels of visual processing (i.e., stimulus-specific pattern memories across a trained retinotopically mapped region, which are acquired through extensive training in recognizing print; Nazir & Huckauf, 2007). So, according to this view, although skilled readers can read words despite variations in script, font, size, or retinal location, the perceptual operation that underlies efficient visual word recognition may not adapt to large variation in surface features. This would explain why word recognition becomes slow in a letter-by-letter mode (a kind of processing typically observed with beginning readers) when the reader is asked to identify words in a very unfamiliar format, such as in a vertical display (Nazir & Huckauf, 2007).

Brief Overview of fMRI Evidence

In recent years, significant progress has been achieved in the study of processes for rapid identification of visual words with the use of brain imaging techniques. Due to rapid advances in functional imaging, it is now possible to decipher the cortical dynamics of component processes and the functional brain organization for reading (and its failure). An impressive amount of brain imaging papers on the neurobiology of reading has emerged in the last decade, but a detailed account of these is beyond the scope of this chapter; others have done that remarkably well (see Dehaene, 2010; McCandliss et al., 2003; Price, 2012, 2013; Price & Mechelli, 2005; Schlaggar & McCandliss, 2007). The intent here is to frame our central discussion about the reading-related N170 electrophysiological marker within the context of a more global picture that specifies the consequences of literacy on the brain.

Functional imaging studies have long associated written word recognition with a largely distributed network of brain areas mainly at the left hemisphere, which sustain orthographic, semantic and phonological processing. Specifically, these studies consider that three major neural systems play a role during a reading task: one anterior system around the inferior frontal gyrus mainly involved in word analysis (decoding; among other functions, e.g. phonological memory, syntactic processing), and two posterior systems. One in the temporoparietal region (including the angular and supramarginal gyrus, and the superior temporal gryus encompassing the Wernicke's Area) is involved in mapping visual percepts of print onto the phonological and semantic structure of language, and the other more inferior in the occipitotemporal region is responsible for fluent and automatic reading (for an overview see Price & Mechelli, 2005; Schlaggar & McCandliss, 2007; Shaywitz & Shaywitz, 2008).

Moreover, neuroimaging studies have demonstrated that both increased familiarity with specific words and increased reading skill are associated with a shift in the relative activation of the cortical systems involved in reading – from predominantly dorsal (temporoparietal) to predominantly ventral (occipitotemporal). For example, Katz and colleagues (2005) found evidence for this shift as skilled readers acquired familiarity with unfamiliar words via repetition. These findings are compatible with a fundamental principle shared by most theories of reading development: that in normal reading development, readers progress from a phonological decoding strategy towards a reliance on more efficient automatic word recognition of whole word-forms (Ehri, 1995, 2007; Frith, 1986). Behavioral evidence is also in agreement (Backman, Bruck, Hebert, & Seidenberg, 1984; Johnston, Thompson, Fletcher-Flinn, & Holligan, 1995; Sprenger-Charolles, Siegel, Béchennec, & Serniclaes, 2003).

The Particular Case of the "Visual Word Form Area" in Reading

Brain imaging studies have demonstrated that the acquisition of literacy leads to a significant reorganization of the brain system, which has consequences in the processing of linguistic visual stimuli (and also non-linguistic; Dehaene, 2010). One of the most relevant examples of such debate is the role of the left fusiform gyrus located in the inferior part of the occipitotemporal cortex. Cohen and colleagues (Cohen et al., 2002; McCandliss et al., 2003) tentatively termed this region the "visual word form area" (VWFA), as it is held to be a relatively "early" processing area that shows preferential processing (i.e., stronger activation) of visually presented words and letter strings compared with a variety of control stimuli, such as checkerboards (e.g., Cohen et al., 2002), geometric symbols (e.g., Tarkiainen, Helenius, Hansan, Cornelissen, & Salmelin, 1999), or line drawings (e.g., Szwed et al., 2011). Its activity was also found to be strictly visual, with no hint of an activation to spoken words (Dehaene, Le Clec'H, Poline, Le Bihan, & Cohen, 2002).

It is thus commonly accepted that, during reading acquisition, skilled processing of letters drives the emergence of a perceptual mechanism specifically tuned to the properties of the orthographic code, instantiated in the left occipitotemporal region (Cohen et al., 2002; McCandliss et al., 2003). Schlaggar and McCandliss (2007, p. 480) described the VWFA as supporting "a form of perceptual expertise for visual word recognition that enables rapid perception of visual words in one's own language.'' Moreover, less activation in ventral subsystems, particularly the occipitotemporal skill zone, has been shown in individuals with reading disabilities, who thus develop compensatory responses in frontal and right hemisphere systems (Cao, Bitan, Chou, Burman, & Booth, 2006; Kronschnabel, Schmid, Maurer, & Brandeis, 2013; Maurer et al., 2011; Monzalvo, Fluss, Billard, Dehaene, & Dehaene-Lambertz, 2012; van der Mark et al., 2009; Wimmer et al., 2010). Accordingly, a meta-analysis of functional neuroimaging studies emphasizes the importance of early recruitment of the left occipitotemporal region in the development of reading, and an early failure of this engagement in dyslexia (Richlan, Kronbichler, & Wimmer, 2011).

Some recent findings have brought new evidence regarding the specificity of visual word form recognition, by suggesting that the remarkable efficacy of reading partly originates earlier than the VWFA in the occipital cortex (Szwed et al., 2011). Greater responses to written words than to objects were found not only in the VWFA, but also in visual areas V1/V2 and V3/V4. The authors' interpretation was that these early visual areas are recruited to detect and amplify visual features relevant for reading, providing highly parallel input to the VWFA and greatly accelerating recognition. The VWFA region then carries out orthographic analysis of whole-word forms (Binder, Medler, Westbury, Liebenthal, & Buchanan, 2006; Glezer, Jiang, & Riesenhuber, 2009; Kronbichler et al., 2007). Other recent works have also proposed that at least two levels of VWFA specialization exist: a fast, coarse specialization for print (letter sequences versus visual control stimuli) and a specialization for processing letter sequences at the whole-word level as well, as reflected in VWFA sensitivity to the orthographic familiarity (Bruno, Zumberge, Manis, Lu, & Goldman, 2008; van der Mark et al., 2009). For instance, it has been reported that an increase in the familiarity of letter strings in five levels from the unfamiliar (i.e., pseudowords) to the highly familiar (i.e., high-frequency words) was accompanied by a decrease in brain activation in the left occipitotemporal cortex (Kronbichler et al., 2004). This finding contrasts with VWFA's conceptualization in terms of a strictly prelexical hub that computes and stores only prelexical orthographic representations in a primarily feedforward manner (Dehaene et al., 2002).

Findings indicating there is a region of the left occipitotemporal sulcus that becomes attuned to visual word recognition processes now must be reconciled with the fact that human genome evolution could not have been influenced by such a culturally recent activity as reading (Dehaene, 2010). Under this perspective, Dehaene and colleagues proposed the *neural recycling hypothesis* (Dehaene, 2010; Dehaene & Cohen, 2007), according to which a prior neurocircuitry for visual object recognition in ventral occipitotemporal brain areas is adapted or "recycled" to compute the specific characteristics of printed words. Importantly, plastic neuronal changes occur in the context of strong constraints imposed by the prior evolution of the cortex; for example, a tight proximity and strong reciprocal interconnection to spoken language representations in the lateral temporal lobe conspire to make this cortical site optimal for written word recognition (Dehaene & Cohen, 2011). Interestingly, in a study comparing illiterate versus literate adults, it was found that, with increasing literacy, there is an enhancement of the response to letter strings in the VWFA. Remarkably, a significant activation decrease in response to faces was also seen in this same region, with this response was then displaced to the right hemispheric fusiform gyrus (Dehaene et al., 2010). So, data support the existence of competition for cortical space between the emerging VWFA and the preexisting neural coding of other categories, particularly of faces.

An Electrophysiological Marker of Visual Expertise for Print

Event-related potentials (ERPs) have a high temporal resolution (with millisecond precision) that hemodynamic measures lack, and so are very useful in isolating cognitive processes during visual word recognition tasks. The brain specialization for the visual aspects of print is signaled by the N170 electrophysiological component (also known as N1 or "word recognition potential") related to reading expertise (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999). The N170 is a negative deflection peaking at approximately 150-200 ms post stimulus onset, which is significantly enhanced for orthographic strings including words and pseudowords compared with other low-level control items like symbols, forms or shapes (Bentin et al., 1999; Brem et al., 2009; Helenius, Tarkiainen, Cornelissen, Hansen, & Salmelin, 1999; Maurer, Brem, Bucher, & Brandeis, 2005; Maurer et al., 2006; Wong, Gauthier, Woroch, DeBuse, & Curran, 2005). Studying children longitudinally before and after learning to read, Maurer and colleagues observed no reliable difference in the N70 elicited by words and symbols in kindergarten children, unlike the stronger difference in second grade (Maurer et al., 2007; Maurer et al., 2006). Recently, N170 difference in the ERPs between words and false-font strings was found by the end of the first grade, both at the group and individual response level (Eberhard-Moscicka, Jost, Raith, & Maurer, 2014). Thus, fast brain processes as indexed by the N170 sensitivity for print develop rapidly as children learn to read, as early as the very initial stages of reading acquisition. Yet the N170 specialization in typical readers has been shown to follow a nonlinear U-shaped developmental trajectory, which peaks in beginning readers and decreases subsequently with age (Brem et al., 2009; Maurer et al., 2006). The largest sensitivity of the N170 at the initial phases of reading acquisition –that is, when models of reading acquisition emphasize the importance of grapheme-to-phoneme decoding– may characterize the increased plasticity and emerging visual expertise during that time.

Studies using intracranial recordings and magnetoencephalography (MEG) have localized selective responses to letters in the N170 time-window into inferior occipitotemporal regions, predominantly of the left hemisphere (Nobre, Allison, & McCarthy, 1994; Tarkiainen, Cornelissen, & Salmelin, 2002; Tarkiainen et al., 1999). Therefore, it has been proposed that the N170 electrophysiological response to visual words could be associated with the cortical activity found using fMRI in the VWFA left fusiform gyrus (Allison, McCarthy, Nobre, Puce, & Belger, 1994; Brem et al., 2006; Maurer, Brem et al., 2005). N170 can be viewed as an index of specialized processing for letters: the more the stimuli resemble letter-strings, the larger (more negative) their N170 component compared to control stimuli (Tarkiainen et al., 1999). Similar effects have been found in the preceding P1 component

(~50-150 ms; Maurer, Brem et al., 2005; Maurer et al., 2011) and the early P1-N170 peak(s) might thus reflect a reorganization of the brain that occurs as a function of reading training. Importantly, this reading-related N70 specialization can be detected across languages varying in the structure (opaque versus transparent letter-sound mappings) of their orthography (e.g., orthography of intermediate depth: Araújo, Faísca, Bramão, Petersson, & Reis, 2012; opaque orthography: Maurer, Brandeis, & McCandliss, 2005; transparent orthography: Maurer, Brem et al., 2005); though the left-lateralized topographic effect might be to some extent language-specific.

Researchers have found similar N170 effects in other forms of visual expertise related to faces or objects that result from extensive training (e.g., Rossion, Joyce, Cottrell, & Tarr, 2003; e.g., Tanaka & Curran, 2001), but such effects tend to be bilateral or right-lateralized. Thus, the left lateralization of the N170 response to orthographic material has been proposed as a phenomenon that differentiates word reading from other forms of visual expertise (Maurer, Brandeis et al., 2005; Maurer & McCandliss, 2007). Another result supporting the claim that the N170 response reflects a specific brain training effect, "tuning to print", comes from studies with populations with different reading expertise. For instance, print tuning reflected by a typical left-lateralized N170 modulation does not emerge before the onset of formal schooling (Maurer, Brem et al., 2005) and is reduced in groups lacking reading expertise such as children and adults with developmental dyslexia (Araújo et al., 2012; Hasko, Groth, Bruder, Bartling, & Schulte-Körne, 2013; Helenius et al., 1999; Mahé, Bonnefond, Gavens, Dufour, & Doignon-Camus, 2012; Maurer et al., 2007). N170 hence has been linked to fluent reading (Figure 4.1). Moreover, previous results from kindergarten pre-readers (especially those with high letter knowledge) demonstrated an interesting phenomenon of a right-lateralized N170-like effect of familiar script relative to unfamiliar control stimuli, possibly reflecting a visual precursor of literacy due to visual familiarity with letter strings (Maurer, Brem et al., 2005). Also, in a longitudinal developmental study by Maurer and colleagues (2007), the topography of the N170 specialization for words was still bilateral in children in second grade, but the increase from kindergarten to second grade was stronger over the left-hemisphere than over the right hemisphere, indicating that not only the amplitude of the N170 specialization but also its lateralization plays an important role in the first years of reading acquisition. Likewise, Kast and colleagues (Kast, Elmer, Jancke, & Meyer, 2010) observed that the visual word N170 component in children was bilateral in children of approximately 10-years of age (see also Spironelli & Angrilli, 2009), while in a study from our group (Araújo et al., 2012), a left hemisphere dominance for letter sequences was already evidenced in pre-adolescent normal readers at 10–13 years old.

To explain the left-lateralization of the N170 for visual words, Maurer and McCandliss (2007) proposed *the phonological mapping hypothesis*: the topographic differences found between early childhood compared to adulthood are driven by differences in the automaticity of links between orthography and phonology at the level of grapheme-phoneme associations. More specifically, according to this hypothesis, initially recruited right-lateralized processes may become increasingly left-lateralized as reading skills progress under the influence of pre-existing left-lateralized higher-order processes of the auditory language system, namely phonological processing. The grapheme-phoneme decoding of visual words, exercised consistently and repeatedly over the course of reading acquisition, will drive the characteristic left lateralization of the N170 expertise effect for written words, given the predominant engagement of the left hemisphere in phonological processing.

Empirical studies testing the validity of this hypothesis are just emerging. For example, using an artificial orthography paradigm, Yoncheva and colleagues (Yoncheva, Blau, Maurer, & McCandliss, 2010) extended this hypothesis to specifically regard the role of attention to grapheme-phoneme unit sizes in print-to-speech mapping as a factor that is important for the emergence of the left-lateralized N170 response. In this study, two groups of literate adults were trained to read a novel artificial writing system under instructions that directed attention to grapheme-phoneme versus whole-word associations. Post-training, a left-lateralized N170 response was observed for trained words as well as for transfer words in the grapheme-phoneme group, relative to the right-lateralized N170 ERP of the whole-word group. The authors' interpretation was that explicit attentional focus on grapheme-phoneme mappings during training is necessary to drive a left-lateralized N170 response. This interpretation fits well with the phonological mapping hypothesis. Likewise, in another study Brem and colleagues (2010) demonstrated that the N170 print tuning, absent in illiterate kindergarteners, emerged after brief grapheme–phoneme training.

Cross-linguistic studies have provided further support for this hypothesis. For example, these studies have shown that the reading of pseudowords elicits a left hemisphere modulation of the N170 in readers of German, but not in English (Maurer, Brandeis et al., 2005; Maurer, Brem et al., 2005). Also, a study involving Koreans who were educated in both Chinese and written English reported a left-lateralized N170 effect for both English and Korean words but a bilateral N170 effect for Chinese characters and pictures (Hsu, Tsai, Lee, & Tzeng, 2009; Kim, Yoon, & Park, 2004). A prominent difference in the comparison between German and English lies in the level of transparency with each letter's map onto sounds; therefore, pseudowords are more ambiguous for English speakers to pronounce. Chinese, in turn, uses a rather logographic system, in which graphic symbols represent lexical morphemes. It thus seems that a left-lateralized specialization of the N170 word effect may specifically relate to the extent that processes involved in spelling-to-sound mapping at the grapheme-phoneme level are engaged during reading. Moreover, the relationship between phonological recoding and the emergence of the letter-specialized system is supported by studies showing that the N170 component is strongly associated with phonological processing (Madec, Rey, Dufau, Klein, & Grainger, 2012; Parviainen, Helenius, Poskiparta, Niemi, & Salmelin, 2006) and with nonword reading fluency (Maurer et al., 2007).

A recent study tested the effects of four cognitive reading components (vocabulary, rapid naming, phonological awareness, and auditory memory span) on the N170 neurophysiological marker. However, only vocabulary was found to contribute to the variance in print tuning in the first year of reading acquisition (Eberhard-Moscicka et al., 2014). The authors suggested therefore that the N170 reflected differences between words and false-fonts consisting of two processes: a dominating process reflecting general perceptual expertise for orthographic strings, and the other a reflecting lexical-semantic processing (as indicated by the correlation of print tuning with vocabulary).

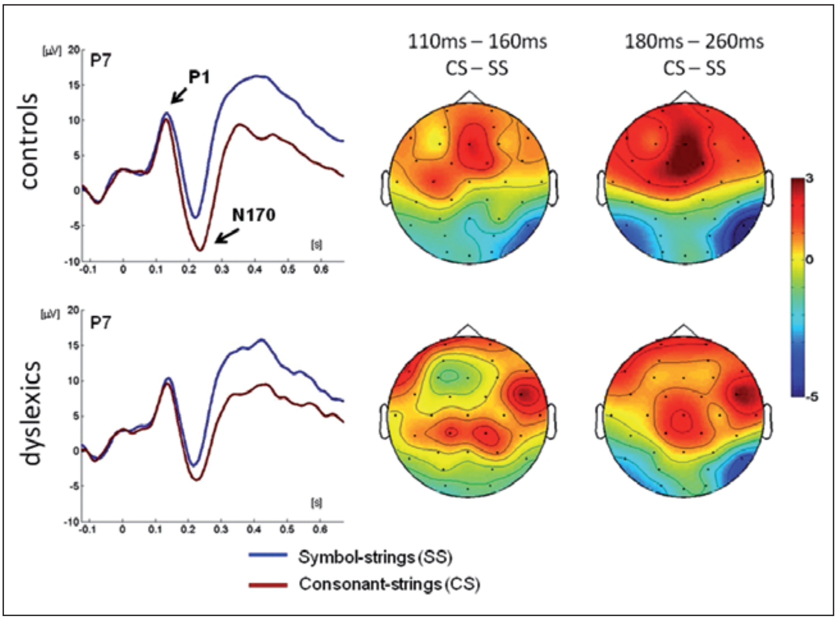


Figure 4.1. ERPs elicited by consonant-sequences (CS) and symbol-sequences (SS) for selected electrodes, averaged separately for skilled readers and dyslexic readers (left panel). Topographic distribution of the P1 (110-160 ms) and N1 (280-260 ms) effects (right panel). The difference voltage maps were computed by subtracting the average ERPs to CS from the average ERPs to SS.

Source: Adapted from Araújo et al. (2012).

The N170: Modulated by Lower- or Higher-order Linguistic Properties?

As reviewed above, ERP studies have identified the N170 component as consistently evoked by orthographic material, and also as a neural marker in reading disability. Yet there is controversy about N170's specificity in the visual word recognition process (i.e., regarding which specific properties of words trigger this effect in the N170 component).

One theoretical position is that the N170 just reflects perceptual expertise for letters recognition, that is, it is primarily related to visual and abstract prelexical computations of written words. For example, one set of studies demonstrated that words, pronounceable pseudowords and even consonant strings elicited similar N170 responses, which differed from those elicited by symbol strings (Araújo et al., 2012; Bentin et al., 1999; Eberhard-Moscicka et al., 2014; Hasko et al., 2013; Kast et al., 2010; Maurer, Brem et al., 2005). Likewise, in a study conducted in our lab we found no modulation by different levels of word frequency on the N170 amplitudes (Araújo et al., 2012). These findings thus suggest that the N170-evoked response might arise at the earliest prelexical stages of the orthographic system.

However, on the other side of the debate, there are also reports of sensitivity to higher-order linguistic properties of stimuli during the N170 range, including the recognition of familiar patterns of letters within visual word-forms. Some studies did find significant lexicality effects in this ERP component, with pseudowords eliciting stronger brain activity than words (Hauk et al., 2006; Sereno, Rayner, & Posner, 1998). Studies have also found larger amplitudes in response to low-frequency words compared to high-frequency words (Assadollahi & Pulvermuller, 2003; Hauk et al., 2006; Hauk & Pulvermüller, 2004; Sereno, Brewer, & O'Donnell, 2003; Sereno et al., 1998). Word frequency and lexicality effects support a lexical function of the N170 effect, as they likely reflect a facilitated access to lexical orthographic information for familiar words. But how can we then reconcile these inconsistent findings? One possibility has to do with developmental aspects. Most of the studies reporting null lexicality or frequency effects were conducted in the early reading stages of reading development (e.g., in ten-year-old children, Araújo et al., 2012; and in eight-year-old children, Hasko et al., 2013), while significant effects typically originate from studies with adult readers (e.g., Araújo, Faísca, Bramão, Reis, & Petersson, under revision; Hauk et al., 2006). Perhaps the developmental stage of reading acquisition influences the degree of the lexicality/frequency effect in a way that, when the reading process is not yet fully automatized (as in young children), N170 is likely an index of pre-lexical processing only. However, with increasing reading expertise (as in adults), it might reflect sensitivity to lexical orthographic information as well. Still other reasons could explain the inconsistencies in results, such as differences in task demands, experimental parameters, and properties of the writing system. Further research is therefore warranted.

In recent years, another aspect that has attracted the attention of researchers concerns early brain sensitivity to the sublexical structure of words. Some studies have described an effect of orthographic sublexical regularity in earlier time windows encompassing the N170, localized into its left inferior temporal areas (Coch & Mitra, 2010; Hauk et al., 2006). For example, using ERPs and a lexical decision task, Hauk and colleagues (2006) found the earliest effect of orthographic typicality, as measured by bi-/trigram frequency, was around 100 ms: words and pseudowords with atypical orthography elicited stronger brain activation than typical items. In our lab, using an implicit reading task we further explored other measures of orthotactic dependencies, as sequential constraints (Araújo et al., under revision). Contrasting pseudowords (orthographically legal) with nonwords containing at least one illegal letter bigram, we found significant differences in the N170 waveform for skilled adult readers. It thus seems that the adult brain is sensitive to the dependencies among letters and positions within word-forms (sublexical orthographic structure of words) in a very early stage of the reading process, as early as ~100 ms after stimulus onset. Interestingly, in this study we also observed enhanced ERPs to pseudohomophones at the right posterior sites when compared with those elicited by words and also pseudowords, during the same time window. Pseudohomophones sound like real words (are phonologically familiar) but are spelled incorrectly, which means that their phonological representations do not match the orthographic representations in memory (unlike words and pseudowords). Therefore, we interpret our ERP results as likely reflecting the brain's electrical response to the conflict between stored orthographic and phonological information. This suggests that the N70 component is sensitive not just to letter identity but also to higher-order linguistic information, and in particular that information about the phonological structure of the stimulus exerts a top-down influence on visual-orthographic processing relatively early (see also, for example, Braun, Hutzler, Ziegler, Dambacher, & Jacobs, 2009). Data is thus more compatible with a conceptualization of reading as a fully interactive processing system whereby higher-level linguistic information, not necessarily orthographic, modulates early orthographic processing (for a recent review, see Carreiras et al., 2014).

Concluding Remarks

Characterizing the neurobiological basis of cortical plasticity during normal reading acquisition is, ultimately, crucial to the understanding of developmental reading disorders. Plentiful evidence in the recent decades has converged to conclude that fast visual word processing ability in literate humans may rely on a perceptual mechanism that is especially attuned to the recurrent properties of the orthographic code. This specialized system for written words develops during reading acquisition, thereby optimizing orthographic processing. In particular, this specialization due to reading acquisition is signaled by the left-lateralized N70 electrophysiological component – which could be an automatic response, related to typical visual word recognition – and by stronger responses to letter strings in the left occipitotemporal region. One emerging hypothesis for the typical left-lateralized N170 effect, the phonological mapping hypothesis, holds that a left lateralized modulation may develop under the influence of grapheme-phoneme conversion during the process of learning to read.

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References

Allison, T., McCarthy, G., Nobre, A., Puce, A., & Belger, A. (1994). Human extrastriate visual cortex and the perception of faces, words, numbers, and colors. *Cerebral Cortex*, *4*, 544-554.

Araújo, S., Faísca, L., Bramão, I., Petersson, K. M., & Reis, A. (2012). Electrophysiological correlates of impaired reading in dyslexic pre-adolescent children. *Brain and Cognition*, *79*, 79-88.

Araújo, S., Faísca, L., Bramão, I., Reis, A., & Petersson, K. M. (under revision). Lexical and sublexical orthographic processing: An ERP study with skilled and dyslexic adult readers.

Assadollahi, R., & Pulvermuller, F. (2003). Early infuences of word length and frequency: A group study using MEG. *NeuroReport*, *14*(8), 1183-1187.

Backman, J., Bruck, M., Hebert, M., & Seidenberg, M. S. (1984). Acquisition and use of spelling sound correspondences in reading. *Journal of Experimental Child Psychology*, *38*, 114-133.

Bentin, S., Mouchetant-Rostaing, Y., Giard, M. H., Echallier, J. F., & Pernier, J. (1999). ERP manifestations of processing printed words at different psycholinguistic levels: Time course and scalp distribution *Journal of Cognitive Neuroscience*, *11*(3), 235-260.

Binder, J. R., Medler, D. A., Westbury, C. F., Liebenthal, E., & Buchanan, L. (2006). Tuning of the human left fusiform gyrus to sublexical orthographic structure. *Neuroimage*, *33*(2), 739-748.

Braun, M., Hutzler, F., Ziegler, J. C., Dambacher, M., & Jacobs, A. M. (2009). Pseudohomophone effects provide evidence of early lexico-phonological processing in visual word recognition. *Human Brain Mapping*, *30*, 1977-1989.

Brem, S., Bach, S., Kucian, K., Guttorm, T. K., Martin, E., Lyytinen, H., et al. (2010). Brain sensitivity to print emerges when children learn letter–speech sound correspondences. *PNAS*, *107*(17), 7939-7944.

Brem, S., Bucher, K., Halder, P., Summers, P., Dietrich, T., & Martin, E. (2006). Evidence for developmental changes in the visual word processing network beyond adolescence. *Neuroimage*, *29*, 822-837.

Brem, S., Halder, P., Bucher, K., Summers, P., Martin, E., & Brandeis, D. (2009). Tuning of the visual word processing system: distinct developmental ERP and fMRI effects. *Human Brain Mapping*, *30*(6), 1833-1844.

Bruno, J. L., Zumberge, A., Manis, F. R., Lu, Z., & Goldman, J. G. (2008). Sensitivity to orthographic familiarity in the occipito-temporal region. *NeuroImage*, *39*, 1988-2001.

Cao, F., Bitan, T., Chou, T., Burman, D. D., & Booth, J. R. (2006). Deficient orthographic and phonological representations in children with dyslexia revealed by brain activation patterns. *Journal of Child Psychology and Psychiatry*, *47*(10), 1041-1050.

Carreiras, M., Armstrong, B. C., Perea, M., & Frost, R. (2014). The what, when, where, and how of visual word recognition. *Trends in Cognitive Sciences*, *18*(2), 90-98.

Castles, A., Bates, T., Coltheart, M., Luciano, M., & Martin, N. G. (2006). Cognitive modelling and the behaviour genetics of reading. *Journal of Research in Reading*, *29*(1), 92-103.

Coch, D., & Mitra, P. (2010). Word and pseudoword superiority effects reflected in the ERP waveform. *Brain Research*, *1329*, 159-174.

Cohen, L., & Dehaene, S. (2004). Specialization within the ventral stream: the case for the visual word form area *NeuroImage*, *22*(1), 466-476.

Cohen, L., Lehericy, S., Chochon, F., Lemer, C., Rivaud, S., & Dehaene, S. (2002). Language-specific tuning of visual cortex functional properties of the visual word form area. *Brain*, *125*, 1054-1069.

Coltheart, M. (2007). Modeling reading: The dual-route approach. In M. J. Snowling & C. Hulme (Eds.), *The science of reading: A handbook* (pp. 6-23). UK: Blackwell Publishing.

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. C. (2001). DRC: A Dual Route Cascaded model of visual word recognition and reading aloud. *Psychological Review*, *108*(1), 204-256.

Dehaene, S. (2010). *Reading in the brain: The new science of how we read*. UK: Penguin Book.

Dehaene, S., & Cohen, L. (2007). Cultural recycling of cortical maps. *Neuron*, *56*, 384-398.

Dehaene, S., & Cohen, L. (2011). The unique role of the visual word form area in reading. *Trends in Cognitive Sciences*, *15*(6), 254-262.

Dehaene, S., Le Clec'H, G., Poline, J.-B., Le Bihan, D., & Cohen, L. (2002). The visual word form area: a prelexical representation of visual words in the fusiform gyrus *Neuroreport*, *13*, 321-325.

Dehaene, S., Pegado, F., Braga, L. W., Ventura, P., Filho, G. N., Jobert, A., et al. (2010). How learning to read changes the cortical networks for vision and language. *Science*, *330*, 1359-1364.

Eberhard-Moscicka, A. K., Jost, L. B., Raith, M., & Maurer, U. (2014). Neurocognitive mechanisms of learning to read: print tuning in beginning readers related to word-reading fluency and semantics but not phonology. *Developmental Science*, 1-13.

Ehri, L. C. (1995). Phases of development in learning to read words by sight. *Journal of Research in Reading*, *18*, 116-125.

Ehri, L. C. (2007). *Development of sight word reading: Phases and findings*. In M. J. Snowling & C. Hulme (Eds.), The science of reading: A handbook (pp. 135-154). UK: Blackwell Publishing.

Frith, U. (1986). A developmental framework for developmental dyslexia. *Annals of Dyslexia*, *36*, 69-81.

Glezer, L. S., Jiang, X., & Riesenhuber, M. (2009). Evidence for highly selective neuronal tuning to whole words in the "Visual Word Form Area". *Neuron*, *62*, 192-204.

Grainger, J., Dufau, S., Montant, M., Ziegler, J. C., & Fagot, J. (2010). Orthographic Processing in Baboons (Papio papio). *Science*, *336*, 245-248.

Hasko, S., Groth, K., Bruder, J., Bartling, J., & Schulte-Körne, G. (2013). The time course of reading processes in children with and without dyslexia: An ERP study. *Frontiers in Human Neuroscience*, 7:570.

Hauk, O., Patterson, K., Woollams, A., Watling, L., Pulvermüller, L., & Rogers, T. T. (2006). [Q:] When would you prefer a SOSSAGE to a SAUSAGE? [A:] At about 100 msec. ERP correlates of orthographic typicality and lexicality in written word wecognition. *Journal of Cognitive Neuroscience*, *18*(5), 818-832.

Hauk, O., & Pulvermüller, F. (2004). Effects of word length and frequency on the human event-related potential. *Clinical Neurophysiology*, *115*, 1090-1103.

Helenius, P., Tarkiainen, A., Cornelissen, P. L., Hansen, P. C., & Salmelin, R. (1999). Dissociation of normal feature analysis and deficient processing of letter-strings in dyslexic adults. *Cerebral Cortex*, *9*, 476-483.

Hsu, C.-H., Tsai, J.-L., Lee, C.-Y., & Tzeng, O. J.-L. (2009). Orthographic combinability and phonological consistency effects in reading Chinese phonograms: An event-related potential study. *Brain and Language*, *108*, 56-66.

Johnston, R. S., Thompson, G. B., Fletcher-Flinn, C. M., & Holligan, C. (1995). The functions of phonology in the acquisition of reading: Lexical sentence processin. *Memory & Cognition*, *23*, 749-766.

Kast, M., Elmer, S., Jancke, L., & Meyer, M. (2010). ERP differences of pre-lexical processing between dyslexic and non-dyslexics children. *International Journal of Psychophysiology*, *77*, 59-69.

Katz, L., Lee, C. H., Tabor, W., Frost, S. J., Mencl, W. E., Sandak, R., et al. (2005). Behavioral and neurobiological effects of printed word repetition in lexical decision and naming. *Neuropsychologia*, *43*, 2068-2083.

Kim, K. H., Yoon, H. W., & Park, H. W. (2004). Spatiotemporal brain activation pattern during word/picture perception by native Koreans. *NeuroReport*, *15*(7), 1099-1103.

Kronbichler, M., Bergmann, J., Hutzler, F., Staffen, W., Mair, A., Ladurner, G., et al. (2007). Taxi vs. Taksi: On orthographic word recognition in the left ventral occipitotemporal cortex. *Journal of Cognitive Neuroscience*, *19*(10), 1584-1594.

Kronbichler, M., Hutzler, F., Wimmer, H., Mair, A., Staffen, W., & Ladurner, G. (2004). The visual word form area and the frequency with which words are encountered: Evidence from a parametric fMRI study. *Neuroimage*, *21*, 946-953.

Kronschnabel, J., Schmid, R., Maurer, U., & Brandeis, D. (2013). Visual print tuning deficits in dyslexic adolescents under minimized phonological demands. *NeuroImage*, *74*, 58-69.

Lupker, S. J. (2007). Visual word recognition: Theories and findings. In M. J. Snowling & C. Hulme (Eds.), *The science of reading: A handbook* (pp. 39-60). UK: Blackwell Publishing.

Madec, S., Rey, A., Dufau, S., Klein, M., & Grainger, J. (2012). The time course of visual letter perception. *Journal of Cognitive Neuroscience*, *24*(7), 1645-1655.

Mahé, G., Bonnefond, A., Gavens, N., Dufour, A., & Doignon-Camus, N. (2012). Impaired visual expertise for print in French adults with dyslexia as shown by N170 tuning. *Neuropsychologia*, *50*(14), 3200-3206.

Maurer, U., Brandeis, D., & McCandliss, B. D. (2005). Fast visual specialization for reading in English revealed by the topography of the N170 ERP response. *Behavioral and Brain Functions*, *1*, 1-13.

Maurer, U., Brem, S., Bucher, K., & Brandeis, D. (2005). Emerging neurophysiological specialization for letter strings. *Journal of Cognitive Neuroscience*, *17*(10), 1532-1552.

Maurer, U., Brem, S., Bucher, K., Kranz, F., Benz, R., Steinhausen, H., et al. (2007). Impaired tuning of a fast occipito-temporal response for print in dyslexic children learning to read. *Brain*, *130*, 3200-3210.

Maurer, U., Brem, S., Kranz, F., Bucher, K., Benz, R., Halder, P., et al. (2006). Coarse neural tuning for print peaks when children learn to read. *NeuroImage*, *33*, 749-758.

Maurer, U., & McCandliss, B. D. (2007). The development of visual expertise for words: The contribution of electrophysiology. In E. L. Grigorenko & A. J. Naples (Eds.), *Single-word reading: Biological and behavioral perspectives*. Mahwah, NJ: Lawrence Erlbaum Associates.

Maurer, U., Schulz, E., Brem, S., der Mark, S. V., Bucher, K., Martin, E., et al. (2011). The development of print tuning in children with dyslexia: Evidence from longitudinal ERP data supported by fMRI. *Neuroimage*, *57*, 714-722.

McCandliss, B. D., Cohen, L., & Dehaene, S. (2003). The visual word form area: Expertise for reading in the fusiform gyrus. *Trends in Cognitive Sciences*, *7*(7), 293-299.

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: I. An account of basic findings. *Psychological Review 88*, 375.

Monzalvo, K., Fluss, J., Billard, C., Dehaene, S., & Dehaene-Lambertz, G. (2012). Cortical networks for vision and language in dyslexic and normal children of variable socio-economic status. *NeuroImage*, *61*, 258-274.

Nazir, T. A., & Huckauf, A. (2007). The visual skill “reading”. In E. L. Grigorenko & A. J. Naples (Eds.), *Single-word reading: Biological and behavioral perspectives*. Mahwah, NJ: Lawrence Erlbaum Associates.

Nobre, A., Allison, T., & McCarthy, G. (1994). Word recognition in the human inferior temporal lobe. *Nature*, *372*, 260-263.

Parviainen, T., Helenius, P., Poskiparta, E., Niemi, P., & Salmelin, R. (2006). Cortical sequence of word perception in beginning readers. *Journal of Neuroscience*, *26*(22), 6052-6061.

Price, C. J. (2012). A review and synthesis of the first 20 years of PET and fMRI studies of heard speech, spoken language and reading. *NeuroImage*, *62*(2), 816-847.

Price, C. J. (2013). Current themes in neuroimaging studies of reading. *Brain & Language*, *125*, 131-133.

Price, C. J., & Mechelli, A. (2005). Reading and reading disturbance. *Current Opinion in Neurobiology*, *15*, 231-238.

Reicher, G. M. (1969). Perceptual recognition as a function of meaningfulness of stimulus material. *Journal of Experimental Psychology*, *81*, 275-280.

Richlan, F., Kronbichler, M., & Wimmer, H. (2011). Meta-analyzing brain dysfunctions in dyslexic children and adults. *NeuroImage*, *56*(3), 1735-1742.

Rossion, B., Joyce, C. J., Cottrell, G. W., & Tarr, M. J. (2003). Early lateralization and orientation tuning for face, word and object processing in the visual cortex. *NeuroImage*, *20*, 1609-1624.

Schlaggar, B. L., & McCandliss, B. D. (2007). Development of neural systems for reading. *Annu. Rev. Neurosci.*, *30*, 475-503.

Sereno, S. C., Brewer, C. C., & O'Donnell, P. J. (2003). Context effects in word recognition: Evidence for early interactive processing. *Psychological Science*, *14*, 328-333.

Sereno, S. C., Rayner, K., & Posner, M. I. (1998). Establishing a timeline of word recognition: Evidence from eye movements and event-related potentials. *NeuroReport*, *9*, 2195-22200.

Shaywitz, S. E., & Shaywitz, B. A. (2008). Paying attention to reading: The neurobiology of reading and dyslexia. *Development and Psychopathology*, *20*, 1329-1349.

Spironelli, C., & Angrilli, A. (2009). Developmental aspects of automatic word processing: Language lateralization of early ERP components in children, young adults and middle-aged subjects. *Biological Psychology*, *80*(1), 35-45.

Sprenger-Charolles, L., Siegel, L. S., Béchennec, D., & Serniclaes, W. (2003). Development of phonological and orthographic processing in reading aloud, in silent reading, and in spelling: A four-year longitudinal study. *Journal of Experimental Child Psychology, 84*, 194-217.

Szwed, M., Dehaene, S., Kleinschmidt, A., Eger, E., Valabrègue, R., Amadon, A., et al. (2011). Specialization for written words over objects in the visual cortex. *NeuroImage, 56*(1), 330-344.

Tanaka, J. W., & Curran, T. (2001). A neural basis for expert object recognition. *Psychological Science, 12*, 43-47.

Tarkiainen, A., Cornelissen, P. L., & Salmelin, R. (2002). Dynamics of visual feature analysis and object-level processing in face versus letter-string perception. *Brain, 125*, 1125-1136.

Tarkiainen, A., Helenius, P., Hansan, P. C., Cornelissen, P. L., & Salmelin, R. (1999). Dynamics of letter string perception in the human occipitotemporal cortex. *Brain, 122*, 2119-2131.

van der Mark, S., Bucher, K., Maurer, U., Schulz, E., Brem, S., Buckelmüller, J., et al. (2009). Children with dyslexia lack multiple specializations along the visual word-form (VWF) system. *NeuroImage, 47*, 1940-1949.

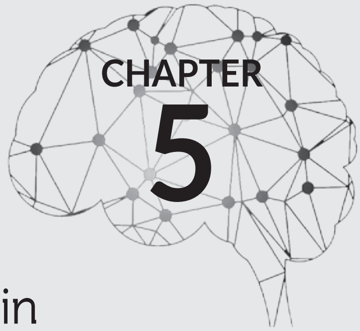
Wimmer, H., Schurz, M., Sturm, D., Richlan, F., Klack, J., Kronbichler, M., et al. (2010). A dual-route perspective on poor reading in a regular orthography: An fMRI study. *Cortex, 46*, 1284-1298.

Wong, A. C. N., Gauthier, I., Woroch, B., DeBuse, C., & Curran, T. (2005). An early electrophysiological response associated with expertise in letter perception. *Cognitive Affective & Behavioral Neuroscience, 5*(3), 306-318.

Yamada, Y., Stevens, C., Dow, M., Harn, B., Chard, D. J., & Neville, H. J. (2011). Emergence of the neural network for reading in five-year-old beginning readers of different levels of pre-literacy abilities: An fMRI study. *NeuroImage, 57*, 704-713.

Yoncheva, Y. N., Blau, V. C., Maurer, U., & McCandliss, B. D. (2010). Attentional focus during learning impacts N170 ERP responses to an artificial script. *Developmental Neuropsychology, 35*(4), 423-445.

Ziegler, J. C., & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin*, *131*(1), 3-29.



CHAPTER
5

Aging of memory and brain functions – Usual and successful

Sara Pudas

Introduction

The study of age-related cognitive decline has a long tradition, and is today as topical as ever. Due to increased life-expectancy in many countries around the world, it is becoming increasingly important to find ways to preserve cognitive abilities into older age so that as many individuals as possible are able to maintain independence and lead meaningful and productive lives into older age. One important piece to this puzzle is understanding how age-related changes in brain structure and function relate to decline in cognitive abilities, and conversely, identifying brain characteristics that underlie successful cognitive aging. Doing this may enable earlier detection of individuals at risk of cognitive decline and dementia, and a better understanding of target brain structures for intervention studies aimed at promoting successful aging.

This chapter will first provide a selective review of typical age-related changes in neurocognitive function, before moving on to describe findings pertaining specifically to successful cognitive aging. The final section will discuss lifestyle factors related to the preservation of brain and cognition in aging.

Both brain and memory functions have been shown to vary substantially across older individuals, even in the absence of pathological conditions such as Alzheimer's disease (Habib, Nyberg, & Nilsson, 2007; Raz et al., 2005; Wilson et al., 2002). Memory is one of many interrelated cognitive abilities that decline with age. There is evidence that a relatively large portion (up to two thirds) of age-related cognitive decline shares a common factor, i.e. that different cognitive abilities tend to decline together (Ghisletta, Rabbitt, Lunn, & Lindenberger, 2012), but there is also apparent dimensionality, even within the memory domain. Working memory and episodic long-term memory abilities decline clearly with age (Hultsch, Hertzog, Small, McDonald-Miszczak, & Dixon, 1992; Nyberg et al., 2014; Park et al., 2002; Rönnlund, Nyberg, Bäckman, & Nilsson, 2005), whereas for instance priming and semantic long-term memory have been shown to be relatively more spared by the effects of age in some studies (Fleischman, Wilson, Gabrieli, Bienias, & Bennett, 2004; Rönnlund et al., 2005; Schaie, 1994).

Within the declarative memory system, there is a distinction between episodic and semantic memory. Semantic memory, which has to do with general world knowledge such as the meanings or words, shows relatively modest decrements up until the 7th decade of life (Rönnlund et al., 2005), when assessed in longitudinal studies, i.e., studies that follow the same individuals over time. On the other hand, average episodic memory decline begins around the age of 60-65, making it more difficult to remember people, places and events that one encounters (Rönnlund et al., 2005). Episodic memory is generally held to be the memory system with most consistent decline in normal aging (Nilsson, 2003), , and deficits in this system have also been shown to be one of the earliest signs of Alzheimer’s disease (Bäckman, Small, & Fratiglioni, 2001). Therefore, the following paragraphs will mainly consider how brain functions underlie episodic memory decline, and maintenance, in older age.

How do Brain Changes in Aging Relate to Memory Function?

The aging brain undergoes many changes to its structure and function, observable on micro- and macroscopic levels. For instance, there is a general volume loss, enlargement of the ventricles, deterioration of white matter integrity, reduction of function in certain neurotransmitter systems, and alterations of brain function observable with functional neuroimaging methods (for a review, see Dennis & Cabeza, 2008). Many studies show clear evidence of individual differences in the amount of such age-related brain changes (e.g. Persson et al., 2012; Raz et al., 2005; Resnick, Pham, Kraut, Zonderman, & Davatzikos, 2003).

Two brain regions that have received the most interest when it comes to age-related episodic memory changes are the hippocampal formation and the prefrontal cortex (PFC). They are by no means the only regions involved, but are prominent in aging research due to a combination of their well-documented involvement in memory functions from studies of brain-injured patients (Scoville & Milner, 1957; Wheeler, Stuss, & Tulving, 1995) and neuroimaging studies of memory in healthy young participants (Buckner, Kelley, & Petersen, 1999; Cabeza & Nyberg, 2000; Fernández et al., 1998; Nyberg, McIntosh, Houle, Nilsson, & Tulving, 1996), as well as their known sensitivity to age-related changes, as will be reviewed in the next paragraph. These two structures play different roles in the formation and retrieval of episodic memories. The hippocampus, together with related structures in the medial temporal lobe, is believed bind together different features of our experiences (Eichenbaum, 2004), which themselves are processed in other parts of the cortex. The

PFC on the other hand seems to be responsible for more strategic aspects of memory processing, such as organization and manipulation of to-be-remembered information during encoding (Blumenfeld & Ranganath, 2007), and search, verification and monitoring of stored information during memory retrieval (Fletcher & Henson, 2001).

Prefrontal Cortex Function in Aging

When it comes to aging, the PFC quite consistently shows the one of the steepest rates of age-related decline in gray- and white matter volume across the cortex, (Raz et al., 2005; Resnick et al., 2003; Salat, Kaye, & Janowsky, 1999). In functional neuroimaging studies of memory, a common observation is that older individuals have reduced brain activity in the left PFC during memory encoding (Dennis & Cabeza, 2008; Rajah & D'Esposito, 2005), a brain region that is particularly important for successful encoding into long-term memory (Habib, Nyberg, & Tulving, 2003; Kim, 2011). When such reductions are observed they are usually interpreted as a functional impairment, causing performance decrements. However, in several studies increased, or additional, PFC activation has been observed in older adults when compared to young individuals (Cabeza, Anderson, Locantore, & Mcintosh, 2002; Grady et al., 1995; Logan, Sanders, Snyder, Morris, & Buckner, 2002). This is commonly seen in high-performing older individuals (Cabeza et al., 2002), and such findings have received much attention since they raise the possibility that older adults may somehow be able to "compensate" for age-related deficits elsewhere in the brain by increasing frontal recruitment (Cabeza et al., 2002; Reuter-Lorenz & Cappell, 2008). However, since increased or additional frontal activation has sometimes been observed in low-performing elderly (Duverne, Motamedinia, & Rugg, 2009; Miller et al., 2008), and individuals with prior cognitive decline (Persson et al., 2006) the compensation account does not capture all instances of age-related PFC activation increases. Although explanations such as partial or unsuccessful compensations have been raised in such instances, others have claimed that increased activation reflects a dysfunction manifested as less selectivity in the neural response

(Logan, Sanders, Snyder, Morris, & Buckner, 2002) or a breakdown of functional specialization (Li, Lindenberger, & Frensch, 2000).

Another explanation for some instances of apparent age-related increases in frontal activation is that they may be driven by high-performing individuals in cross-sectional studies. That is, studies comparing individuals at one point in time, such as old vs. young, or high- vs. low-performing. This notion was supported by a study in which both cross-sectional and longitudinal analyses were made on the same sample (Nyberg et al., 2010). The cross-sectional analyses indicated increased frontal activation with age, whereas longitudinal analyses, investigating actual within-group changes across six years, showed declining right frontal activation over the six year period, for the same sample. Hence, the apparent frontal increases were an artifact of the cross-sectional design, rather than a true increase over time. More recently, it has been demonstrated that age-related increases in PFC activity can in fact be found longitudinally (Goh, Beason-Held, An, Kraut, & Resnick, 2013). In this instance they were associated with declining executive functions over time. Participants who reduced their activation levels over time had stable or even improving cognition, indicating that in this case, the reduced activation levels might reflect learning, i.e. less effort being expended to be able to perform the task. The authors conclude that age-related changes in PFC function likely are both region and process-specific. This assertion is likely accurate, since the frontal cortex is a large heterogeneous structure, with many different cognitive functions ascribed to it (Cabeza & Nyberg, 2000; Fletcher & Henson, 2001). This leaves open the possibility that both increased and decreased activation can co-occur. Support for this notion was found in a cross-sectional study demonstrating increased activation levels with increasing age in a task-general brain network, thought to reflect cognitive control processes, which encompassed regions in the bilateral PFC (Salami, Eriksson, & Nyberg, 2012). This was coupled with decreased activation in a memory-specific network, including the hippocampus, and different PFC regions. The findings were interpreted as increased reliance on the general cognitive control network, as the structure and function of the memory-specific network suffered age-related losses.

To summarize, frontal cortex function clearly changes with age, but the relative increases or decreases in activation measured in neuroimaging studies should be interpreted with caution, and critical factors such as study design, task difficulty and the performance level of the participants need to be taken into account. Although various explanations have been put forth, as of yet there is no consensus regarding frontal cortex changes in aging, partially due to the heterogeneity of the structure itself.

Hippocampal Function in Aging

When it comes to the hippocampus, which is perhaps the most episodic memory-relevant brain structure (Eichenbaum, 2004), clear age-related volume losses have been demonstrated in longitudinal studies, albeit not as pronounced as those in the PFC (Fjell et al., 2009; Raz et al., 2005). However, functional neuroimaging studies, which have been predominantly cross-sectional in nature, have provided mixed findings regarding hippocampal function in aging. There are studies reporting that older individuals fail to activate the hippocampus during memory processing (e.g. Grady et al., 1995), whereas others have found significantly reduced activation levels in older compared to younger individuals during both memory encoding and retrieval (Daselaar, Veltman, Rombouts, Raaijmakers, & Jonker, 2003a, 2003b; Dennis, Daselaar, & Cabeza, 2007; Grady, McIntosh, & Craik, 2005; Gutchess et al., 2005). However, several reports have also demonstrated that older individuals can have equivalent levels of hippocampal activation compared to young (Düzel, Schütze, Yonelinas, & Heinze, 2011; Miller et al., 2008; Persson, Kalpouzos, Nilsson, Ryberg, & Nyberg, 2011). There could be several reasons for the discrepancy between studies, including the nature and difficulty of the task. It could also be that the samples in the studies finding no differences in activation were younger, healthier and more high-performing than average, due to biased sampling. However, it has also been argued that normal aging may not affect hippocampal function, but rather that memory impairments in aging are caused by failures of cortical processing (Rand-Giovannetti et al., 2006). Relatedly, it has been suggested that unintentional inclusion of individuals in early, undiagnosed stages of Alzheimer's disease could be responsible for the hippocampal impairments observed in some aging studies (Buckner, 2004), since Alzheimer's disease causes more pronounced damage to brain structures responsible for memory processing. While all of the above mentioned factors could account for the diversity of findings, the interpretation of the findings in the literature is also complicated by the scarcity of studies with repeated measurements of brain function. Since it has previously been demonstrated that longitudinal data may have increased sensitivity compared to cross-sectional measures, when detecting age-related changes in brain structure (Raz et al., 2005), it remains possible that some cross-sectional studies fail to detect true age-related changes that are in fact present.

One longitudinal study demonstrated that hippocampal activation during an associative memory task reliably declined over a two-year period in a group 30 older adults with signs of very mild cognitive impairments at baseline, of which 18 went on to experience further cognitive decline during the follow-up period (O'Brien et al., 2010). No signs of hippocampal decline were detected in individuals free from cognitive impairment at baseline, and who maintained stable cognition up until the follow-up session. However, in this study, cognition was assessed with a clinical dementia rating test, on which declining scores could indicate progression to actual dementia or mild cognitive impairment. In fact, nine of the decliners in the study met diagnostic criteria for mild cognitive impairment at follow-up, and five had progressed to probable dementia. It is also of interest whether functional decline in the hippocampus is present in healthy elderly with more subtle memory decline. This was investigated in a longitudinal fMRI-study in which the participants had partaken in regular memory assessments during 20 years, as well as two fMRI-sessions, separated by six years (Persson et al., 2012). It was found that change in memory performance correlated with change in left hippocampal activation across the six-year period, so that individuals experiencing more memory decline also reduced their activation more across the follow-up interval (see Figure 5.1). Importantly, the study sample had been cognitively stable up until the first fMRI-assessment, and performed in the normal range on a dementia screening test at follow-up. This study hence provides complementary evidence that functional decline in the hippocampus can underlie age-related memory decline, even in the range of healthy aging. Furthermore, it can be noted that Persson et al. observed a correlation between volume reduction in the right hippocampus and memory decline, which, however, appeared independent of the functional decline. Functional and structural brain decline may therefore have somewhat independent contributions to age-related memory decline.

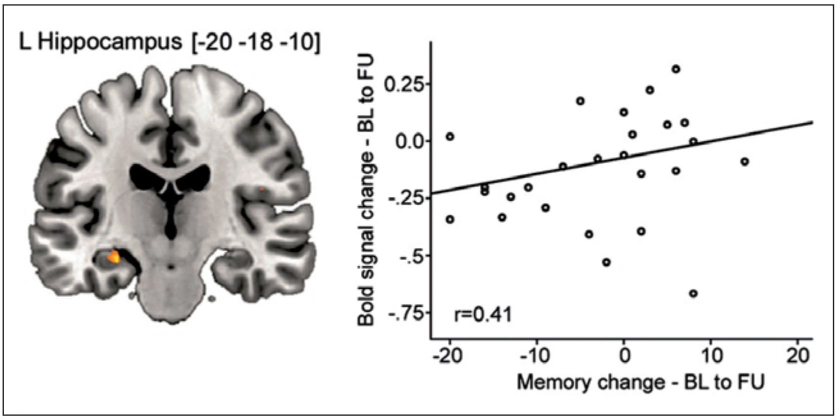


Figure 5.1 The relationship between BOLD signal change in the left hippocampus and change in episodic memory performance, from baseline (BL) assessment to follow-up (FU) approximately six years later. The BOLD signal estimates reflect incidental episodic memory encoding, contrasted with a fixation baseline.

Source: Adapted with permission, from Persson et al., (2012). Longitudinal structure-function correlates in elderly reveal MTL dysfunction with cognitive decline. Cerebral Cortex, 22 (10), 2297–2304.

In summary, functional deficits in the hippocampus are not always observed in aging, but longitudinal imaging studies have demonstrated functional decline, specifically associated with decline in memory function. It remains to be fully elucidated under which conditions, and in which older individuals, spared hippocampal function can be expected.

Defining and Characterizing Successful Neurocognitive Aging

In scientific terms, the definition of successful cognitive aging might not be as straightforward as it seems at first glance. Two common definitions are to consider an older adult successfully aged if he or she performs either above the mean performance level of young adults, or above the mean of his or her age-group. Both these definitions are based on cross-sectional comparisons (i.e. only observing individuals at one time point) and therefore problematic. Comparisons against young individuals may be biased by so-called cohort-effects (Schaie & Labouvie-Vief, 1974), i.e. that older and younger generations differ with respect to other factors than age, that might influence cognitive ability. One important factor is educational level (Rönnlund et al., 2005), which tends to be higher in younger individuals, and also associated with better episodic memory performance. An older individual might thus perform worse than young individuals partially due to lower educational level, although he or she has not suffered age-related cognitive decline and could in fact be considered successfully aged. On the other hand, within-group comparisons restricted to the older age-span might be confounded by performance differences that were present already in youth. Individual differences in cognitive ability levels are in fact quite stable across the human life-span (Deary, Whalley, Lemmon, Crawford, & Starr, 2000), with correlations in the magnitude of 0.6-0.7 between cognitive ability in childhood and old age (Gow et al., 2011). In other words, an individual's performance tends to rank similarly compared to that of his or her peers in both youth and older age. Therefore cognitive decline cannot be assumed in an older adult performing below the mean of his or her peers at one measurement occasion, since there is a chance that he/she has been low-performing since youth. Also, when defining successful aging on a cross-sectional basis there is a risk of misclassifying individuals who have declined from very high levels of cognitive performance in youth, but still perform above average.

The gist of the preceding discussion is that longitudinal data is important for the study of individual differences in aging, including successful aging. The importance of this has been underscored by two neuroimaging studies indicating that individual differences established in youth may confound results in aging studies. First, Karama and collegues (2014) observed that while cognitive ability was associated with cortical thickness in older age, more than two-thirds of this association was accounted for by differences in cognitive ability that were present already in childhood. When childhood ability was statistically controlled for, no association remained between brain and cognitive measures in older age. The authors interpreted these results to reflect that the association between cognitive ability and cortical thickness is a life-long trait, rather than one emerging in older adulthood, but also acknowledged that other explanations are possible, such as better maintenance of cognitive ability and brain structure in individuals with high childhood ability levels. The type of findings observed by Karama et al., do not only apply to cortical thickness. It has also been demonstrated that midlife memory ability could reliably predict memory-related brain activity in the hippocampus and PFC 15-20 years later, independently of differences in gray matter density (Pudas, Persson, Nilsson, & Nyberg, 2014). In fact, in some brain regions, more of the activity-differences between individuals were explained by differences in their midlife memory ability levels, rather than differences in their cognitive change over the preceding decade. These types of results show that differences in cognitive ability and brain status among older individuals may be remnants from younger years, which is why definitions of successful aging should include measures of cognitive change over time.

When it comes to neuroimaging studies specifically studying successful aging, there are relatively few longitudinal studies to date. However, one cross-sectional imaging study (Pudas et al., 2013), defined successful aging relative to the average memory change over 15-20 years in a large population-based sample of 1521 older individuals. This study showed that successfully aged individuals had higher encoding-related brain activation in the frontal cortex and the hippocampus than age-matched individuals with average memory change. Importantly, these differences remained when individual differences in midlife memory were equated. In the left hippocampus, the activation of the successfully aged older adults was equivalent to that of young individuals in their thirties, whereas the average older adults had significantly reduced activation levels (Figure 5.2). Similar patterns were observed across clusters in the PFC (Figure 5.2), although the reduced activation of the average older individuals compared to young was not statistically significant. Further, in one cluster in the left inferior PFC (cluster a, Figure 5.2), the successfully aged individuals actually had higher activation levels than the young individuals. Since longitudinal imaging data was not available in this study, it cannot be concluded that these individuals had increased their activation levels over time in a compensatory manner. Lack of correlations between frontal activation and task performance also discouraged a compensatory interpretation. The frontal activation differences may equally well have reflected differences that were present already in youth, which, however, in turn could have contributed to the preservation of cognitive function in aging. In either case, the results demonstrate that longitudinally-defined successful cognitive aging is characterized by high levels of task-related activation in the hippocampus and PFC.

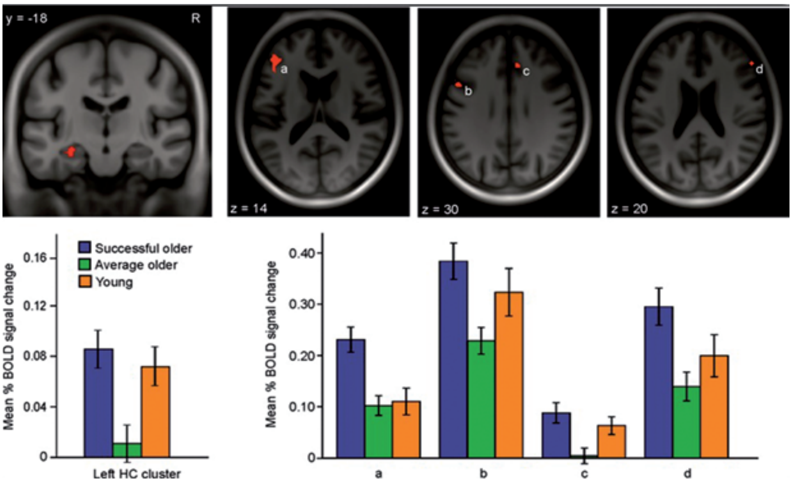


Figure 5.2 Hippocampal and frontal BOLD signal differences between young individuals, and successful and average older adults. BOLD signal estimates reflect epissodic memory encoding of face-name associations, contrasted with an active baseline task.

Source: Adapted, with permission, from: Pudas et al., (2013). Brain characteristics of individuals resisting age-related cognitive decline over two decades. *Journal of Neuroscience, 33*(20), 8668–8677.

In the study by Pudas et al., (2013) the functional differences between successful and average older participants were not driven by differences in gray matter volume, which sometimes may propagate to a lower BOLD-signal (Kalpouzos, Persson, & Nyberg, 2012). Thus, it was likely not structural atrophy that caused the reduced activation levels of the average older individuals. This observation also suggests that successful aging might be more determined by functional, rather than structural brain characteristics. Previous cross-sectional studies have made similar observations. For instance, Walhovd et al., (2010) showed that hippocampal metabolism, as measured with PET, explained individual differences in memory ability among healthy elderly without cognitive impairments, whereas volume and cortical thickness of medial temporal lobe structures did not. The structural characteristics did, however, explain memory differences within a sample classified as having mild cognitive impairment. This could indicate that it is only when neurocognitive losses have reached a more progressed state that they are observable for structural neuroimaging, whereas the distinction between successful aging and more subtle age-related cognitive decline is better accounted for by functional brain properties. Still, it should be noted that successful cognitive aging has also been linked to preserved brain structure.

In a large-scale longitudinal study, Rosano et al., (2012) found older that individuals who had maintained cognitive performance over a decade had larger gray matter volume of the medial temporal lobe, which includes the hippocampal formation, when compared to individuals with decline. An important difference between this study, and that by Pudas et al., is that the comparison was made against individuals with decline on a global dementia screening test, hence likely also capturing individuals with a more progressed state of decline. Furthermore, the successful agers in Rosano et al.'s study were also on average 13 years older than those investigated by Pudas et al., suggesting a more pronounced role for structural atrophy in determining cognitive function in later senescence. Hence, successful aging appears to be best accounted for by functional brain properties in early senescence, and when compared to those with mild cognitive decline, but structural preservation might play a role in more progressed age. Alternatively, structural and functional brain characteristics might have somewhat independent contributions to cognition in older age.

What Determines Successful Aging?

Broadly speaking, two main routes to maintaining cognitive function throughout life have been suggested it the literature. One line of theorizing has focused on how individuals might stay high-functioning despite accumulating degenerative changes associated with aging, either through brain (Satz, 1993) or cognitive reserve (Stern, 2009). Another, more recent account argues that the main determinant of successful cognitive aging is the relative absence of age-related brain pathology in the first place, i.e. brain maintenance (Nyberg, Lövdén, Riklund, Lindenberger & Bäckman, 2012).

The two reserve concepts are somewhat overlapping, with the brain reserve account suggesting that individuals differ in certain brain characteristics that allow some individuals to withstand more detrimental brain changes than others, before a negative effect on cognitive function becomes evident. Evidence in line with this has been found in studies showing that for instance larger brain size (Perneczky et al., 2010) and/or a higher neuronal count (Katzman et al., 1988) may delay the onset of cognitive impairment in the face of a given amount of brain pathology. One conceptualization of brain reserve is the threshold theory (Satz, 1993), which suggests that brains with higher reserve can accumulate more damage before the threshold for cognitive impairment is reached, since more neural substrate is available to support function. Cognitive reserve, on the other hand, posits that there are individual differences in cognitive processes, or their neural implementation, that allow some individuals' brains to remain high-functioning despite brain pathology (Stern, 2009). The cognitive reserve account rests on evidence from both epidemiological and neuroimaging studies, showing that individuals with a high exposure to mentally stimulating activities such as education, occupational complexity and/or leisure activities can withstand more pathology before cognition begins to decline, and that their brains might process cognitive tasks in a different manner from individuals with less exposure to such experiences (Stern, 2009). Steffener and Stern (2012) review provisional evidence for two ways in which cognitive reserve may operate in the brain. One is neural compensation, i.e. recruiting additional brain networks in the face of detrimental changes to the primary task networks, in a similar manner as discussed above in connection with PFC alterations in aging. Alternatively, the resilience of individuals with high cognitive reserve could derive from a so-called neural reserve, manifested as inherently higher capacity, efficiency, and/or flexibility in their brain networks. These properties could originate both from innate factors and lifetime exposures (Barulli & Stern, 2013). It is also conceivable that cognitive reserve may operate on a more behavioral level, with high-reserve individuals selecting more efficient cognitive strategies in order to perform mental tasks (Barulli, Rakitin, Lemaire, & Stern, 2013), which may also be more robust in the face of brain pathology.

While the reserve theories attempt to account for the observed discrepancy between amount of brain pathology and degree of cognitive impairment, they appear to overlook that some individuals may remain high-performing because they avoid, or acquire less, age-related brain pathology in the first place, which is emphasized by the brain maintenance account. There is ample evidence for this idea from structural, functional and neurochemical brain investigations, as reviewed by Nyberg and colleagues (2012). This evidence comprises both cross-sectional studies in which older adults with more youth-like brain profiles perform better than their peers, or equivalently to young (e.g. Düzel et al., 2011; Nagel et al., 2009), as well as longitudinal studies showing that relative sparing of structural and functional brain properties is associated with preserved cognition (e.g. Persson et al., 2012). The brain maintenance and reserve accounts should be viewed as complementary explanations of preservation of cognitive function in aging, since it is probable that some individuals age successfully by not acquiring as much age-related pathology, while others manage to stay relatively high-functioning despite such pathology. Also, the behavioral and neural factors associated with the different accounts may interact. For instance, it is conceivable that factors such as the mentally stimulating activities that are associated with cognitive reserve can assert their influences through building brain reserve, and/or promoting brain maintenance in aging.

Whether accomplished through brain maintenance, or through some sort of reserve, research has identified a somewhat consistent set of factors associated with a reduced risk of cognitive decline in aging, or increased chances for successful cognitive aging. Firstly, genes certainly have a large influence on cognitive ability, but twin studies tend to show that they have less influence on rate of cognitive change in aging and that environmental factors influence cognition to a larger degree with increasing age (Harris & Deary, 2011; Lee, Henry, Trollor, & Sachdev, 2010). Also, relatively few specific genes have thus far been identified that can consistently be linked to individual differences in rate of cognitive decline in old age (Harris & Deary, 2011; Payton, 2009). A notable exception is the APOE-gene, which is linked to increased risk of Alzheimer's disease (Corder et al., 1993) and impaired cognition in cognitively healthy older individuals (Wisdom, Callahan, & Hawkins, 2011). The knowledge about genetic determinants of age-related cognitive decline is likely to grow substantially in the future, as much effort is being devoted to such investigations. The following paragraphs will however focus on lifestyle factors, which are potentially more amendable to intervention, although in effect difficult to disentangle fully from genetic factors, due to gene-environment and gene-lifestyle interactions.

When it comes to maintaining brain and cognitive function in old age, one rather obvious strategy is to try to stay healthy, since a number of negative health conditions including, hypertension and other cardiovascular diseases, diabetes, and obesity among others, have been linked to poorer neurocognitive outcomes in aging (Barnes et al., 2007; Raz & Rodrigue, 2006; Yaffe et al., 2009). It is unsurprising that general health and brain health go hand in hand. Therefore health-promoting factors such as a healthy diet and physical exercise are associated with less age-related cognitive decline (Plassman & Williams, 2010). Further, and as already alluded to, engaging in mentally stimulating activities such as attending higher education, holding a complex occupation, and participating in stimulating leisure activities, have repeatedly been demonstrated to be protective against age-related cognitive decline (Fratiglioni, Paillard-Borg, & Winblad, 2004; Hultsch, Hertzog, Small, & Dixon, 1999; Stern, 2009), and sometimes even been shown to lessen age-related atrophy in brain regions such as the hippocampus (Valenzuela, Sachdev, Wen, Chen, & Brodaty, 2008). Mentally stimulating activates are put forth as important for preserving cognition by both the brain maintenance and reserve accounts. One of the most commonly cited protective factors is educational attainment, but its status as a standalone buffer for cognitive decline in aging has been disputed by longitudinal studies that have found it to be more associated with level rather than change in cognition (Lövdén et al., 2004; Zahodne et al., 2011). In other words, these studies suggest that education might improve the level of cognitive performance, but not prevent age-related decline. However, it could also be that the crucial component for protection of brain tissue and cognition is the continuation of mentally stimulating activities in older age. It is possible that highly educated individuals to a larger extent tend to continue with mentally stimulating activities throughout life, which could explain the association between education and preservation of cognition found in some studies. Mentally stimulating activities have also been under investigation in several cognitive intervention studies, which provide stronger evidence for causal interpretations than observational studies, thanks to the experimental manipulations involved. While encouraging results are sometimes reported in such studies, such as spatial navigation training leading to lesser hippocampal atrophy in both older and younger participants (Lövdén et al., 2012), the general consensus in the field is the transfer effects, i.e. generalizability of the trained skill to daily activities, are rather limited (Buitenweg, Murre, & Ridderinkhof, 2012; but also see Ball, Edwards, Ross, & McGwin, 2010). Nevertheless, it could still be possible that the cognitive training protects neural tissue against age-related losses.

A special class of mentally stimulating activity is social interaction, which has also received much attention for its potential for protecting against cognitive decline and dementia. Studies have shown that individuals who have large social networks, are married or live together with someone, and/or participate in social leisure activates have an decreased risk for cognitive decline and dementia in older adulthood (Fratiglioni et al., 2004; Josefsson, de Luna, Pudas, Nilsson, & Nyberg, 2012; Lövdén, Ghisletta, & Lindenberger, 2005). It has also been observed that social participation attenuates the connection between Alzheimer-related brain pathology and cognitive function, so that the cognitive performance of individuals with large social networks is less affected by pathology than individuals with low social participation (Bennett, Schneider, Tang, Arnold, & Wilson, 2006), even after controlling for other factors such as depression, and other cognitive and physical activities. However, the mechanisms behind such observations are still unclear, and it can sometimes be difficult to firmly establish that there is a causal relationship between social participation and preservation of cognition in face of brain pathology in purely observational studies. Lövdén et al, (2005) used statistical modelling of longitudinal data to investigate whether an active lifestyle really alleviated age-related cognitive decline, or whether it in fact was the case that a high cognitive function in older age facilitated and engaged and active lifestyle. They found support for the former notion, specifically that higher social participation scores preceded and predicted less decline in perceptual speed within their sample.

Another lifestyle factor that has been shown to have positive effects on neurocognitive function in aging is physical activity, which also is a good candidate for intervention studies. Beneficial effects on cognitive performance and/or risk for dementia have been reported in many observational, as well as intervention studies (Colcombe & Kramer, 2003; Fratiglioni et al., 2004; Kramer, Erickson, & Colcombe, 2006). In a meta-analytic review of intervention studies involving physical exercise, Colcombe and Kramer (2003) observe that a combination of aerobic and strength training appears to have the most beneficial effects of cognitive function, and the cognitive domain that benefits the most is executive functions. Direct beneficial effects of physical activity have also been observed when it comes to preservation of brain tissue, or even increases in brain volume.

For instance, increases in both temporal and frontal brain volumes following a 6-month physical activity intervention were observed in a sample of 59 previously sedentary healthy older adults (Colcombe et al., 2006). These increases were only significant for those participants assigned to aerobic exercise, not in individuals participating in a stretching and toning intervention. Similarly, Erickson et al., (2011) found increases in anterior hippocampal volume over a one-year interval in a group of 60 older adults who took part of an aerobic exercise intervention, and in this study the volumetric increased also correlated with increases in spatial memory performance over the same time. In contrast, a control group receiving a stretching intervention during the same time experienced significant decrease in volume, which however was partially attenuated by higher levels of physical fitness at baseline. Protective effects of self-reported physical activity on hippocampal atrophy have also been observed in older individuals with an elevated risk for Alzheimer's disease (Smith et al., 2014). Although animal studies suggest that physical activity can increase neurogenesis (i.e. birth of new neurons in the brain) even in aged individuals (van Praag, Shubert, Zhao, & Gage, 2005), such conclusion cannot be drawn in human studies using volumetric measures derived from neuroimaging. In these studies increases in volume may be driven by factors such as increased vascularization, dendritic branching, axonal integrity or increase in number of glial (supportive) cells, or other factors. Nevertheless, if reliable beneficial effects are seen on cognitive function, such as in the study by Erickson and colleagues (2011), the exact mechanisms might be of less practical concern.

In summary, several lifestyle factors appear contribute positively to maintenance of cognitive functions in aging. Broadly these include maintenance of physical health, as well as having a mentally, physically and socially engaged lifestyle. And although the exact neurophysiological mechanisms behind these positive effects remain to be fully elucidated, and more long-term studies are needed, the results hold promise for better prevention of age-related neurocognitive losses in the future.

Summary

Memory abilities, and brain structure and function are all negatively affected by advancing age, but some individuals appear more spared from these changes than others. Successful cognitive aging could reflect higher cognitive or brain reserve, and/or maintenance of youthful brain structure and function to older age. Findings reviewed in this chapter indicate that plausible mechanisms behind successful aging include structural preservation of the hippocampus and frontal cortex, in combination with a high degree of task-related activation in these areas. On a more practical level, having a mentally, physically, and socially engaged lifestyle appears to promote successful cognitive aging, although genetic factors are certainly also important. Future advances in the field will likely come from upcoming large-scale longitudinal imaging studies to further consolidate and explicate the neural mechanisms behind both typical and successful aging. To fully capture the multidimensional nature of age-related brain changes, useful information will certainly be learned from studies combining different imaging techniques, such as fMRI, positron emission tomography, and diffusion tensor imaging. Informed by such efforts, intervention studies will continue to elucidate ways to preserve and enhance neurocognitive function in aging.

References

Ball, K., Edwards, J. D., Ross, L. A. & McGwin, G. (2010). Cognitive training decreases motor vehicle collision involvement of older drivers. *Journal of the American Geriatrics Society*, *58* (11), 2107–2113. doi:10.1111/j.1532-5415.2010.03138.x

Barnes, D. E., Cauley, J. A., Lui, L.-Y., Fink, H. A., McCulloch, C., Stone, K. L., & Yaffe, K. (2007). Women who maintain optimal cognitive function into old age. *Journal of the American Geriatrics Society*, *55*(2), 259–264. doi:10.1111/j.1532-5415.2007.01040.x

Barulli, D., Rakitin, B.C., Lemaire, P. & Stern, Y. (2013). The influence of cognitive reserve on strategy selection in normal aging.

Journal of the International Neuropsychological Society, 19(7), 841-844. doi: 10.1017/S1355617713000593

Barulli, D., & Stern, Y. (2013). Efficiency, capacity, compensation, maintenance, plasticity: emerging concepts in cognitive reserve. Trends in Cognitive Sciences, 17(10), 502-509. doi: 10.1016/j.tics.2013.08.012

Bennett, D. A., Schneider, J. A., Tang, Y., Arnold, S. E., & Wilson, R. S. (2006). The effect of social networks on the relation between Alzheimer's disease pathology and level of cognitive function in old people: a longitudinal cohort study. *Lancet Neurology*, *5*(5), 406–412. doi:10.1016/S1474-4422(06)70417-3

Blumenfeld, R. S., & Ranganath, C. (2007). Prefrontal cortex and long-term memory encoding: An integrative review of findings from neuropsychology and neuroimaging. *The Neuroscientist*, *13*(3), 280–291. doi:10.1177/1073858407299290

Buckner, R. L. (2004). Memory and executive function in aging and AD: Multiple factors that cause decline and reserve factors that compensate. *Neuron*, *44*(1), 195–208. doi:10.1016/j.neuron.2004.09.006

Buckner, R. L., Kelley, W. M., & Petersen, S. E. (1999). Frontal cortex contributes to human memory formation. *Nature Neuroscience*, *2*(4), 311–314. doi:10.1038/7221

Buitenweg, J. I. V., Murre, J. M. J., & Ridderinkhof, K. R. (2012). Brain training in progress: a review of trainability in healthy seniors. *Frontiers in Human Neuroscience*, *6*, 183. doi:10.3389/fnhum.2012.00183

Bäckman, L., Small, B. J., & Fratiglioni, L. (2001). Stability of the preclinical episodic memory deficit in Alzheimer's disease. *Brain*, *124*(1), 96–102. doi:10.1093/brain/124.1.96

Cabeza, R., Anderson, N. D., Locantore, J. K., & Mcintosh, A. R. (2002). Aging gracefully: Compensatory brain activity in high-performing older adults. *NeuroImage*, *17*, 1394–1402. doi:10.1006/nimg.2002.1280

Cabeza, R., & Nyberg, L. (2000). Imaging cognition II: An empirical review of 275 PET and fMRI studies. *Journal of Cognitive Neuroscience*, *12*(1), 1–47. doi:10.1162/08989290051137585

Colcombe, S. J., Erickson, K. I., Scalf, P. E., Kim, J. S., Prakash, R., McAuley, E., … Kramer, A. F. (2006). Aerobic Exercise Training Increases Brain Volume in Aging Humans. *The Journal of Gerontology*, *61*(11), 1166–1170. doi:10.1093/gerona/61.11.1166

Colcombe, S. J., & Kramer, A. F. (2003). Fitness effects on the cognitive function of older adults: A Meta-Analytic study. *Psychological Science*, *14*(2), 125–130. doi:10.1111/1467-9280.t01-1-01430

Corder, E. H., Saunders, A. M., Strittmatter, W. J., Schmechel, D. E., Gaskell, P. C., Small, G. W., … Pericak-Vance, M. (1993). Gene dose of Apolipoprotein E type 4 allele and the risk of Alzheimer' s disease in late onset families. *Science*, *261*(5123), 921–923. doi:10.1126/science.8346443

Daselaar, S. M., Veltman, D. J., Rombouts, A. R. B., Raaijmakers, J. G. W., & Jonker, C. (2003a). Neuroanatomical correlates of episodic encoding and retrieval in young and elderly subjects. *Brain*, *126*, 43–56. doi:10.1093/brain/awg005

Daselaar, S. M., Veltman, D. J., Rombouts, S. A. R. B., Raaijmakers, J. G. W., & Jonker, C. (2003b). Deep processing activates the medial temporal lobe in young but not in old adults. *Neurobiology of Aging*, *24*(7), 1005–1011. doi:10.1016/S0197-4580(03)00032-0

Deary, I. J., Whalley, L. J., Lemmon, H., Crawford, J. R., & Starr, J. M. (2000). The stability of individual differences in mental ability from childhood to old age: Follow-up of the 1932 Scottish mental survey. *Intelligence*, *28*(1), 49–55. doi:10.1016/S0160-2896(99)00031-8

Dennis, N. A., & Cabeza, R. (2008). Neuroimaging of healthy cognitive aging. In F. I. M. Craik & T. A. Salthouse (Eds.), *The Handbook of Aging and Cognition* (3rd ed., pp. 1–54). New York: Psychology Press.

Dennis, N. A., Daselaar, S., & Cabeza, R. (2007). Effects of aging on transient and sustained successful memory encoding activity.

Neurobiology of Aging, *28*(11), 1749–1758. doi:10.1016/j.neurobiolaging.2006.07.006

Duverne, S., Motamedinia, S., & Rugg, M. D. (2009). The relationship between aging, performance, and the neural correlates of successful memory encoding. *Cerebral Cortex*, *19*(3), 733–744. doi:10.1093/cercor/bhn122

Düzel, E., Schütze, H., Yonelinas, A. P., & Heinze, H.-J. (2011). Functional phenotyping of successful aging in long-term memory: Preserved performance in the absence of neural compensation. *Hippocampus*, *21*(8), 803–814. doi:10.1002/hipo.20834

Eichenbaum, H. (2004). Hippocampus: Cognitive processes and neural representations that underlie declarative memory. *Neuron*, *44*, 109–120. doi:10.1016/j.neuron.2004.08.028

Erickson, K. I., Voss, M. W., Prakash, R. S., Basak, C., Szabo, A., Chaddock, L., ... Kramer, A. F. (2011). Exercise training increases size of hippocampus and improves memory. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(7), 3017–3022. doi:10.1073/pnas.1015950108

Fernández, G., Weyerts, H., Schrader-Bölsche, M., Tendolkar, I., Smid, H., Tempelmann, C., ... Heinze, H.-J. (1998). Successful verbal encoding into episodic memory engages the posterior hippocampus: A parametrically analyzed functional magnetic resonance imaging study. *The Journal of Neuroscience*, *18*(5), 1841–1847.

Fjell, A. M., Walhovd, K. B., Fennema-Notestine, C., McEvoy, L. K., Hagler, D. J., Holland, D., ... Dale, A. M. (2009). One-year brain atrophy evident in healthy aging. *The Journal of Neuroscience*, *29*(48), 15223–15231. doi:10.1523/JNEUROSCI.3252-09.2009

Fleischman, D. a, Wilson, R. S., Gabrieli, J. D. E., Bienias, J. L., & Bennett, D. a. (2004). A longitudinal study of implicit and explicit memory in old persons. *Psychology and Aging*, *19*(4), 617–625. doi:10.1037/0882-7974.19.4.617

Fletcher, P. C., & Henson, R. (2001). Frontal lobes and human memory: Insights from functional neuroimaging. *Brain*, *124*(5), 849–881. doi:10.1093/brain/124.5.849

Fratiglioni, L., Paillard-Borg, S., & Winblad, B. (2004). An active and socially integrated lifestyle in late life might protect against dementia. *Lancet Neurology*, *3*(6), 343–353. doi:10.1016/S1474-4422(04)00767-7

Ghisletta, P., Rabbitt, P., Lunn, M., & Lindenberger, U. (2012). Two thirds of the age-based changes in fluid and crystallized intelligence, perceptual speed, and memory in adulthood are shared. *Intelligence*, *40*(3), 260–268. doi:10.1016/j.intell.2012.02.008

Goh, J. O., Beason-Held, L. L., An, Y., Kraut, M. A., & Resnick, S. M. (2013). Frontal function and executive processing in older adults: Process and region specific age-related longitudinal functional changes. *NeuroImage*, *69*, 43–50. doi:10.1016/j.neuroimage.2012.12.026

Gow, A. J., Johnson, W., Pattie, A., Brett, C. E., Roberts, B., Starr, J. M., & Deary, I. J. (2011). Stability and change in intelligence from age 11 to ages 70, 79, and 87: The Lothian Birth Cohorts of 1921 and 1936. *Psychology and Aging*, *26*(1), 232–240. doi:10.1037/a0021072

Grady, C. L., McIntosh, A. R., & Craik, F. I. M. (2005). Task-related activity in prefrontal cortex and its relation to recognition memory performance in young and old adults. *Neuropsychologia*, *43*(10), 1466–1481. doi:10.1016/j.neuropsychologia.2004.12.016

Grady, C. L., McIntosh, A. R., Horwitz, B., Maisog, J. M., Ungerleider, L. G., Mentis, M. J., … Haxby, J. V. (1995). Age-related reductions in human recognition memory due to impaired encoding. *Science*, *269*(5221), 218–221. doi:10.1126/science.7618082

Gutchess, A. H., Welsh, R. C., Hedden, T., Bangert, A., Minear, M., Liu, L. L., & Park, D. C. (2005). Aging and the neural correlates of successful picture encoding: Frontal activations compensate for decreased medial-temporal activity. *Journal of Cognitive Neuroscience*, *17*(1), 84–96. doi:10.1162/0898929052880048

Habib, R., Nyberg, L., & Nilsson, L.-G. (2007). Cognitive and non-cognitive factors contributing to the longitudinal identification of successful older adults in the Betula study. *Aging, Neuropsychology, and Cognition*, *14*(3), 257–273. doi:10.1080/13825580600582412

Habib, R., Nyberg, L., & Tulving, E. (2003). Hemispheric asymmetries of memory: The HERA model revisited. *Trends in Cognitive Sciences*, *7*(6), 241–245. doi:10.1016/S1364-6613(03)00110-4

Harris, S. E., & Deary, I. J. (2011). The genetics of cognitive ability and cognitive ageing in healthy older people. *Trends in Cognitive Sciences*, *15*(9), 388–394. doi:10.1016/j.tics.2011.07.004

Hultsch, D. F., Hertzog, C., Small, B. J., & Dixon, R. a. (1999). Use it or lose it: engaged lifestyle as a buffer of cognitive decline in aging? *Psychology and Aging*, *14*(2), 245–263. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10403712

Hultsch, D. F., Hertzog, C., Small, B. J., McDonald-Miszczak, L., & Dixon, R. a. (1992). Short-term longitudinal change in cognitive performance in later life. *Psychology and Aging*, *7*(4), 571–584. doi:10.1037/0882-7974.7.4.571

Josefsson, M., de Luna, X., Pudas, S., Nilsson, L.-G., & Nyberg, L. (2012). Genetic and lifestyle predictors of 15-year longitudinal change in episodic memory. *Journal of the American Geriatrics Society*, *60*(12), 2308–2312. doi:10.1111/jgs.12000

Kalpouzos, G., Persson, J., & Nyberg, L. (2012). Local brain atrophy accounts for functional activity differences in normal aging. *Neurobiology of Aging*, *33*(3), 623.e1–623.e13. doi:10.1016/j.neurobiolaging.2011.02.021

Karama, S., Bastin, M. E., Murray, C., Royle, N. A., Penke, L., Muñoz Maniega, S., ... Deary, I. J. (2014). Childhood cognitive ability accounts for associations between cognitive ability and brain cortical thickness in old age. *Molecular Psychiatry*, *19*, 555–559. doi:10.1038/mp.2013.64

Katzman, R., Terry, R., DeTeresa, R., Brown, T., Davies, P., Fuld, P., ... Peck, A. (1988). Clinical, pathological, and neurochemical changes in dementia: a subgroup with preserved mental status and numerous neocortical plaques. *Annals of Neuology*, *23*(2), 138–144. doi:10.1002/ana.410230206

Kim, H. (2011). Neural activity that predicts subsequent memory and forgetting: A meta-analysis of 74 fMRI studies. *NeuroImage*, *54*(3), 2446–2461. doi:10.1016/j.neuroimage.2010.09.045

Kramer, A. F., Erickson, K. I., & Colcombe, S. J. (2006). Exercise, cognition, and the aging brain. *Journal of Applied Physiology*, *101*(4), 1237–1242. doi:10.1152/japplphysiol.00500.2006

Lee, T., Henry, J. D., Trollor, J. N., & Sachdev, P. S. (2010). Genetic influences on cognitive functions in the elderly: a selective review of twin studies. *Brain Rearch Reviews*, *64*(1), 1–13. doi:10.1016/j.brainresrev.2010.02.001

Li, S.-C., Lindenberger, U., & Frensch, P. A. (2000). Unifying cognitive aging: From neuromodulation to representation to cognition. *Neurocomputing*, *32-33*(1-4), 879–890. doi:10.1016/S0925-2312(00)00256-3

Logan, J. M., Sanders, A. L., Snyder, A. Z., Morris, J. C., & Buckner, R. L. (2002). Under-recruitment and nonselective recruitment: Dissociable neural mechanisms associated with aging. *Neuron*, *33*(5), 827–840. doi:10.1016/S0896-6273(02)00612-8

Lövdén, M., Ghisletta, P., & Lindenberger, U. (2005). Social participation attenuates decline in perceptual speed in old and very old age. *Psychology and Aging*, *20*(3), 423–434. doi:10.1037/0882-7974.20.3.423

Lövdén, M., Rönnlund, M., Wahlin, A., Bäckman, L., Nyberg, L., & Nilsson, L.-G. (2004). The extent of stability and change in episodic and semantic memory in old age: Demographic predictors of level and change. *The Journal of Gerontology*, *59*(3), 130–134. doi:10.1093/geronb/59.3.P130

Lövdén, M., Schaefer, S., Noack, H., Bodammer, N. C., Kühn, S., Heinze, H.-J., ... Lindenberger, U. (2012). Spatial navigation training protects the hippocampus against age-related changes during early and late adulthood. *Neurobiology of Agingging*, *33*(3), 620.e9–620.e22. doi:10.1016/j.neurobiolaging.2011.02.013

Miller, S. L., Celone, K., DePeau, K., Diamond, E., Dickerson, B. C., Rentz, D., ... Sperling, R. A. (2008). Age-related memory impairment associated with loss of parietal deactivation but preserved hippocampal activation. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(6), 2181–2186. doi:10.1073/pnas.0706818105

Nagel, I. E., Preuschhof, C., Li, S.-C., Nyberg, L., Bäckman, L., Lindenberger, U., & Heekeren, H. R. (2009). Performance level modulates adult age differences in brain activation during spatial working memory. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(52), 22552–7. doi:10.1073/pnas.0908238106

Nilsson, L.-G. (2003). Memory function in normal aging. *Acta Neurologica Scandinavica*, *179*, 7–13. doi:10.1034/j.1600-0404.107.s179.5.x

Nyberg, L., Andersson, M., Kauppi, K., Lundquist, A., Persson, J., Pudas, S., & Nilsson, L.-G. (2014). Age-related and Genetic Modulation of Frontal Cortex Efficiency. *Journal of Cognitive Neuroscience*, *26*(4), 746–754. doi:10.1162/jocn

Nyberg, L., Lövdén, M., Riklund, K., Lindenberger, U., & Bäckman, L. (2012). Memory, aging and brain maintenance. *Trends in Cognitive Sciences*, *16*(5), 292–305. doi:10.1016/j.tics.2012.04.005

Nyberg, L., McIntosh, A., Houle, S., Nilsson, L., & Tulving, E. (1996). Activation of the medial temporal lobe structures during memory retrieval. *Nature*, *380*(6576), 715–717.

Nyberg, L., Salami, A., Andersson, M., Eriksson, J., Kalpouzos, G., Kauppi, K., … Nilsson, L.-G. (2010). Longitudinal evidence for diminished frontal cortex function in aging. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(52), 22682–22686. doi:10.1073/pnas.1012651108

O’Brien, J. L., O’Keefe, K. M., LaViolette, P. S., DeLuca, A. N., Blacker, D., Dickerson, B. C., & Sperling, R. A. (2010). Longitudinal fMRI in elderly reveals loss of hippocampal activation with clinical decline. *Neurology*, *74*(24), 1969–1976. doi:10.1212/WNL.0b013e3181e3966e

Park, D. C., Lautenschlager, G., Hedden, T., Davidson, N. S., Smith, A. D., & Smith, P. K. (2002). Models of visuospatial and verbal memory across the adult life span. *Psychology and Aging*, *17*(2), 299–320. doi:10.1037//0882-7974.17.2.299

Payton, A. (2009). The impact of genetic research on our understanding of normal cognitive ageing: 1995 to 2009. *Neuropsychology Review*, *19*(4), 451–477. doi:10.1007/s11065-009-9116-z

Perneczky, R., Wagenpfeil, S., Lunetta, K. L., Cupples, L. A., Green, R. C., Decarli, C., … Kurz, A. (2010). Head circumference, atrophy, and cognition: implications for brain reserve in Alzheimer disease. *Neurology*, *75*(2), 137–142. doi:10.1212/WNL.0b013e3181e7ca97

Persson, J., Kalpouzos, G., Nilsson, L.-G., Ryberg, M., & Nyberg, L. (2011). Preserved hippocampus activation in normal aging as revealed by fMRI. *Hippocampus*, *21*(7), 753–766. doi:10.1002/hipo.20794

Persson, J., Nyberg, L., Lind, J., Larsson, A., Nilsson, L.-G., Ingvar, M., & Buckner, R. L. (2006). Structure-function correlates of cognitive decline in aging. *Cerebral Cortex*, *16*(7), 907–915. doi:10.1093/cercor/bhj036

Persson, J., Pudas, S., Lind, J., Kauppi, K., Nilsson, L.-G., & Nyberg, L. (2012). Longitudinal structure-function correlates in elderly reveal MTL dysfunction with cognitive decline. *Cerebral Cortex*, *22*(10), 2297–2304. doi:10.1093/cercor/bhr306

Plassman, B., & Williams, J. (2010). Systematic review: Factors associated with risk for and possible prevention of cognitive decline in later life. *Annals of Internal Medicine*, *153*, 182–193. doi:10.1059/0003-4819-153-3-201008030-00258

Pudas, S., Persson, J., Josefsson, M., de Luna, X., Nilsson, L.-G., & Nyberg, L. (2013). Brain characteristics of individuals resisting age-related cognitive decline over two decades. *Journal of Neuroscience*, *33*(20), 8668–8677. doi:10.1523/JNEUROSCI.2900-12.2013

Pudas, S., Persson, J., Nilsson, L.-G., & Nyberg, L. (2014). Midlife memory ability accounts for brain activity differences in healthy aging.

Neurobiology of Aging. Advance online publication. doi:10.1016/j.neurobiolaging.2014.05.022

Rajah, M. N., & D'Esposito, M. (2005). Region-specific changes in prefrontal function with age: A review of PET and fMRI studies on working and episodic memory. *Brain*, *128*, 1964–1983. doi:10.1093/brain/awh608

Rand-Giovannetti, E., Chua, E. F., Driscoll, A. E., Schacter, D. L., Albert, M. S., & Sperling, R. A. (2006). Hippocampal and neocortical activation during repetitive encoding in older persons. *Neurobiology of Aging*, *27*(1), 173–182. doi:10.1016/j.neurobiolaging.2004.12.013

Raz, N., Lindenberger, U., Rodrigue, K. M., Kennedy, K. M., Head, D., Williamson, A., … Acker, J. D. (2005). Regional brain changes in aging healthy adults: General trends, individual differences and modifiers. *Cerebral Cortex*, *15*(11), 1676–1689. doi:10.1093/cercor/bhi044

Raz, N., & Rodrigue, K. M. (2006). Differential aging of the brain: patterns, cognitive correlates and modifiers. *Neuroscience and Biobehavioral Reviews*, *30*(6), 730–748. doi:10.1016/j.neubiorev.2006.07.001

Resnick, S. M., Pham, D. L., Kraut, M. A., Zonderman, A. B., & Davatzikos, C. (2003). Longitudinal magnetic resonance imaging studies of older adults: A shrinking brain. *The Journal of Neuroscience*, *23*(8), 3295–3301.

Reuter-Lorenz, P. A., & Cappell, K. A. (2008). Neurocognitive aging and the compensation hypothesis. *Current Directions in Psychological Science*, *17*(3), 177–182. doi:10.1111/j.1467-8721.2008.00570.x

Rosano, C., Aizenstein, H. J., Newman, A. B., Venkatraman, V., Harris, T., Ding, J., … Yaffe, K. (2012). Neuroimaging differences between older adults with maintained versus declining cognition over a 10-year period. *NeuroImage*, *62*(1), 307–313. doi:10.1016/j.neuroimage.2012.04.033

Rönnlund, M., Nyberg, L., Bäckman, L., & Nilsson, L.-G. (2005). Stability, growth, and decline in adult life span development of declarative memory: Cross-sectional and longitudinal data from a population-based study. *Psychology and Aging*, *20*(1), 3–18. doi:10.1037/0882-7974.20.1.3

Salami, A., Eriksson, J., & Nyberg, L. (2012). Opposing effects of aging on large-scale brain systems for memory encoding and cognitive control. *The Journal of Neuroscience*, *32*(31), 10749–10757. doi:10.1523/JNEUROSCI.0278-12.2012

Salat, D. H., Kaye, J. A., & Janowsky, J. S. (1999). Prefrontal gray and white matter volumes in healthy aging and Alzheimer disease. *Archives of Neurology*, *56*(3), 338–344. doi:10.1001/archneur.56.3.338

Satz, P. (1993). Brain reserve capacity on symptom onset after brain injury: A formulation and review of evidence for threshold theory. *Neuropsychology*, *7*(3), 273–295. doi:10.1037//0894-4105.7.3.273

Schaie, K. W. (1994). The course of adult intellectual development. *The American Psychologist*, *49*(4), 304–313. doi:10.1037/0003-066X.49.4.304

Schaie, K. W., & Labouvie-Vief, G. (1974). Generational versus ontogenetic components of change in adult cognitive behavior: A fourteen-year cross-sequential study. *Developmental Psychology*, *10*(3), 305–320. doi:10.1037/h0036445

Scoville, W. B., & Milner, B. (1957). Loss of recent memory after bilateral hippocampal lesions. *Journal of Neurology, Neurosurgery and Psychiatry*, *20*(1), 11–21.

Smith, J. C., Nielson, K. A., Woodard, J. L., Seidenberg, M., Durgerian, S., Hazlett, K. E., ... Rao, S. M. (2014). Physical activity reduces hippocampal atrophy in elders at genetic risk for Alzheimer's disease. *Frontiers in Aging Neuroscience*, *6*, 1–7. doi:10.3389/fnagi.2014.00061

Steffener, J., & Stern, Y. (2012). Exploring the neural basis of cognitive reserve in aging. *Biochimica et Biophysica Acta*, *1822*(3), 467-473. doi: 10.1016/j.bbadis.2011.09.012

Stern, Y. (2009). Cognitive reserve. *Neuropsychologia*, *47*(10), 2015–2028. doi:10.1016/j.neuropsychologia.2009.03.004

Valenzuela, M. J., Sachdev, P., Wen, W., Chen, X., & Brodaty, H. (2008). Lifespan mental activity predicts diminished rate of hippocampal atrophy. *PloS One*, *3*(7), e2598. doi:10.1371/journal.pone.0002598

Walhovd, K. B., Fjell, A. M., Dale, A. M., McEvoy, L. K., Brewer, J., Karow, D. S., … Fennema-Notestine, C. (2010). Multi-modal imaging predicts memory performance in normal aging and cognitive decline. *Neurobiology of Aging*, *31*(7), 1107–1121. doi:10.1016/j.neurobiolaging.2008.08.013

Van Praag, H., Shubert, T., Zhao, C., & Gage, F. H. (2005). Exercise enhances learning and hippocampal neurogenesis in aged mice. *The Journal of Neuroscience*, *25*(38), 8680–8685. doi:10.1523/JNEUROSCI.1731-05.2005

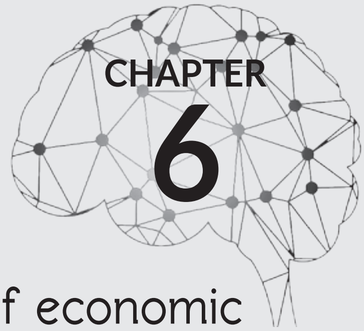
Wheeler, M. A., Stuss, D., & Tulving, E. (1995). Frontal lobe damage produces episodic memory impairment. *Journal of the International Neuropsychological Society*, *1*, 525–536. doi:10.1017/S1355617700000655

Wilson, R. S., Beckett, L. A., Barnes, L. L., Schneider, J. A., Bach, J., Evans, D. A., & Bennett, D. A. (2002). Individual differences in rates of change in cognitive abilities of older persons. *Psychology and Aging*, *17*(2), 179–193. doi:10.1037//0882-7974.17.2.179

Wisdom, N. M., Callahan, J. L., & Hawkins, K. A. (2011). The effects of apolipoprotein E on non-impaired cognitive functioning: A meta-analysis. *Neurobiology of Aging*, *32*(1), 63–74. doi:10.1016/j.neurobiolaging.2009.02.003

Yaffe, K., Fiocco, A. J., Lindquist, K., Vittinghoff, E., Simonsick, E. M., Newman, A. B., … Harris, T. B. (2009). Predictors of maintaining cognitive function in older adults: The Health ABC study. *Neurology*, *72*(23), 2029–2035. doi:10.1212/WNL.0b013e3181a92c36

Zahodne, L., Glymour, M., Sparks, B., Bontempo, D., Dixon, R., SWS, M., & Manly, J. (2011). Education does not slow cognitive decline with aging: 12-year evidence from the Victoria Longitudinal Study. *Journal of the International Neuropsychological Society*, *17*(6), 1039–1046. doi:10.1017/S1355617711001044.Education



CHAPTER 6

The neural foundations of economic decision-making

Nicola Canessa, Alessandra Dodich
Chiara Crespi & tefano F. Cappa

Introduction: Interdisciplinary Cross-roads in the Study of Decision-making in the Brain

The development of neurobiological models of reasoning and decision-making is a highly interdisciplinary sector of cognitive neuroscience based on the integration of notions, methods and results from different fields addressing the relationship between mind and behavior, with psychology, neuroscience and behavioral economics playing a key and leading role (Sanfey et al., 2006). In recent years, the growing integration among such a large number of contributing disciplines resulted in different, although strictly intertwined, sub-areas, including the field of Neuroeconomics. These areas concern both the "core" investigation of the neural bases of decision-making (i.e. *which neural systems take part in the evaluative processes underlying decision-making?*) and its translational counterpart (i.e. *how do neurological or psychiatric diseases affect decision-making and underlying neural activity or structure?*) (Sharp et al., 2012).

The variety of the topics addressed in Neuroeconomics reflects in the use of different research techniques, ranging from the investigation of psychological factors driving one's own (normal or impaired) choices and underlying neural activity with neuroimaging techniques (functional Magnetic Resonance Imaging —fMRI—, Positron Emission Tomography —PET—, MagnetoEncephalography —MEG—), to the assessment of the effects of brain stimulation on both these levels of analysis, with transcranial magnetic stimulation (TMS) or direct current stimulation (tDCS). As in other sectors of Cognitive Neuroscience, the most recent developments of Neuroeconomics concern the investigation of a genetic basis to the individual differences in decision-making (Kuhnen et al., 2013), i.e. in terms of the modulation exerted on choice-related neural activity by specific neurotransmission systems which other fields, at yet another level of analysis, have connected to specific personality dimensions such as "reward dependence" and "harm avoidance" (Cloninger, 1994). The increasing integration among these different levels of analysis is providing support to the notion that making choices is the final stage of processes in charge of evaluating stimuli and/or stimuli-related actions in terms of their potential rewarding vs. punishing value, as well as of updating such value through mechanisms of *adaptive behavioral learning*. At the neural level, such mechanisms reflect in the activity of specific mesolimbic structures, such as the ventral striatum and amygdala, generating those appetitive and aversive drives constituting the basis of motivated behavior and of individual differences in decisional style (Canessa et al., 2013, De Martino et al., 2010, Tom et al., 2007). This highly integrated view, connecting genes to behavior, represents the present and the future of this young research field. Its origins, however, date back up to the unfortunate case of Phineas Gage, the railroad construction foreman whose medial prefrontal cortex was destroyed by the passage of an iron rod in a work accident.

The Origins of Neuroeconomics: The Ventromedial Prefrontal Cortex and Emotion-based Decision-making

From an historical perspective, indeed, the first steps of Neuroeconomics are strictly intertwined with the neuropsychological investigation on the relative contribution of cognitive and affective processing in decision-making, pursued by Antonio Damasio and Antoine Bechara starting from the mid ‘90s. In those years its main precursor is represented by the *quantitative* assessment of the affective and decisional impairments associated with a severe damage of the ventromedial prefrontal cortex (vmPFC; see (Bechara et al., 2000), inspired by the qualitative reports of Gage’s behavioral deficits reported by Dr. John Harlow (Harlow, 1848). Since the first weeks after the accident, the singularity of this case resulted from the mixture of behavioral and social impairments, i.e. disinhibition, poor affectivity and personality changes, in the face of preserved sensory, cognitive, linguistic and motor skills. In the long run, however, it became clear that the behavioral impairment was more extensive than what originally estimated, and that, alongside a normal affectivity, Gage had lost the ability to make advantageous (i.e. adaptive, according to the current terminology) choices (Damasio et al., 1994). While neither intelligence nor encyclopedic learning had been affected, his choices appeared to reflect an insensitivity to their future consequences that, for the first time in the neurological literature, highlighted a relationship between a specific brain region and the ability to adapt one’s behavior to experience.

More than one century later Damasio and colleagues investigated the cognitive, affective and neural correlates of such a “myopia for the future” with the classical Iowa Gambling Task, aiming to mimic key components of everyday choices such as potential rewards, punishments, uncertainty about the probability of their occurrence, but also potential learning from the outcome of past choices (Bechara, 2004). In this task participants are asked to make a series of selections from 4 decks of cards, each resulting in a variable financial gain or loss, in order to maximize their final payoff. The schedules of gains and losses associated with each deck (and their size) are pre-programmed, so that decks A and B result in high gains in the first trials, but also in even higher losses later on, while decks C and D are associated with smaller gains and losses.

Good performance in this task thus requires the ability to learn that decks A and B, initially associated with high rewards, are actually disadvantageous compared with decks C and D. Indeed, healthy individuals adaptively switch from the former to the latter decks throughout the task, displaying behavioral learning from past outcome experiences. The same choice profile is shown by patients with lesions in the dorsolateral prefrontal cortex or outside the prefrontal cortex, while a strong impairment in switching from “bad” to “good” decks is typically observed in association with a bilateral lesion in the vmPFC (Bechara et al., 1994). Crucially, the peculiar choice profile in vmPFC patients mirrors their reduced affectivity, even more than a conscious awareness of the value of each deck. By recording skin conductance response (SCR; a measure of affective arousal) during the task, Bechara et al. (Bechara et al., 1996) showed that, in healthy individuals, switching to “good decks” reflects in increasing SCRs before card selection (anticipatory SCRs), and particularly before selecting a risky deck. The rise of this affective “alarm” signal parallels adaptive learning when, after experiencing the first punishments, they feel a hunch about which decks are riskier. This “somatic marker” of risk (Damasio, 1996) is absent in vmPFC patients, even when they reach a full awareness of which decks are risky.

Based on these observations, Damasio’s somatic marker hypothesis aims to explain the mechanisms by which anticipated emotions guide decision-making and ensuing behavior via a learning process involving several brain structures. It predicts that past choices are stored in memory not only as declarative traces, but also in terms of the positive or negative feelings elicited by their outcome, represented in limbic and somatosensory cortex. Being engaged in a new choice may reactivate, not only the episodic traces, but also the affective ones via the vmPFC, which provides a neural connection between factual knowledge and the pattern of bioregulatory states associated with the anticipated outcome of a given option. Such a "somatic marker" acts as an alarm signal, delimiting the decisional space and simplifying the choice process. A lesion of the vmPFC, the pivot region of the somatic marker system, would thus impair the balance between incentive and alarm signals, reducing the ability to inhibit appetitive drives towards potentially rewarding stimuli. In line with this view, several studies reported defective performance in the Iowa Gambling Task in different conditions belonging to the spectrum of impulse control disorders, such as substance dependence (Barry and Petry, 2008) and pathological gambling (Kraplin et al., 2014).

Overall, the somatic marker hypothesis provides a system-level description of the anatomo-functional mechanism underlying choice behavior in health, and their impairment in specific diseases. Besides the vmPFC, this neural system includes structures associated with the generation of appetitive and aversive drives (ventral striatum and amygdala, respectively), and with their inhibition by higher level mechanisms of cognitive control involving the dorsal sector of anterior cingulate cortex (dACC). In this framework, an imbalance between incentive and alarm signals, and/or reduced top-down inhibition of such signals by cognitive control mechanisms, may characterize several psychiatric or neurological disorders involving defective decision-making (Gleichgerrcht et al., 2010).

From an historical perspective, the clinical observations underlying this hypothesis not only provided the neuropsychological foundations of Neuroeconomics. They also opened the avenue for the neuroscientific investigation of the interacting roles of cognitive computations and emotional responses during decision-making in healthy individuals. In particular, they offered an interpretative framework for the integration with the neurophysiological approach, concerned with the investigation of the neuronal mechanisms of adaptive behavioral learning in the mesocorticolimbic dopaminergic pathway, which nowadays represents the core of the discipline.

The Computational Side of Neuroeconomics: Reinforcement Learning

Adaptive behavior requires the ability to select those actions that, in a given state and depending on one's own knowledge, are more likely to result in the desired goal. Converging interdisciplinary evidence suggests that the basic mechanism underlying optimal action selection is the ability to *estimate the value* of different stimuli, and of different stimuli-related actions that may be performed (Rushworth and Behrens, 2008). The notion of "expectation" is crucial here, because while the rewarding or punishing value of some stimuli/actions are innate (e.g., a sweet taste or a painful stimulation), in most cases estimating their value depends on previous experience. Equally important is the ability to *update*–or even reversing–such expectations, in a rapidly changing environment. This process finally results in approach vs. escape/avoidance behaviors concerning, respectively, potentially rewarding or punishing stimuli/action-outcomes.

These are the basic principles of an interdisciplinary research field that investigates motivated animal behavior by combining concepts and methods from psychology, neuroscience, economics and computer science. Although rooted in the computational approach of Reinforcement Learning Theory (RLT((Sutton and Barto, 1998), the basic concepts of this field range from the behaviorists notions of classical and instrumental conditioning to the neurophysiological substrate of behavioral learning signals in dopaminergic neurons. Equally widespread are its potential implications, ranging from understanding decision-making in the healthy brain to a novel framework for the interpretation of mental disease, whose agenda is effectively captured by the notion of "computational psychiatry" (Montague et al., 2012). The common theoretical ground of this field is represented by the notion of "reinforcement", whose computational description provides an operationalization of the notion of adaptive behavioral learning.

The basic mechanisms of adaptive behavioral learning: rewards, punishers, reinforcers

Classical (Pavlovian) and operant (instrumental) conditioning represent the basis of behavioral learning. In classical conditioning, an unconditioned stimulus (US; e.g. food) spontaneously elicits an unconditioned response (UR; e.g. salivation). When a neutral stimulus (i.e. the sound of a bell) is consistently paired with the US it may become a conditioned stimulus (CS+) that elicits the same response (conditioned response, CR) to a greater extent than a stimulus (CS-) that did not undergo such coupling.

Instrumental conditioning, instead, requires the production of an explicit action (an "operant"). As suggested by Thorndike's (Thorndike, 1927) Law of effect, actions that are reinforced or punished are more or less likely to be repeated, respectively. Instrumental conditioning thus allows to exert a *control* on the delivery of the unconditioned stimulus. Therefore, it differs from classical conditioning because, as a result of its consequences, it entails a modification of the individual's behavior and of the surrounding environment.

Classical and instrumental conditioning are now interpreted within a theory of adaptive learning from experience rooted in the notion of reinforcement based on rewards and punishers (see Rolls, 2005). It is assumed that an organism's basic and hardwired motivation is to approach rewards and to avoid punishments. The motivational facet is intrinsic in the notion of reinforcement, in that a reward is something for which an animal will spend resources to approach it, i.e. increasing the probability of actions on which it is contingent. A punisher, instead, is something that an animal will spend resources to escape from or avoid, i.e. decreasing the probability of actions on which it is contingent. Therefore, rewards and punishers are actually called reinforcers, in that they entail a learning process: reinforcers are thus stimuli whose occurrence, termination or omission in association with a behavioral response alters the probability of its emission in the future (Rolls, 2005). The contingencies between such stimuli and responses define four main learning situations, involving either processes of reinforcement or punishment (increasing and decreasing the probability of emission of a response, respectively). In positive reinforcement, a reinforcer (a reward) increases the probability of emission of a response on which it is contingent, and whose outcome is rewarding (e.g. food). In negative reinforcement, a reinforcer (a punisher, e.g. a painful stimulation) increases the probability of emission of a response which leads to its omission (e.g. active avoidance) or termination (e.g. escape). In positive punishment, a punisher (e.g. a painful stimulation) decreases the probability of emission of a response on which it is contingent, and whose outcome is punishing (e.g. pain). In negative punishment, a punisher (a reward) decreases the probability of emission of a response which elicits its omission or termination (extinction or "time out", respectively) (Rolls, 2005). The difference between the notions of reward/punisher and reinforcer is made explicit, here, by the fact that what is "reinforcing" is a change in the delivery of rewards or punishers.

Converging results highlight the evaluation of stimuli in terms of reward and punishment as the crucial interface between systems involved in sensory processing and those involved in action-selection and executive control (i.e. decision-making) (Rolls, 2005, Doya, 2008). Decoding the rewarding/punishing value of sensory stimuli and actions, on a short-range common currency making them comparable with each other, would then represent one of the core processes of brain functioning. This is the framework of a research field known as Neurophysiology of learning and motivation, in which these assumptions are first formalized with the conceptual tools of RLT, and then directly tested in terms of the activity of single neurons in animals, or of brain networks in humans (see Schultz et al., 2013; Rolls, 2005).

The computational approach to adaptive behavioral learning

Early after the diffusion of the behaviorists descriptions of classical and instrumental conditioning, many scholars noted that the complexity of these processes could be hardly explained only in terms of simple mental associations. These concerns led to more refined interpretations of these phenomena, explicitly focused on the notion of "*learning to predict*" the consequences of behavior. This view was then enormously expanded by RLT (see Sutton and Barto, 1998), that provided a computational description of trial and error learning from reward and punishment experience (Montague et al., 1996, Schultz et al., 1997). RLT, indeed, is a sector of machine learning that studies how agents, in order to maximize cumulative reward a given environment, should select actions by learning to predict their consequences. This approach is based on the notion of "expectation", of either rewards or punishments, that results from learning a relationship between given stimuli or actions and the amount or probability of the reward/punishment that may follow them. As in the original behaviorist notions, the mechanisms that are supposed to be involved in such learning process realize an interface between sensory processing (i.e. the analysis of the environmental states) and action-selection. However, in RLT a computational approach aims to unravel the underlying mechanisms, by introducing concepts directly related with an *internal model* of the expectations generated, as well as algorithms for updating them based on increasing experience.

The typical reinforcement learning model includes a set of environmental states and a set of possible actions, that may determine the transitions from one state to another, that in turn will determine an outcome. The latter can entail either positive or negative utilities, which also depend on the motivational state of the agent. In the typical case, the agent does not know the rules of transition from one state to another, nor the outcome that actions and transitions will produce. It must learn them from experience, by generating predictions about the contingency between an action in a given state, and the reward associated with the state that action will determine. This process entails the estimation of *value functions*, i.e. action-state pairs informing about the reward that, given the current state, is expected by performing an action which will move its agent to another state. Estimating such value functions, in turn, requires learning algorithms that update them based on new experience (i.e. action-state pairs). A widely known algorithm is the Temporal Difference (TD) learning rule, that updates the expectation of final reward by computing at every time-step an "error term" (i.e. a "prediction-error", the difference between predicted and actual reward). This difference (positive or negative, when the outcome is, respectively, better or worse than predicted at the previous step) is then used to update the expectation, i.e. the values of states, state-action pairs or both, according to a given learning-rate, in order to make it closer to the prediction at the subsequent step. Prediction-errors constitute a crucial term for reward-based learning, which has been shown to account for instrumental (Barto, 1990a) and classical (Barto, 1990b) conditioning. Overall, RLT provides a unified framework for interpreting findings from apparently distant fields, from classical and instrumental conditioning to optimal decision-making and adaptive behavioral learning, by grounding them on the common adaptive function of learning to predict outcomes from the *consequences of actions*. Neurophysiological studies now highlight its neural correlates in the activity of specific neurons within a network centered on the mesocorticolimbic dopaminergic pathway.

The neural bases of reinforcement learning

Neurophysiological studies on animals, and more recently neuroimaging studies on humans, are providing a neurobiological validation of the main concepts of RLT (Schultz et al., 2013). Reward expectations (concerning both its amount and probability), prediction-errors and the ensuing reward-based learning are consistently associated with activity in the dopaminergic mesencephalic system, a neurotransmitter system originating in midbrain dopaminergic nuclei (ventral tegmental area-VTA and substantia nigra pars compacta), and projecting to large areas of the brain through four major pathways. Among them, the mesocorticolimbic pathway (connecting the VTA to the striatum, limbic system and medial prefrontal cortex) is a crucial component of the reward-system. Critical supporting evidence concerns single-cell recordings from dopaminergic neurons in the striatum, highlighting response patterns that mimic the basic RTL parameters, and particularly the dynamics of the reward prediction-error (Schultz, 2007). These neurons do not respond to cues signaling no reward, but they show phasic (rapid bursts) activity in response to unexpected rewards (i.e., positive prediction-error). Subsequent learning steps reduce such positive prediction-error (and the phasic response at outcome) and increase the response to the reward-predicting cues (a neural marker of their increasing predictive power). When learning is stable, a phasic response follows the cue (signaling reward prediction), but not the actual delivery of reward (which entails a null prediction-error). After learning, the strength of striatal dopaminergic responses quantitatively codes an *expectation* of reward (either its magnitude or probability) when a cue is presented, and a prediction-error at the expected time of reward delivery. Importantly, a similar mechanism also underpins *negative* expectations. The omission of expected rewards elicits a tonic (sustained) depression of the response consistent with the computation of negative prediction-errors. Moreover, a reduction of the dopaminergic response is also elicited by cues predicting either the absence of a reward, or the delivery of a punishment. This reduction may result from the inhibition exerted on dopamine cells by the lateral habenula, whose neurons display a reverse pattern of response compared with that just described, i.e. activation by stimuli predicting the absence of rewards and deactivation by stimuli that predict their delivery (Lecourtier et al., 2008).

As previously discussed, prediction-errors are used to update expectations and improve predictions at subsequent steps. Converging evidence suggests that the computation of prediction-errors in the striatum may represent the basic mechanism of the “actor-critic” model, entailing two distinct computational modules: a “critic” that learns state-values and involves the ventral striatum, and an “actor” that learns stimulus-response associations and involves the dorsal striatum (Maia, 2009). Importantly, however, neuronal responses that reflect the computation of prediction-errors and reward expectations are not limited to midbrain and striatal dopaminergic nuclei. Neural responses tracking RLT parameters have been also observed in other regions receiving dopaminergic projections, namely vmPFC and dACC. To date, the amygdala (Belova et al., 2007) and vmPFC (Matsumoto et al., 2007) have been associated with the coding of both positive and negative reward prediction and prediction-errors. In addition, the vmPFC is related to the representation of goal-directed value (Valentin et al., 2007), and the dACC with coding uncertainty (Behrens et al., 2007) and performing cost-benefit analyses (Croxson et al., 2009).

One debated issue concerns the neural coding of *aversive* stimuli and events, as well as their prediction-errors, which have been shown to reflect in the inhibition of dopaminergic activity (Dayan and Niv, 2008). However, expectations of aversive events may also be coded by additional mechanisms involving negatively valenced affective responses. Indeed, increasing evidence (e.g., Canessa et al., 2013; De Martino et al., 2010) suggests that in decision-making dopaminergic structures may interact with a neural system centered on the amygdala, which is crucial for learning the *aversive* value of stimuli and action-outcomes, and the associated motivational and emotional states (see LeDoux, 2012).

Adaptive Learning from Complex Emotions: Counterfactual Reasoning and Regret

As previously discussed, the core notion of emotion-based decision-making is that choices are driven by the anticipation of affects people expect to feel at outcome. Maximizing expected emotions may thus be different from maximizing expected utilities, as people tend to select options that minimize negative affects (Mellers et al., 1999). Small gains may even result more pleasurable than larger ones, depending on expectations and on *comparisons* between possible alternative outcomes. Based on the nature of such outcomes and comparisons, different types of emotion, at different levels of complexity, can emerge. When the alternative outcome is worse or better than the actual one, people experience the basic feelings of elation or disappointment, reflecting positive and negative prediction-errors, respectively. Importantly, both these feelings arise from comparisons between actual outcomes whose occurrence depends on nature (e.g. the stop of the arrow in a wheel-of-fortune). Qualitatively different emotions result from attending (or anticipating) outcomes for which one is directly responsible, for instance the outcomes of both the chosen and unchosen options. In this case, emotions are amplified by the awareness that things might have been better, or worse, under a different choice, elicited by *counterfactual* comparisons between the obtained (factual) and the foregone (counterfactual) outcomes. These comparisons, associated with a sense of responsibility for the consequences of choice, amplify the resulting emotions of regret or relief when the obtained outcome is, respectively, worse or better than the foregone one. As stated by Kahneman and Miller (Kahneman and Miller, 1986), they act as emotional amplifiers of choice-related emotions and of their influence on subsequent choices. In other words, experiencing the painful emotion of regret boosts adaptive behavioral learning and the motivation to avoid it in the future. Once again, this process involves the mesocorticolimbic dopaminergic pathway and its cortical targets, particularly the vmPFC.

The neural bases of regret: ventromedial prefrontal cortex and fictive prediction-errors

The behaviorally adaptive role of the experience and anticipation of regret and relief has been functionally characterized in recent studies involving both healthy and brain-lesioned individuals (Camille et al., 2004; Coricelli et al., 2005; Canessa et al., 2009). These studies employed a gambling-task aimed to elicit in the participants the two main precursors of regret and relief. That is, knowing that things would have been better under a different choice, when one is also directly responsible for her/his outcomes (Coricelli et al., 2007).

This task includes several consecutive trials, requiring participants to choose which, between two gambles, they wish to play. Gambles are depicted as "wheels-of-fortune", in which different probabilities of variable amounts of gain or loss are represented by the relative size of colored sectors of the wheel. In order to modulate the quality and intensity of participants' emotional reactions to the outcomes, in different conditions they may receive either "partial" or "complete" feedbacks. In the first case they are shown only the outcome of the chosen gamble (depending on the random rotation of the spinning-wheel), and can thus experience either elation for gains or disappointment for losses. In "complete-feedback" conditions, instead, they are shown the outcomes of both the chosen and discarded gambles which, once compared, will generate either relief of regret. The *intensity* of such emotions is manipulated via the size of gains or losses, e.g. a factual loss of 200 in the face of a counterfactual gain of 50 will elicit an overall regret of 250.

Using this task, Camille et al. (2004) addressed the neural bases of both the experience of regret at outcome, and of regret-based adaptive learning at choice, by comparing healthy and participants with vmPFC lesions. In both groups, emotional reactions to outcomes depended on their valence, with gains and losses eliciting positive and negative reactions, respectively. In healthy individuals, however, such reactions also crucially depend on the foregone outcome, so that a loss of 50 does not elicit a negative affect when the foregone outcome is a larger loss of 200, while positive outcomes may even result in regret if compared to a better foregone outcome. Patients, instead, displayed no affective reaction to regretful events, nor they showed behavioral adaptations elicited by its experience and, unlike controls, they end the task with a negative payoff. Besides highlighting the adaptive behavioral role of regret, as distinct from mere disappointment for losses, these results also show the critical role of vmPFC in generating this affective facet of counterfactual comparisons. These data suggest an alternative interpretation of the role of this region in emotion-based decision-making, differing from Damasio's Somatic Marker hypothesis in terms of the nature of emotions engaged. While, in the latter, vmPFC acts as a "neural link" between the memory of past experiences and a bottom-up emotional "hunch" marking risky choices, the data on regret highlight the involvement of a *top-down* modulation elicited by counterfactual thinking, i.e. by high-level cognitive processing. Regardless of a specific interpretation of the role of vmPFC, the decisional impairment displayed after its damage supports its role in adaptive behavioral learning. Indeed, the functional mechanisms of regret-based learning have been subsequently described in a neuroimaging study on healthy subjects playing the same gambling-task (Coricelli et al., 2005). The results of this study confirmed that regret and disappointment are mediated by different neural structures, with the former specifically involving the vmPFC alongside the affective/motivational component of the pain-matrix (dorsal ACC). Moreover, the vmPFC and the amygdala underpin a *learning* process prompted by the experience of regret, aimed to minimize its occurrence.

By using a different task,(Lohrenz et al., 2007) distinguished the affective facet of regret from its computational mechanisms, which they reinterpret in terms of reinforcement learning. This proposal originates from a computational characterization of the difference between obtained and foregone outcomes, defined as a "fictive prediction-error". Neuroimaging evidence highlighted the co-existence of classical and fictive prediction-errors in 54 participants playing a sequential investment game, and receiving feedback information on both the chosen and unchosen options. Behavioral analyses showed that fictive prediction-errors constitute an additional learning signal that allows to predict participants' subsequent choices, increasing the explanatory power of reinforcement learning models based on classical prediction-errors (Lohrenz et al., 2007). At the neural level these two signals involved common portions of the striatum, but the dorsal striatum was specifically engaged by the fictive prediction-error. As previously discussed, this structure seems to underpin the "actor" component of the temporal-difference learning algorithm. Its involvement in the processing of a fictive prediction-error may then reflect the final step (i.e. action-selection) of regret-based adaptive learning.

Social Decision-making: Learning from Others' Regret

Highlighting the role of emotions on choice entails important consequences in terms of the capabilities of behavioral learning. Emotions are shared and, although there may be several ways in which others' emotional states can be understood, one such mechanism is based on the vicarious responses of the brain regions associated with the observer's first-person emotional experience (Gallese et al., 2004). Therefore, any evidence that emotions as regret shape decision-making raises the issue of potential *social* influences on choice, possibly via the activation of outcome-related emotions in the observer's brain. Indeed, behavioral studies (van Harreveld et al., 2008) and neural-networks simulations (Marchiori and Warglien, 2008) show that, in social contexts, one's own decisions may be influenced by interactive learning, i.e. learning from the regret that others experience as a result of their choices. Other studies examined counterfactual reasoning in social contexts, and showed that merely attending others' negative outcomes elicits in the observer the same alternative post-decisional solutions as in a first-person situation (Girotto et al., 2007).

Based on these consistent data, (Canessa et al., 2009, Canessa et al., 2011) used the regret gambling-task previously described to test whether a "resonant" neural mechanism is activated both when experiencing and when attending complex emotions such as regret, and whether this vicarious activation affects subsequent choice behavior. In different trials participants either chose one of the two gambles, resulting in real gains or losses, or observed the outcomes of another individual playing the same task. In two related experiments they showed that *attending* the regretful outcomes of another's choices activates the same regions that are engaged by first-person experiences of regret, i.e. vmPFC, dACC and hippocampus (Canessa et al., 2009). This finding suggests that even a complex emotion such as regret can be shared through the activation of the same brain regions that mediate its first-person painful experience, i.e. through a direct-mapping on the same affective states. In a subsequent study, the same authors observed that this resonant mechanism also underpins learning from others' previous outcomes, besides from one's own ones (Canessa et al., 2011). Trial by trial, subjects' risk-aptitude changed consistently with the outcomes of their previous choices, i.e. with increased risk-seeking after "relief for a risky choice" and "regret for a non-risky choice", and reduced risk-seeking after "relief for a non-risky choice" and "regret for a risky choice". Such behavioral adaptation to past outcomes reflected in cerebral regions specifically coding the effect of previously experienced regret/relief when making a new choice. Activity in subgenual cortex and dorsal striatum tracked the outcomes that increased risk-seeking. These regions were also more strongly activated by final risky, compared with non-risky, choices, and their activity likely reflects the motivational drive arising from previous outcomes that highlighted the reward-value of risky options (Daw and Doya, 2006). Instead, activity in vmPFC and amygdala reflected the outcomes reducing risk-seeking. All these regions, along with anterior insula, were also more strongly activated while making non-risky *vs.* risky choices. Based on available knowledge on their functional role, the vmPFC likely reflects adaptive learning reducing risk-seeking when, via connections with amygdala, insula and periaqueductal grey-matter (Reynolds and Zahm, 2005), previous outcome-related emotions activate the negative feeling associated with regret and its anticipation.

Importantly, significant behavioral adaptations were also elicited by the other player's previous outcomes of regret or relief, while disappointment or elation, elicited by the outcomes of random-choices by the computer and thus devoid of personal responsibility, had no effect. At the neural level, learning from others' experience of regret and relief involved a subset of the regions recruited by behavioral adaptations in the personal domain. This finding extended the concept of emotional resonance to the decisional domain, where such a vicarious response might represent a neural mechanism underlying social learning. Paralleling the behavioral effects of others' emotions, this mechanism would entail the mapping of the emotional consequences of others' choices on the same emotional states and cerebral regions that are involved as a 1st-person.

The Clinical Side of Economic Decision-making

Many neurological and psychiatric disorders can be associated with impaired decision-making, in particular in social contexts. Impairments of the processing of information requiring the attribution of mental states (such as cognitive or affective states) to co-specifics, leading to defective decision making, result from focal damage due to stroke, tumours or head injury involving the neural networks discussed above (in particular, the vmPFC, anterior cingulate and amygdala). In many of these instances, however, the disorder is only relatively specific, as lesions typically extend beyond these areas, resulting in additional impairments of executive functioning, memory, language or visuo-spatial perception. When this is the case, it is often difficult to exclude that the defective performance observed in tasks derived from decision-making and neuroeconomic research may reflect subtle disorders of basic cognitive processing requirements, such as perceptual abilities, instruction understanding and working memory capacity. The investigation of early stages of neurodegenerative disorders and of selected developmental and psychiatric condition is providing an additional window for research in decision-making, and is promoting insights into the clinical phenotype of frequent conditions, such as Parkinson's disease (Delazer et al., 2009) and autism (Rilling and Sanfey, 2011).

A particularly interesting condition is the behavioral variant of fronto-temporal dementia, which belongs to frontotemporal lobar degeneration (FTLD) spectrum (Piguet et al., 2011, Cerami and Cappa, 2013), and is the second most common young-onset neurodegenerative dementia subtype after Alzheimer's Disease (AD). The mean age at onset is typically in the 50s, with an equal prevalence in men and women. The condition is neuropathologically heterogeneous: the main neuropathological substrates are FTLD-microtubule protein tau (FTLD-tau) and FTLD-transactive response DNA binding protein (FTLD-TDP43) (Halliday et al., 2012). The different pathologies share a selectivity for the frontal and temporal lobes, involving both hemispheres, often with a right sided prevalence (Whitwell et al., 2012). In the early phase of disease, the pathology is typically localized in paralimbic (anterior cingulate cortex, anterior insula, and lateral orbitofrontal cortex), limbic (hippocampus), and subcortical (ventral striatum and dorsomedial thalamus) areas. Additional evidence from structural and functional connectivity studies is in line with the hypothesis of a selective involvement of a specific large scale network dedicated to social cognition (Seeley et al., 2009). The condition is often genetic, with multiple genetic autosomal dominant mutations identified (most frequently mutations involving microtubule-associated protein tau (MAPT), progranulin (GRN) genes and the large hexanucleotide (GGGGCC) repeat expansion in the first intron of C9ORF72 mutation (Cerami et al., 2012).

The new consensus criteria (Rascovsky et al., 2011) require for the diagnosis the presence of 3 out of 6 clinically discriminating features (i.e. disinhibition, apathy/inertia, loss of sympathy/empathy, perseverative/compulsive behaviors, hyperorality and dysexecutive neuropsychological profile). The most common early manifestations of bvFTD are insidious changes in personality, interpersonal conduct and emotional modulation, in the absence of clinically significant impairment in other cognitive areas. Apathy and social withdraw often coexist with disinhibition, impulsivity and socially embarrassing behavior. Defective decision-making in social contexts may provide a theoretical framework to interpret inappropriate behaviors, which can be considered as a consequence of impaired identification of contextual social and emotional signals associated with a potential reward or punishment value (Ibanez and Manes, 2012). The changes lead to personality modifications, and therefore to progressive social isolation. BvFTD patients are typically impaired in tasks assessing the recognition of basic emotions (Kumfor and Piguet, 2012), comprehension and inference of other's mental states and emotions (Cerami et al., 2014, Adenzato et al., 2010), and social decision-making (Torralva et al., 2009; Gleichgerrcht et al., 2010).

Conclusions

The brief and selective review presented here can hardly account for the true explosion of research in this area in the last decade. Among the many exciting aspects of this field, we believe that the application of the rigorous and computationally explicit models of experimental economics to neuroimaging and neuropsychological studies of human subjects provides a powerful tool for the investigation of decision-making in health and disease. The quantification of parameters such as risk aversion, loss aversion, delay discounting, explorative behavior or cooperation may represent a significant advance in the definition of otherwise elusive aspects of human behavior. As mentioned above, many psychiatric and neurological disorders involve reward processing and decision-making, including common and socially relevant conditions such as addiction and personality disorders (Sharp et al., 2012). Research in this area has thus, besides the obvious theoretical interest, a large translational potential that is starting to be appreciated by the scientific community. Among the open issues are the development of training procedures to induce desirable changes in decision-making by stimulation of brain plasticity (Bavelier et al., 2012), the possibility of pharmacological interventions involving, for example, the dopamine system (Chowdhury et al., 2013), sexual hormones (Bos et al., 2010) and oxytocin (Declerck et al., 2010), as well as the growing interest in neurostimulation techniques such as Transcranial-Magnetic-Stimulation (TMS) and transcranial-Direct-Current-Stimulation (tDCS) (Miniussi and Ruzzoli, 2013; Sharp et al., 2012).

References

Adenzato, M., Cavallo, M. & Enrici, I. 2010. Theory Of Mind Ability In The Behavioural Variant Of Frontotemporal Dementia: An Analysis Of The Neural, Cognitive, And Social Levels. *Neuropsychologia*, 48**,** 2-12.

Barry, D. & Petry, N. M. 2008. Predictors Of Decision-Making On The Iowa Gambling Task: Independent Effects Of Lifetime History Of Substance Use Disorders And Performance On The Trail Making Test. *Brain And Cognition*, 66**,** 243-252.

Barto, A. G., Sutton, R.S., & Watkins, C. 1990a. Sequential Decision Problems And Neural Networks *In:* Touretzky, D. S. (Ed.) *Advances In Neural Information Processing Systems 2*\.

Barto, A. G., Sutton, R.S., Watkins, C.J.C.H. 1990b. Learning And Sequential Decision Making. *Learning And Computational Neuroscience: Foundations Of Adaptive Networks* Mit Press.

Bavelier, D., Green, C. S., Pouget, A. & Schrater, P. 2012. Brain Plasticity Through The Life Span: Learning To Learn And Action Video Games. *Annu Rev Neurosci*, 35**,** 391-416.

Bechara, A. 2004. The Role Of Emotion In Decision-Making: Evidence From Neurological Patients With Orbitofrontal Damage. *Brain Cogn*, 55**,** 30-40.

Bechara, A., Damasio, A. R., Damasio, H. & Anderson, S. W. 1994. Insensitivity To Future Consequences Following Damage To Human Prefrontal Cortex. *Cognition*, 50**,** 7-15.

Bechara, A., Tranel, D. & Damasio, H. 2000. Characterization Of The Decision-Making Deficit Of Patients With Ventromedial Prefrontal Cortex Lesions. *Brain*, 123 (Pt 11)**,** 2189-202.

Bechara, A., Tranel, D., Damasio, H. & Damasio, A. R. 1996. Failure To Respond Autonomically To Anticipated Future Outcomes Following Damage To Prefrontal Cortex. *Cereb Cortex*, 6**,** 215-25.

Behrens, T. E., Woolrich, M. W., Walton, M. E. & Rushworth, M. F. 2007. Learning The Value Of Information In An Uncertain World. *Nat Neurosci*, 10**,** 1214-21.

Belova, M. A., Paton, J. J., Morrison, S. E. & Salzman, C. D. 2007. Expectation Modulates Neural Responses To Pleasant And Aversive Stimuli In Primate Amygdala. *Neuron*, 55**,** 970-84.

Bos, P. A., Terburg, D. & Van Honk, J. 2010. Testosterone Decreases Trust In Socially Naive Humans. *Proc Natl Acad Sci U S A*, 107**,** 9991-5.

Camille, N., Coricelli, G., Sallet, J., Pradat-Diehl, P., Duhamel, J. R. & Sirigu, A. 2004. The Involvement Of The Orbitofrontal Cortex In The Experience Of Regret. *Science*, 304**,** 1167-70.

Canessa, N., Crespi, C., Motterlini, M., Baud-Bovy, G., Chierchia, G., Pantaleo, G., Tettamanti, M. & Cappa, S. F. 2013. The Functional And Structural Neural Basis Of Individual Differences In Loss Aversion. *J Neurosci*, 33**,** 14307-17.

Canessa, N., Motterlini, M., Alemanno, F., Perani, D. & Cappa, S. F. 2011. Learning From Other People's Experience: A Neuroimaging Study Of Decisional Interactive-Learning. *Neuroimage*, 55**,** 353-62.

Canessa, N., Motterlini, M., Di Dio, C., Perani, D., Scifo, P., Cappa, S. F. & Rizzolatti, G. 2009. Understanding Others' Regret: A Fmri Study. *Plos One*, 4**,** E7402.

Cerami, C. & Cappa, S. F. 2013. The Behavioral Variant Of Frontotemporal Dementia: Linking Neuropathology To Social Cognition. *Neurol Sci*, 34**,** 1267-74.

Cerami, C., Dodich, A., Canessa, N., Crespi, C., Marcone, A., Cortese, F., Chierchia, G., Scola, E., Falini, A. & Cappa, S. F. 2014. Neural Correlates Of Empathic Impairment In The Behavioral Variant Of Frontotemporal Dementia. *Alzheimers Dement*.

Cerami, C., Scarpini, E., Cappa, S. F. & Galimberti, D. 2012. Frontotemporal Lobar Degeneration: Current Knowledge And Future Challenges. *J Neurol*, 259**,** 2278-86.

Chowdhury, R., Guitart-Masip, M., Lambert, C., Dayan, P., Huys, Q., Duzel, E. & Dolan, R. J. 2013. Dopamine Restores Reward Prediction Errors In Old Age. *Nat Neurosci*, 16**,** 648-53.

Cloninger, C. R. 1994. *The Temperament And Character Inventory (Tci): A Guide To Its Development And Use*, St. Louis, Mo., Center For Psychobiology Of Personality, Washington University.

Coricelli, G., Critchley, H. D., Joffily, M., O'doherty, J. P., Sirigu, A. & Dolan, R. J. 2005. Regret And Its Avoidance: A Neuroimaging Study Of Choice Behavior. *Nat Neurosci*, 8**,** 1255-62.

Coricelli, G., Dolan, R. J. & Sirigu, A. 2007. Brain, Emotion And Decision Making: The Paradigmatic Example Of Regret. *Trends Cogn Sci*, 11**,** 258-65.

Croxson, P. L., Walton, M. E., O'reilly, J. X., Behrens, T. E. & Rushworth, M. F. 2009. Effort-Based Cost-Benefit Valuation And The Human Brain. *J Neurosci*, 29**,** 4531-41.

Damasio, A. R. 1996. The Somatic Marker Hypothesis And The Possible Functions Of The Prefrontal Cortex. *Philos Trans R Soc Lond B Biol Sci*, 351**,** 1413-20.

Damasio, H., Grabowski, T., Frank, R., Galaburda, A. M. & Damasio, A. R. 1994. The Return Of Phineas Gage: Clues About The Brain From The Skull Of A Famous Patient. *Science*, 264**,** 1102-5.

Daw, N. D. & Doya, K. 2006. The Computational Neurobiology Of Learning And Reward. *Curr Opin Neurobiol*, 16**,** 199-204.

Dayan, P. & Niv, Y. 2008. Reinforcement Learning: The Good, The Bad And The Ugly. *Curr Opin Neurobiol*, 18**,** 185-96.

De Martino, B., Camerer, C. F. & Adolphs, R. 2010. Amygdala Damage Eliminates Monetary Loss Aversion. *Proc Natl Acad Sci U S A*, 107**,** 3788-92.

Declerck, C. H., Boone, C. & Kiyonari, T. 2010. Oxytocin And Cooperation Under Conditions Of Uncertainty: The Modulating Role Of Incentives And Social Information. *Horm Behav*, 57**,** 368-74.

Delazer, M., Sinz, H., Zamarian, L., Stockner, H., Seppi, K., Wenning, G., Benke, T. & Poewe, W. 2009. Decision Making Under Risk And Under Ambiguity In Parkinson's Disease. *Neuropsychologia*, 47**,** 1901-1908.

Doya, K. 2008. Modulators Of Decision Making. *Nat Neurosci*, 11**,** 410-6.

Gallese, V., Keysers, C. & Rizzolatti, G. 2004. A Unifying View Of The Basis Of Social Cognition. *Trends Cogn Sci*, 8**,** 396-403.

Girotto, V., Ferrante, D., Pighin, S. & Gonzalez, M. 2007. Postdecisional Counterfactual Thinking By Actors And Readers. *Psychol Sci*, 18**,** 510-5.

Gleichgerrcht, E., Ibanez, A., Roca, M., Torralva, T. & Manes, F. 2010. Decision-Making Cognition In Neurodegenerative Diseases. *Nat Rev Neurol*, 6**,** 611-23.

Halliday, G., Bigio, E. H., Cairns, N. J., Neumann, M., Mackenzie, I. R. & Mann, D. M. 2012. Mechanisms Of Disease In Frontotemporal Lobar Degeneration: Gain Of Function Versus Loss Of Function Effects. *Acta Neuropathol*, 124**,** 373-82.

Harlow, J. M. 1848. Passage Of An Iron Bar Through The Head. *Boston Medical And Surgical Journal*, 39**,** 389-393.

Ibanez, A. & Manes, F. 2012. Contextual Social Cognition And The Behavioral Variant Of Frontotemporal Dementia. *Neurology*, 78**,** 1354-62.

Kahneman, D. & Miller, D. T. 1986. Norm Theory–Comparing Reality To Its Alternatives. *Psychological Review*, 93**,** 136-153.

Kraplin, A., Dshemuchadse, M., Behrendt, S., Scherbaum, S., Goschke, T. & Buhringer, G. 2014. Dysfunctional Decision-Making In Pathological Gambling: Pattern Specificity And The Role Of Impulsivity. *Psychiatry Research*, 215**,** 675-682.

Kuhnen, C. M., Samanez-Larkin, G. R. & Knutson, B. 2013. Serotonergic Genotypes, Neuroticism, And Financial Choices. *Plos One*, 8**,** E54632.

Kumfor, F. & Piguet, O. 2012. Disturbance Of Emotion Processing In Frontotemporal Dementia: A Synthesis Of Cognitive And Neuroimaging Findings. *Neuropsychol Rev*, 22**,** 280-97.

Lecourtier, L., Defrancesco, A. & Moghaddam, B. 2008. Differential Tonic Influence Of Lateral Habenula On Prefrontal Cortex And Nucleus Accumbens Dopamine Release. *Eur J Neurosci*, 27**,** 1755-62.

Ledoux, J. 2012. Rethinking The Emotional Brain. *Neuron*, 73**,** 653-76.

Lohrenz, T., Mccabe, K., Camerer, C. F. & Montague, P. R. 2007. Neural Signature Of Fictive Learning Signals In A Sequential Investment Task. *Proc Natl Acad Sci U S A*, 104**,** 9493-8.

Maia, T. V. 2009. Reinforcement Learning, Conditioning, And The Brain: Successes And Challenges. *Cogn Affect Behav Neurosci*, 9**,** 343-64.

Marchiori, D. & Warglien, M. 2008. Predicting Human Interactive Learning By Regret-Driven Neural Networks. *Science*, 319**,** 1111-3.

Matsumoto, M., Matsumoto, K., Abe, H. & Tanaka, K. 2007. Medial Prefrontal Cell Activity Signaling Prediction Errors Of Action Values. *Nat Neurosci*, 10**,** 647-56.

Mellers, B., Schwartz, A. & Ritov, I. 1999. Emotion-Based Choice. *Journal Of Experimental Psychology-General*, 128**,** 332-345.

Miniussi, C. & Ruzzoli, M. 2013. Transcranial Stimulation And Cognition. *Handb Clin Neurol*, 116**,** 739-50.

Montague, P. R., Dayan, P. & Sejnowski, T. J. 1996. A Framework For Mesencephalic Dopamine Systems Based On Predictive Hebbian Learning. *Journal Of Neuroscience*, 16**,** 1936-1947.

Montague, P. R., Dolan, R. J., Friston, K. J. & Dayan, P. 2012. Computational Psychiatry. *Trends Cogn Sci*, 16**,** 72-80.

Piguet, O., Hornberger, M., Mioshi, E. & Hodges, J. R. 2011. Behavioural-Variant Frontotemporal Dementia: Diagnosis, Clinical Staging, And Management. *Lancet Neurol*, 10**,** 162-72.

Rascovsky, K., Hodges, J. R., Knopman, D., Mendez, M. F., Kramer, J. H., Neuhaus, J., Van Swieten, J. C., Seelaar, H., Dopper, E. G., Onyike, C. U., Hillis, A. E., Josephs, K. A., Boeve, B. F., Kertesz, A., Seeley, W. W., Rankin, K. P., Johnson, J. K., Gorno-Tempini, M. L., Rosen, H., Prioleau-Latham, C. E., Lee, A., Kipps, C. M., Lillo, P., Piguet, O., Rohrer, J. D., Rossor, M. N., Warren, J. D., Fox, N. C., Galasko, D., Salmon, D. P., Black, S. E., Mesulam, M., Weintraub, S., Dickerson, B. C., Diehl-Schmid, J., Pasquier, F., Deramecourt, V., Lebert, F., Pijnenburg, Y., Chow, T. W., Manes, F., Grafman, J., Cappa, S. F., Freedman, M., Grossman, M. & Miller, B. L. 2011. Sensitivity Of Revised Diagnostic Criteria For The Behavioural Variant Of Frontotemporal Dementia. *Brain*, 134**,** 2456-77.

Reynolds, S. M. & Zahm, D. S. 2005. Specificity In The Projections Of Prefrontal And Insular Cortex To Ventral Striatopallidum And The Extended Amygdala. *J Neurosci*, 25**,** 11757-67.

Rilling, J. K. & Sanfey, A. G. 2011. The Neuroscience Of Social Decision-Making. *Annual Review Of Psychology*, 62**,** 23-48.

Rolls, E. 2005. *Emotion Explained*.

Rushworth, M. F. & Behrens, T. E. 2008. Choice, Uncertainty And Value In Prefrontal And Cingulate Cortex. *Nat Neurosci*, 11**,** 389-97.

Sanfey, A. G., Loewenstein, G., Mcclure, S. M. & Cohen, J. D. 2006. Neuroeconomics: Cross-Currents In Research On Decision-Making. *Trends Cogn Sci*, 10**,** 108-16.

Schultz, B. G., Stevens, C. J., Keller, P. E. & Tillmann, B. 2013. The Implicit Learning Of Metrical And Nonmetrical Temporal Patterns. *Q J Exp Psychol (Hove)*, 66**,** 360-80.

Schultz, W. 2007. Behavioral Dopamine Signals. *Trends Neurosci*, 30**,** 203-10.

Schultz, W., Dayan, P. & Montague, P. R. 1997. A Neural Substrate Of Prediction And Reward. *Science*, 275**,** 1593-9.

Seeley, W. W., Crawford, R. K., Zhou, J., Miller, B. L. & Greicius, M. D. 2009. Neurodegenerative Diseases Target Large-Scale Human Brain Networks. *Neuron*, 62**,** 42-52.

Sharp, C., Monterosso, J. & Montague, P. R. 2012. Neuroeconomics: A Bridge For Translational Research. *Biol Psychiatry*, 72**,** 87-92.

Sutton, R. S. & Barto, A. G. 1998. *Reinforcement Learning: An Introduction* Cambridge: Mit Press.

Thorndike, E. 1927. The Law Effect. The American Journal Of Psychology 212-222.

Tom, S. M., Fox, C. R., Trepel, C. & Poldrack, R. A. 2007. The Neural Basis Of Loss Aversion In Decision-Making Under Risk. *Science*, 315**,** 515-8.

Torralva, T., Roca, M., Gleichgerrcht, E., Bekinschtein, T. & Manes, F. 2009. A Neuropsychological Battery To Detect Specific Executive And Social Cognitive Impairments In Early Frontotemporal Dementia. *Brain*, 132**,** 1299-309.

Valentin, V. V., Dickinson, A. & O'doherty, J. P. 2007. Determining The Neural Substrates Of Goal-Directed Learning In The Human Brain. *Journal Of Neuroscience*, 27**,** 4019-4026.

Van Harreveld, F., Van Der Pligt, J. & Nordgren, L. 2008. The Relativity Of Bad Decisions: Social Comparison As A Means To Alleviate Regret. *Br J Soc Psychol*, 47**,** 105-17.

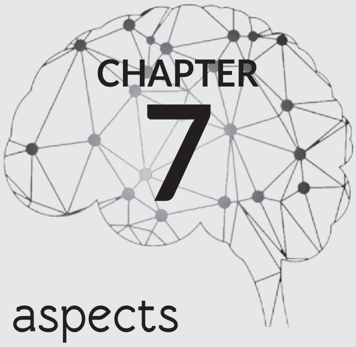
Whitwell, J. L., Weigand, S. D., Boeve, B. F., Senjem, M. L., Gunter, J. L., Dejesus-Hernandez, M., Rutherford, N. J., Baker, M., Knopman, D. S., Wszolek, Z. K., Parisi, J. E., Dickson, D. W., Petersen, R. C., Rademakers, R., Jack, C. R., Jr. & Josephs, K. A. 2012. Neuroimaging Signatures Of Frontotemporal Dementia Genetics: C9orf72, Tau, Progranulin And Sporadics. *Brain*, 135**,** 794-806.

Section

2

Historical-Cultural Neuropsychology

Yulia Solovieva, Ph. D.
Luis Quintanar, Ph. D.
Academid editors



CHAPTER 7

Theoretical and historical aspects of developmental neuropsychology[*]

Janna Glozman

Natural, Theoretical and Practical Premises of the Creation of Developmental Neuropsychology

The theoretical basis of developmental neuropsychology as well as of general neuropsychology comprises three principles, proposed by L.S. Vygotsky and A.R. Luria: the principle of social genesis of higher mental functions (HMF); the principle of system organization of HMF; and the principle of dynamic organization and localization of HMF.

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[*] This chapter is an extension of the chapter of the same author *The history of developmental neuropsychology*, published in the book Glozman, J.M. (2013). Developmental Neuropsychology. New York, Routledge.

In 1922 neuropsychologist Alexander R. Luria wrote his first large (more than 200 pages) book, “Principles of a real psychology”, that was not formally published at the time and the manuscript remained in Luria’s archives until 2003. It is really fantastic that a 20 year old psychologist, recently graduated from the University, formulated in this book **the main principles of a psychological study:**

- To deal with the concrete personality, the living human being, as a biological, social and psychological unity.
- To study individual regularities, uniquely determined sequences, that is, to combine a description of individual, unique processes with the study of lawful, regular processes.
- To study an individual human mind as a whole and particular mental phenomena as functions, which are elements of this whole, that develop in a specific human personality, with the possibility of change through the transformation of social conditions.
- To study individual values of the examined psychological phenomena for the life of the actual personality.

Together with L.S. Vygotsky, Luria developed and followed these principles during his life, and the principles have since been adopted by his students and disciples, and form the basis of the cultural-historical approach to psychology – which is the methodological foundation of Russian / Soviet neuropsychology.

So, the above mentioned principles derive from the *cultural-historical* approach to analysis of development of HMF and of abnormalities in HMF, that is from orientation not to the disease or the defect but to the development, looking at the history of culture for the reasons behind mental phenomena and for the means of their remediation. L.S. Vygotsky proved that a defect interferes with a child’s appropriation of the culture, but cultural means help the child to overcome the defect. Hence, the cultural-historical approach became and remains a methodological basis for remedial education.

The creation by Vygotsky and Luria of the systematic cultural-historical approach in the 1920s and 1930s should be considered the first premise of developmental neuropsychology. One of the first studies based upon this approach is a comparative exploration of mental functions in urban, rural and homeless child. The study proved an influence of social and cultural factors on child cognitive development (Luria, 1928, 1930).

Vygotsky and Luria developed the idea that cognitive processes descend from complex *interaction and interdependence between biological factors* (the individual mind), which is part of physical nature, *and cultural factors*, which appear in the development of a human being. This *social-historical approach in neuropsychology* looks for the origins of human conscience and mental activity not inside the brain, nor in the mechanisms of nervous processes, but in the context of human social life.

Consequently, a "neuropsychological assessment must not be limited to a simple statement that one or another form of mental activity is affected. The assessment must be a *qualitative (structural) analysis* of the symptom under study, which specifies the observed defect and the factors causing it" (Luria, 1969, p. 306). With this, "The structure of the organism presupposes not an accidental mosaic, but a complex organization of separate systems. This organization is expressed paramountly in a functional correlation of these systems… they unite as very definite parts into an integrated functional structure". (Luria, 1932, pp. 6-7).

In all his works L.S. Vygotsky stressed the social nature of functions formation and the *role of mediation –a use of psychological tools (social means)* in the genesis of HMF (Vygotsky's principle of "doubling experience").

To understand the theory of *system structure* of HMF in humans the following factors are the most important: variability of interfunctional relations and connections; formation of complex dynamic systems, integrating many elementary functions; generalized reflection of environment by conscience and mediated mental functioning.

Luria's *principle of dynamic ontogenic localization* of HMF refers to variable levels and types of brain structures and of their functional integration while acknowledging the same cognitive activity by children of different ages.

An analysis of Russian developmental neuropsychology should not forget *psychogenic studies* in the 1920s at the Eugenics Office of Academy of Sciences in St Petersburg, created in 1921 году, and in the Laboratory of Heredity and Human Constitution at the Moscow Medico-biological Institute, created in 1928. The former used the genealogical method, the latter used a more informative (as was proved later) twins method (Ravich-Sherbo & Sygal, 2003), and compared the input of genetic and environmental factors in individual variability of child psychological and neurophysiologic features.

A.R. Luria started his work at the Medico-biological Institute in 1932- the year that the paper by M.S. Lebedinsky "The problem of heredity in psychology and twins method" was already published. The paper analyzed the method as well as the results of assessment of different mental features (reasoning, mediation capacities, temper) in twins at different ages. It revealed the greater genetic similarity of most features in monozygotic twins as compared with dizygotic and also a dependence of similarity on the age of twins and the function assessed. From 1932 till 1937 (when the Medico-biological Institute was closed and the genetics was prohibited) Luria directed studies of genotype–environment relations through cultural – historical theory (Figure 7.1). The group included M.S. Lebedinsky, A.N. Mironova, N.G. Morozova and F.Ya. Yudovich. They were the first in Russia to use "twins model" in experimental study of genetic mechanisms of mentality. The difference from similar studies in Western countries consisted in the use of special tests addressed predominantly to "natural" (genetic) or cultural (environmental) factors instead of use of standardized batteries measuring IQ. For instance, in nonverbal tasks, which better reveal "natural" factors the results were more similar in monozygotic twins than in dizygotic ones.

Figure 7.1. Some of the twins, that participated in the research work of the psychological laboratory of the Medico-biological Institute.

Source: Luria's archive.

Their program for study of genotype/environment relations, based upon Vygotsky-Luria's theory of mental development, revealed changes in the relative input of heredity and environment due to modifications in mental functioning in response to different educative procedures and to the role of speech acquisition in mental development (M. Lebedinsky, 1932; Mironova and Kolbanovsky, 1934; Luria, 1936, 1948, 1963, 2002; Ravich-Sherbo and Sygal, 2003). A study of 130 pairs of twins aged 6-11 years revealed, for instance, that the elementary memory is determined by genotype in all age groups, while mediated remembering using pictograms was dependent on genotype only in preschoolers. To generalize, the influence of «natural» factors on child cognitive functions decreases with age but the influence of «cultural» factors increases. «This evidence indicates that during ontogenic development not only the psychological structure of mental processes but also their internal nature dramatically changes» (Luria, Symernitskaya, Tybulevich, 1973, p. 112).

The research work in the Medico-biological Institute permitted Luria to state the main ideas of developmental neuropsychology: "mental development in childhood is first of all a modification in the child's forms of activity, complication of the structure of this activity and enrichment of mental processes, developing inside this activity" (Luria, 1948, p. 34). In the process of development a mental function "does not rest the same; ... it changes significantly its own structure, it solves the same task using different operations" (Luria, 2002, p. 17). With this "the genotype influences to a great degree the speed of appropriation of these "cultural" forms of mental activity...» (Ibid, p. 18).

The psychogenetic studies proved first the formative effect of speech and language on mental processes and then these studies revealed, that twins form "a group of risk" for mental development. For instance Luria together with Yudovich assessed a pair of 5 years old twins with a lower than normal level of speech and general mental development. The authors supposed that the cause was that "twins situation", did not stimulate verbal activity, replacing it with more primitive forms of communication. The researchers then placed each twin in a different group of the kindergarten, so that an objective need to acquire speech as a means of communication was created (Luria & Yudovich, 1959). Also special lessons to develop speech were given to one of the pair. In 3 months verbal abilities of children (both vocabulary and grammar) changed significantly and the general mental development improved, to the greater degree in the child, who had speech therapy. So, when objective need for verbal communication was created not only did both children acquire new verbal means for communication, but significant modifications in the structure of their conscious activity, based n verbal speech were provoked.

The psychogenetic studies by Luria formed also the basis of neuropsychological remediation, namely the principles of developing games with small children. In a pair of monozygotic (genetically similar) 6 years old twins one was toughed the construction activity with cubes using a "step by step method" (i.e. copying of teacher's actions), the second child was given the "model" method, whereby he saw only the general shape of the construction and had to select himself the elements fitting this shape. The second version of the game, aimed at developing visual reasoning and constructive analysis and synthesis abilities, was much more efficient, and the resulting development included some other forms of creative activity and was stable, being evident 1,5 years after the end of the programme (Luria, 1948).

In Western countries, developmental (also called pediatric) neuropsychology became a major area of research and practice during the second half of the 20th century. “It was in 1960th that the clinical picture of the “clumsy child” (renamed *developmental dysgnosia and dyspraxia)* was described, specific reading disability (renamed *developmental dyslexia)* was investigated from a neuropsychological standpoint, and the concept of *minimal brain dysfunction* (MBD) was formulated to account for these and a myriad of other behavioral disabilities in children. Since this time pediatric neuropsychology has become a flourishing area of inquiry and practice, generating new knowledge and deeper understanding, with the result that today the evaluation and management of children with documented or suspected brain dysfunction by the well-informed neuropsychologists are incomparably more insightful and effective than was the case 20 years ago” (Benton, 2000, p. XV, emphasis in original).

To conclude, I would like to emphasize, that the origin of developmental neuropsychology, as well as the whole development of Russian psychology beginning with Luria’s school is due primarily to the main achievement in the history of psychology – the creation of cultural-historical psychology, which has influenced to a great extent clinical neuropsychology all over the world.

Trends in progress of developmental neuropsychology

The development of Russian neuropsychology by students who have been trained directly by Luria or indirectly by others who were influenced by his ideas, before and after his death in 1977, coincides with the general tendency all over the world to replace the “*static neuropsychology”* (relating subject’s–both adult or child- behaviour to definite brain areas) with *“dynamic neuropsychology”* (analyzing the dynamics of brain / mental functioning interaction through the social conditions of subject’s life that is viewing childhood disorders within a developmental context) (Rourke, 1982, 2000; Tupper, Cicerone, 1991; Glozman, 2002, 2010). The following model represents this evolution in neuropsychology through three overlapping and coexisting phases (Figure.7.2).

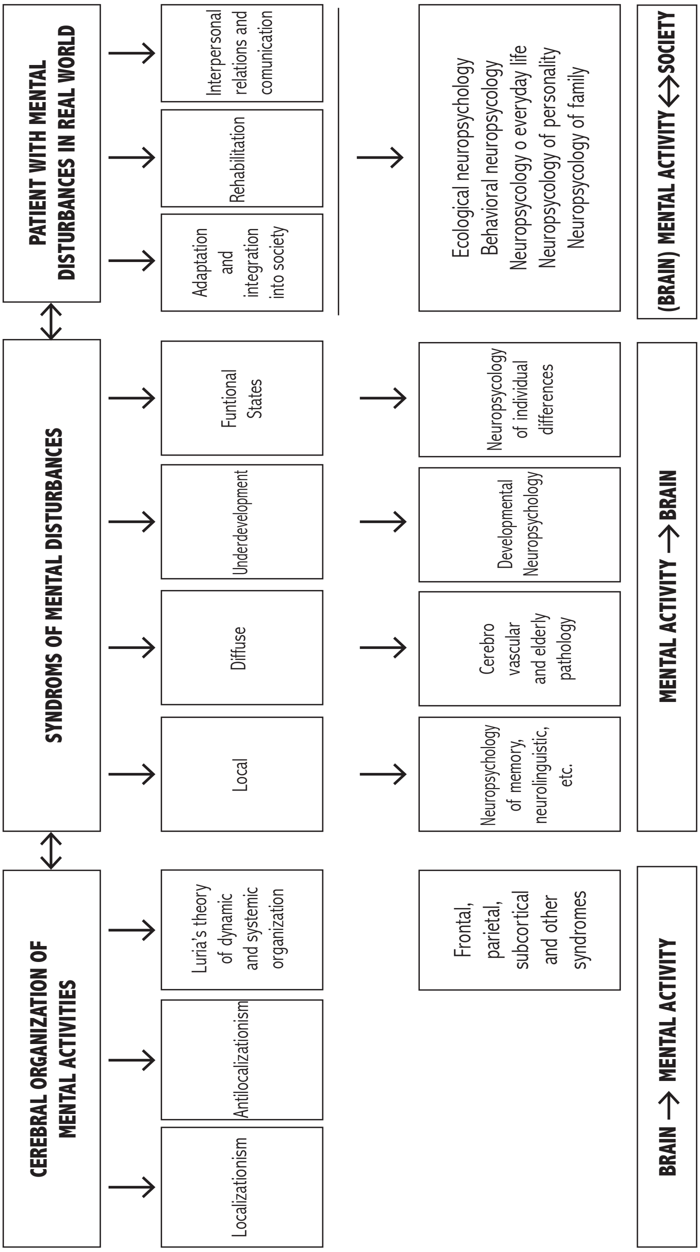


Figure 7.2. Model of development in neuropsychology.

Source: Prepare by author.

In the *first phase*, the emphasis for neuropsychologists was on the brain and its relationship to different behaviors. The neuropsychology of this period was considered by Luria, as well as by occidental neuropsychologists, to be a “field of practical medicine” (Luria, 1973, p. 17). The main and most valuable attainment of this phase is a revision by Luria of concepts of localizationism and antilocalizationism and the creation of the theory of the dynamic and systematic cerebral organization of mental processes. This progress resulted in the functional analysis of different brain systems and description of frontal, parietal, temporal, and other syndromes. The recent development of this approach follows two main lines:

1. A study of functions of the right hemisphere and interhemispheric interactions for different types of memory, perception, and reasoning for compensatory capabilities (Simernitskaya, 1978; Korsakova & Mikadze, 1982; Vasserman & Lassan, 1989; Krotkova, 1998; Homskaya & Batova, 1998; Meerson & Dobrovolskaya, 1998; Moskovich, 2004) and

2. Research in subcortical brain pathology, especially cognitive disturbances in patients with Parkinson’s disease — a specific combination of “natural” brain alterations appearing with age, necessitating a change in strategies, voluntary selection, and use of new forms of mediating mental activity for specific impairments caused by the disease (Korsakova & Moskovichyute, 1985; Korsakova, 1998; Glozman, Levin, & Tupper, 2004).

In the *second phase* of neuropsychology’s development, the structure of mental activity has been the focus of attention and secondarily, its localization in the brain. This phase gave birth to the understanding of different syndromes of mental disturbances: local syndromes, such as the neuropsychology of memory (Luria, 1976a; Korsakova & Mikadze, 1982), neurolinguistics (Luria,1976b, Akhutina, 1981; Akhutina & Glozman, 1995) and so on; diffuse syndromes after cerebrovascular pathology (Moskovich, 2004); syndromes of underdevelopment or atypical development, with heterogeneity in the maturation of brain structures and connections, resulting in learning disabilities (Mikadze & Korsakova, 1994; Akhutina, 1998, 2004; Akhutina, Pylaeva, 2008; Polyakov, 2004; Mikadze, 2008; Glozman, 2009); and finally, mental dysfunctions in normal subjects in specific functional states or with some individual differences or accentuations in cognitive performances. The latter aspect gave birth to the neuropsychology of individual differences, i.e., the application of neuropsychological concepts and methods to the assessment of healthy subjects (Homskaya et al., 1997).

The third phase of development in neuropsychology focuses on the interrelationship between a patient and his or her environment and integrates neuropsychological characteristics, the psychology of health, and real life data. The main role of the neuropsychological assessment is not so much diagnostic but prognostic and to provided corrective suggestions. Neuropsychological assessment in this approach should emphasize the subject's strengths, which are important in one's correction (rehabilitation) program and should help predict their ultimate integration into society. This principle was first realized in aphasiology as the so-called "socio-psychological aspect of rehabilitation" (Tsvetkova et al., 1979; Tsvetkova, 1985) and, subsequently, in studies of the interrelationships between communication disorders and personality in different nosological groups (Glozman, 2004) and in developmental neuropsychology (Mikadze, 2008; Akhutina, Pylaeva, 2008; Glozman, 2010).

Such an approach surmounts the "biologizing" tendencies of the psychology of 19th – 20th centuries and it is of value given that «a division of "natural sciences" and "mental sciences" into different scientific paradigms risks bisecting psychology into two different ones, lacking common subject and methods of research" (Akhutina, 2004, p. 20). It is very close to the definition of the subject of "real psychology" by Luria. In his first book, written in 1922, A.R. Luria sets the task "to study a human like a biological, social and psychological unity" (Luria, 2003, p. 296). Analogously, Lev Vygotsky (1925) represented the psychology of the future like a study of "a biosocial synthesis"–a union of natural and human sciences.

It is not surprising than the main causes of delayed development (immaturity) of child functional mental systems is according to Korsakova et al. (2001) an unfavorable environment during this child formative years (complicated intrafamily relations, bad conditions of everyday living, harmful ecological factors, lack of socialization and of inclusion in educative and upbringing programmes).

This explains the predominant importance of *functional diagnostics* (as distinct from *topical diagnostics* of immature or impaired brain structures) of defects preventing the child from acquiring knowledge and abilities, adapting to society (school or family), and developing to a greater degree his own potentials and personality.

The cultural-historical approach in neuropsychological rehabilitation of brain damaged patients and in remediation of learning disabled children consists in further development of the theory of *mediation.* L.S. Vygotsky and A.R. Luria proved that mediation is a natural process in cognitive development in children and of the psychological compensation of cognitive and physical deterioration both in children and adults. During the 1930's Luria and Vygotsky attempted to help Parkinsonian patients in the neurological hospital of Moscow University. The gait of Parkinsonian patients is often severely impaired (reduced and slow steps, difficulties in turning), but it is rather easy for the patients to go up and downstairs. Luria and Vygotsky explained this observation by the fact that the last process is a visually mediated and voluntary one. The scientists then put pieces of paper on the floor and asked patients to step over these pieces of paper. The patients could walk fluently! In essence, L.S. Vygotsky and A.R. Luria created a program which compensated for the subcortical motor disturbances in Parkinson's disease through a cortical (visual) mediation of movements (Luria, 1948, Vygotsky, 1978). The program consisted of 2 main stages:

1. A training stage, when the patient was trained to use cues with a gradual decrease in external cueing.

2. An internalization stage, when the external cues are gradually replaced by their internal images, that provide the internal means for the patient to control their own motor behavior.

My colleagues and I have used this idea of mediation as a means for transformation of functional systems in an integrated program of the rehabilitation of different mental functions: memory, attention, writing, vocabulary, counting, problem solving, space orientation, movements and the emotional sphere in parkinsonian patients and in learning disabled children (Glozman, 1999a; 2009).

We used the following *methods of mediation*:

VISUAL:
- External marks for walking and space orientation;
- Frames for writing;
- Externalized numbers or signs for counting and attention.

SEMANTIC:
- Logical analysis in counting and problem solving;
- Actualization of semantic relationships for word memorization;
- Actualization of image and word relationships for vocabulary and memorization.

EMOTIONAL:
- Computer games for space orientation and vocabulary;
- Competitive situations;
- Biological feedback.

For instance, external means (toys, indicative of the necessary position in space, a touch on the hand saying “Stop and think about”) help the child with learning problems to form a system of orientation to the activity and development of the ability to self-control one’s movements and actions (Figure 7.3 and 7.4). Frames for writing are very efficient for compensation of micrographia.

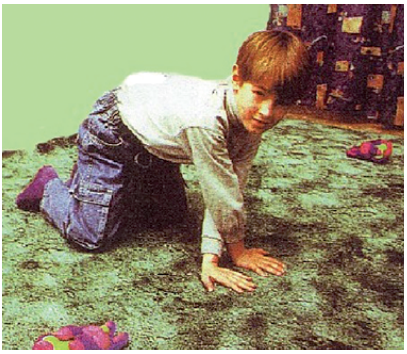


Figure 7.3. Mediated remediation of space orientation in movements

Source: Glozman, 2009.

Figure 7.4. Mediated remediation of self-control for an ADHD child

Source: Glozman, 2009.

In all these methods the resulting effects may concern cognitive and motor abilities, the linguistic formulation of knowledge, permanence in memory, the transfer to other everyday situations, links to other fields and situations, and the motivation and attitudinal disposition of learners.

The resulting effect depends also upon teaching modalities (classical-expositive, participative-guided and peer-collaborative), optimal individualized choice of mediational means, and from interhemispheric interactions. Thus, interfunctional mediation (semantic/visual) is in most subjects more efficient than intrafunctional mediation, with some limitations for patients with specific features of interhemispheric interaction.

Mediation in teams or *co-mediation* may present different characteristics and challenges compared to mediations conducted by a single individual. For instance, a dyadic coping mediates the effectiveness of remediation for learning disabled children as well as group rehabilitation is very efficient for speech restoration in aphasic patients.

In addition, as already stated, Luria's approach presupposes a qualitative analysis of the symptom under study, based upon an understanding of the factors underlying complex psychological activities.

The *quantitative evaluation* of disturbances is of primary value for determining the dynamics of change in cognitive functioning during neuropsychological follow-up, and for measuring the outcome of rehabilitative or remedial procedures. The scoring systems worked out by Luria's disciples take into account beside normative reference, of the qualification of the symptoms (primary or secondary defects), the conditions seen with correction of mistakes and the alternatives used to organize the successful fulfillment of the task with or without external assistance (Glozman, 1999b, 2006).

Conclusion

The actual period of progress in neuropsychology (both of adults and of children) is characterized by extensive development all over the world. The neuropsychologists is assessing now not only patients with organic focal brain lesions but also patients with endogenous, genetic and functional disturbances, with individual variations of normal mental functioning, consequences of specific social situations of development (such as social deprivation or bilingualism) and others (Glozman, 2013). This increase in the types of subjects sent for neuropsychological assessment is explained first by the fact, that specialists in different branches of psychology realized the possibilities of Lurian neuropsychological assessment for differential and functional diagnostics of a great number of abnormal or untypical developmental conditions. Secondly modern methods of neuroimaging reveal organic cerebral pathology in patients with endogenous and functional disorders, like stuttering, schizophrenia or autism. Thirdly, the sphere of neurocognitive disorders increases in conjunction with understanding of systemic troubles, including specific primary, secondary and tertiary symptoms (due to functional reorganization during adaptation to disease or resulting from a particular social situation of development. The fourth reason is the common understanding of the role of dysontogenesis for neurocognitive disorders resulting in greater significance of neuropsychological assessment of different kinds of abnormal or untypical development.

Another feature of contemporary progress in developmental neuropsychology (as well as other branches of neuropsychology) is a tendency to

> (...) enlargement of the sphere of application of neuropsychology outside the clinical, pathological cases of troubles in human mental activity to a study of mentality of healthy subjects. First of all it regards the cases of deviations (for different reasons) in mental and cerebral functioning interfering with subject adjustment in various living situations (Korsakova et al., 2001, p. 7).

The task in the progress of developmental neuropsychology consists is a need to pass from a phenomenological description of abnormal child development to the study of the interactions between brain, genetics, sociology and personality in formation of different kinds of abnormal or untypical development. In other words, developmental neuropsychology should be now based on an integrative multidisciplinary approach, founded by E. Lenneberg (1967).

Due to these tendencies in the progress of developmental neuropsychology it becomes a base for creation of the service of applied psychology for education (Asmolov, 1998).

References

Akhutina TV (1981): Lexical organization upon aphasiological data. In: AA Zalevskaya, ed., *Psycholinguistic Studies of Vocabulary and Phonetics* (pp. 3–12). Kalinin, Kalinin Univ. Press, In Russian.

Akhutina TV (1998): Neuropsychology of individual differences in children as a basis for the application of neuropsychological methods at school. In Homskaya ED & Akhutina TV, eds., *First International Luria Memorial Conference Proceedings* (pp. 201–208). Moscow, Russian Psychological Association Press, In Russian

Akhutina, T.V. (2004) Cultural – historical and natural–scientific foundations of neuropsychology. *Psychological Journal*, *25*(4), 20-27. (In Russian).

Asmolov, A.G. (1998). The world of A.R. Luria and cultural–historical psychology. / Proceedings of the First International Luria Memorial Conference . Ed. by E.D. Khomskaya and T.V. Akhutina.–Moscow: Russian Psychological Association Press, p. 5-7. (In Russian).

Akhutina TV, Glozman J.M. (1995): The neurolinguistic study of semantics. *Aphasiology 9*(2):143–152.

Akhutina TV, Pylaeva NM (2008): *Learning problems overcoming. Neuropsychological approach.* Moscow, Piter.

Benton, A. (2000). Foreword / In: K. Yeates, M. Ris, H. Taylor (Eds). Pediatric neuropsychology. Research, Theory and Practice. New York – London: The Guilford Press, p. XV.

Glozman JM (1999a): Russian Neuropsychology after Luria. *Neuropsychology Review 1*: 33–44.

Glozman JM (1999b): Quantitative and qualitative integration of Lurian procedures. *Neuropsychology Review 9*(1): 23–32.

Glozman JM (2000): Neuropsychology in the former USSR. In: Craighead W & Nemeroff Ch, eds., *The Corsini Encyclopedia of Psychology and Behavioral Science*, *V*. 4 (pp. 1730–1733) New York, John Wiley & Sons.

Glozman, J.M. (2002). The cultural-historical approach as a basis of the neuropsychology of the XXI century. *// Voprosy psikhologii*, No. 4, 62-68. (In Russian)

J.Glozman (2006) A Avaliação Quantitativa dos Dados da Investigação Neuropsicológica. São Paulo: Edição I.P.A.F.

Glozman, J.M. (2010). On the fundamental principles in the contemporary development of Russian neuropsychology / Yu.P. Zinchenko, V.P. Petrenko (Eds.) Psychology in Russia. Scientific yearbook, v. 3, p. 433-451

Glozman J.M. (2013). Developmental neuropsychology. London – New York: Psychology Press – Taylor and Francis group.

Homskaya ED & Batova NY. (1998): *Brain and Emotions*. Moscow, Russian Pedagogical Agency Press. In Russian.

Homskaya ED, Efimova IV, Budyka EV, Enikolopova EV (1997): *Neuropsychology of Individual Differences*. Moscow, Russian Pedagogical Agency Press. In Russian.

Korsakova NK (1998): Neuropsychogerontology: Development of A.R. Luria's school of ideas. In: Homskaya ED & Akhutina TV, eds., *First International Luria Memorial Conference* Pproceedings (pp. 249–254). Moscow, Russian Psychological Association Press. In Russian.

Korsakova NK & Mikadze YuV (1982): Neuropsychological studies of memory: Results and perspectives. In Homskaya ED, Tsvetkova LS, & BV Zeigarnik, eds., *A.R. Luria and Modern* Psychology (pp. 101–110). Moscow, Moscow University Press. In Russian.

Korsakova, N.K.; Mikadze, Yu.V.; Balashova, E.Yu. (2001). Unsuccessful children: neuropsychological assessment of learning difficulties.– Moscow: Russian Psychological Agency. (In Russian).

Korsakova NK & Moskovichyute LI (1985): *Subcortical Structures and Mental Processes*. Moscow, Moscow Univ. Press. In Russian.

Krotkova OA (1998): Interhemispheric interaction and rehabilitation processes after local brain damages. In: E.D. Homskaya & T.V. Akhutina (Eds.). *First international Luria memorial conference proceedings* (pp. 126–131). Moscow: Russian Psychological Association Press, In Russian.

Lebedinsky, M.S. (1932). Problem of heredity in psychology and twins method. // Psychology, № 1-2, p. 163-204. (In Russian).

Lenneberg, E. (1967). Biological foundations of language. New York.

Luria, A.R. (1928). The problem of the cultural behavior of the child. // Journal of Genetic Psychology, 35(3), 493-506.

Luria, A.R. (1930). Speech and intelligence of urban, rural and homeless child. – Moscow Leningrad: Gosizdat (In Russian).

Luria AR (1932): *The Nature of Human Conflicts*. New York, Liveright.

Luria, A.R. (1936). The development of mental functions in twins. *Character and Personality*, *5*, 35-47.

Luria, A.R. (1948). Development of constructive activity in preschoolers. / A.N. Leontiev, A.V. Zaporozhets (Eds.) Psychology of preschoolers./ Bulletin of Russian Pedagogical Academy, p. 34-64. (In Russian).

Luria, A.R. (Ed.). (1963). The mentally retarded child: Essays based on a study of the peculiarities of the higher nervous functioning of child-oligophrenics.–New York: Macmillan/Pergamon.

Luria, AR (1969): *Higher Cortical Functions in Man* (2nd edition). Moscow, Moscow University Press. In Russian. (English translation, Basic Books, 1980).

Luria AR (1973): *The Working Brain. An Introduction to Neuropsychology*. London, Penguin Books.

Luria, AR (1976a): *The Neuropsychology of Memory*. Washington, Winston.

Luria, AR (1976b): *Basic Problems of Neurolinguistics*. The Hague, Mouton.

Luria, A.R. (2002).On nature of mental functions and its variations through genetic analysis. // Voprocy psykhologii, № 4, p. 4- 18. (In Russian).

Luria, A.R. (2003). Principles of real psychology. On some tendencies in contemporary psychology. / Glozman, J.M., Leontiev D.A., Radkovskaya E.G. (Eds.) A.R. Luria Psychological tribute. Selected papers in general psychology.- Moscow: Smysl, p. 295-384. (In Russian).

Luria, A.R.; Symernitskaya, E.G.; Tybulevich, B. (1973). On changes in cerebral organization of mental processes during their functional development / A.N. Leontiev, A.R. Luria, E.D. Khomskaya (Eds.) Psychological studies. Issue 4,–Moscow Univ. Press.- p. 111-119. (In Russian).

Luria, A.R. & Yudovich, F.I. (1959). Speech and the development of mental processes in the child–London: Staples Press.

Meerson YaA & Dobrovolskaya NV (1998): Disorders in perception of absolute and relative objects localization in spatial depth (depth agnosia) after focal damage of the right or left cerebral hemisphere. In Homskaya ED & Akhutina TV, eds., *First International Luria Memorial Conference Proceedings*. Moscow, Russian Psychological Association Press. In Russian.

Mikadze YuV (2008): *Developmental neuropsychology*. Moscow: Piter. In Russian

Mikadze YuV & Korsakova NK (1994): *Neuropsychological Diagnosis and Correction of Primary School Children*. Moscow, Inteltex. In Russian.

Mironova, A.N. & Kolbanovsky V.N. (1934). Comparative study of combination abilities development. Experiences with monozygotic twins. / Papers of the Medico-biological Institute, v. 3,–p. 104-118. (In Russian).

Moskovich LI (2004): Cerebral hemisphere asymmetry on the cortical and subcortical levels. In: Akhutina TV, Glozman JM, Moskovich LI, Robbins D, eds., *A.R. Luria and Contemporary Psychology:Festschrift Celebrating the Centennial of the Birth of Luria* (pp. 11–13). New York, Nova Science.

Polyakov VM (2004): Neuropsychological screening of child population. In: Akhutina TV, Glozman JM, Moskovich LI, Robbins D. eds., *A.R. Luria and Contemporar y Psychology:*

Festschrift Celebrating the Centennial of the Birth of Luria (pp. 93–105). New York, Nova Science.

Ravich-Scherbo I.V. & Sigal N.L. (2003). Alexander Romanovich Luria and national psychogenetics. / A.R. Luria and psychology of 21 century. Proceedings of the 2nd International Conference devoted to 100 years from Luria birth / Ed. by T.V. Akhutina and J.M. Glozman – Moscow: Smysl, p. 324-328. (In Russian).

Rourke, B.P. (Ed.) (1985). Neuropsychology of learning disabilities.–NY.

Rourke B.P. (2000) Rerepresentation and future directions. / In: K. Yeates, M. Ris, H. Taylor (Eds). Pediatric neuropsychology. Research, Theory and Practice. New York – London: The Guilford Press, p.459-470.

Simernitskaya EG (1978): *Hemispheric Dominance*. Moscow, Moscow Univ. Press. In Russian.

Tsvetkova, LS (1985): *Neuropsychological Rehabilitation of Patients*. Moscow, Moscow Univ. Press. In Russian.

Tsvetkova, LS, Glozman, JM, Kalita, NG, Maximenko, MYu, & Tsyganok, AA (1979): *Socio- Psychological Aspect of Aphasics Rehabilitation*. Moscow, Moscow Univ. Press. In Russian.

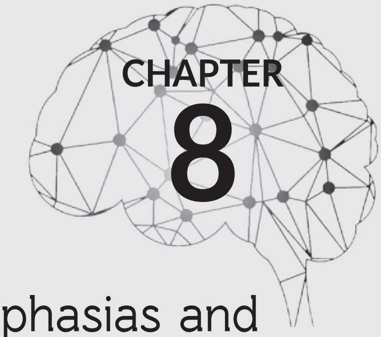
Tupper D., Cicerone K. (eds.) The neuropsychology of everyday life. Issues in development and rehabilitation. Preface. Boston: Kluwer Academic Publishers, 1991,–P. XIII–XIV.

Vasserman, LI & Lassan, LP (1989): Effect of lateralization of subcortical stereotaxic destruction on post surgery dynamics of mental functions in subjects with epilepsy. In: *Clinical Aspects of the Problem of Brain Functional Asymmetry*. Minsk, Belarus. In Russian.

Vygotsky, L.S. (1925) Introduction to the book by Lazursky A.F. General and experimental psychology. – Leningrad: Pedagogica (In Russian).

Vygotsky L. (1930): On psychological systems. In: Vygotsky L. *Collected papers*, v. 1, Moscow: Pedagogika, 1982, p. 109-132. In Russian.

Vygotsky L.S. (1978) *Mind in Society. The development of higher psychological processes.* Cambridge: Harvard Univ. Press.



CHAPTER 8

Luria's classification of aphasias and syndrome analysis principle

Tatiana Akhutina

Introduction

Luria's classification of aphasias was not only empiric task but was also the result of deep theoretical work. First of all A.R. Luria proceeded from the understanding of higher mental functions (HMF) elaborated by L.S. Vygotsky, in accordance with it they are "social in their origin, systemic in their structure, dynamic in their development" (Luria, 1965, p. 390). Vygotsky and Luria elaborated the main principles of formation, functioning and dissolution of HMF. These are the principles of social genesis, systemic structure, and dynamic organization and localization of HMF (Vygotsky, 1997, v. 3, pp. 106, 140-143, 1995; Luria, 1980). From these principles the new diagnostic approach was developed, it is a syndrome analysis of brain lesions symptoms (Luria, 1980, pp. 82-86; see also Akhutina et. al, in press). According to it one has to identify *the primary impaired component* (primary defect), *the secondary systemic* consequences of the primary defect, and *tertiary compensatory reorganizations* as parts of the brain lesion syndrome in adult patients (or of abnormal development in children).

Moreover, to understand the idea of syndrome analysis of HMFs' disorders one needs to take into account one more point. Vygotsky and Luria, along with the famous Russian physiologist N.A. Bernstein, believed that the history of behavioral organization in phylogenesis is reflected in the structure of the brain: "*the brain preserves in itself in a spatial form the documented temporal sequence of development of behavior*" (Vygotsky, 1988, p. 123) and that "*the development of* [the] *brain proceeds according to laws of stratification and superstructure of new stories over the old*" (Vygotsky, Vol. 4, 1997, p. 102). From this point of view, new structures are built on top of the old while preserving the principal relatedness, the same working style, the "*common factor*" (Luria, 1970, pp. 101–3, see also p. 370). This is why, when describing aphasia syndromes, Luria not only wrote about speech itself but also considered related nonverbal deficiencies. This approach is very similar to the modern understanding, according to which "*language (as well as other abstract or higher order skills) emerges from, and is intimately linked to, the more evolutionarily entrenched sensorimotor substrates that allow us to comprehend (auditory/visual) and produce (motor) it*" (Dick et al., 2005, p. 238).

Because of their common morphogenesis and close functional connections, certain brain structures are more closely associated with each other, and the disturbance in the functioning of one will, with high probability, be accompanied by the dysfunction of the other. This is the foundation of the approach that A. R. Luria called "factor analysis" or "syndrome analysis". The beginning of syndrome analysis is laid by analysis of the general factor behind the disturbance of marginal and principal speech areas that was undertaken in "Traumatic aphasia" (1947 R/ 1970).

In this book A.R. Luria writes: "*when a lesion of a primary speech area is observed, we may expect to see gross and complex aphasic symptoms,* *whereas with lesions of the marginal areas, more subtle and limited impairment of speech processes is to be expected*" and continues that gross and complex aphasic symptoms are too difficult to analyze therefore "*we attempt to understand complex aphasic syndromes by studying the partial disturbances which arise with lesions limited to the marginal areas*" (1970, p. 102). Luria puts forward the following very important notion: «For us the study of marginal zone lesions will not be simply an investigation of the symptoms arising from "lesions to neighboring areas" but rather *a methodological step towards unraveling more complex forms of aphasia into their constituent parts"* (Luria, 1970, pp. 102-103, italicized by Luria).

Following this path A.R. Luria first considers speech and movement disorders in premotor area damage that does not affect classical Broca's area. He writes:

> Damage to the premotor areas, especially to the left premotor area, leads to loss of the automatic character of motor habits, i.e. it leads to a situation in which a single generalized impulse is insufficient to generate a series of movement... In very severe cases smooth movements give way to chains of individual acts, each of which is evoked by a special effort (Luria, 1970, pp. 171).

And he added: "*Not only serial movements lack continuity, but it is often difficult for the patient to shift from one act in the sequence to another*" (Luria, 1970, pp. 171). Describing speech impairments following lesions of the bordering on Broca's area Luria reveals "*a loss of the smoothness of speech which is simply one aspect of the change in the smoothness of movements*" (ibid, p.176).

Moving on to the disturbances of inferior parts of premotor area, Luria notes here as well the disturbance in complex consecutive syntheses, encompassing inability to construct complex systems of articulations and difficulty in inhibiting preceding articulations for a smooth transfer from one articulation in a series to the next. These dynamic difficulties constitute the essence (the primary defect) of the true "Broca's aphasia", or, as it conventionally called, "*efferent* (kinetic) *motor aphasia*" (Luria, 1970, p. 187; 1966, p. 207).

Efferent Motor Aphasia

This primary defect leads to the breakdown of word articulatory program. In severe cases of efferent motor aphasia, patients who are able to imitate individual movements of the tongue and lips and repeat isolated sounds are unable to pronounce that serially organized set of articulations that make up a word. In these patients, there is a breakdown of the normally strongly automated smooth series of efferent commands that make up the articulatory schema of a word. As a result, although they can manage the articulation of individual sounds, they cannot pronounce them as part of the whole word that is composed not of "pure sounds" but their positional forms, which depend on the preceding and following sounds in the word.

The disturbance in complex consecutive syntheses leads also to the breakdown of another level of language processing namely the disruption of sentence syntactic schemata. In efferent motor aphasia, the impairment of the grammatical structure of phrases can be very blatant and takes the form of "telegraphic speech". One of Luria's patients suffering from this form of aphasia told the story of his disorder in the following words: "*Here front . . . and then . . . attack . . . then . . . explosion . . . and then . . . nothing . . . then . . . operation . . . splinter . . . speech, speech . . . speech*" (Luria, 1980, p. 235). This very severe form of "telegraphic style" is characterized by pragmatic organization of utterances ("radio – weather – rain", see Akhutina, 1989/ 2012 R, 1991/ 2003b). In the course of recovery it changes to more light forms of anterior agrammatism. For less severe form of agrammatism N (noun) – V (verb) and N – N–V or N – V – N constructions are typical. Only one syntactic rule is kept regularly: The name of an Agent is on the first place (it is a rule of semantic syntax), all other rules are violated very often. The more mild form of anterior agrammatism in Russian is characterized by keeping the most simple rules of Russian grammar: opposition of singular and plural forms of nouns, opposition of Nominative case of nouns (for Agent / Subject) and Accusative case (for Object). Syntactic difficulties in speech production are accompanied by parallel difficulties in speech comprehension (see in more detail Akhutina, 1989 R, 1991/ 2003b).

Luria's account of speech disorders arising from lesions of the anterior division of the left hemisphere also includes one other form of disturbance in spontaneous speech. It can manifest itself in the last stages of recovery from efferent motor aphasia or it can be observed as an independent form of speech disorder arising from a lesion of the left hemisphere situated anteriorly to Broca's area. Luria has called it "dynamic aphasia".

Dynamic Aphasia

In *Traumatic aphasia* Luria wrote:

> Lesions located near the premotor area produce the same types of disturbance of sequential ability, but the motor aspect of speech itself offers no difficulty. The effect of disturbance of the dynamic schemata is shifted to an earlier stage in the formulation of speech, i.e. to a stage which precedes the speech act. Such a patient is deprived of those inner speech schemata which determine all the later stages in the formulation of statements (Luria, 1970, p. 208).

In Luria's words, "*these patients complain of a kind of emptiness in their heads*" noting that their thoughts "*stand still and do not move forward*" and that they have great difficulty when they have to initiate some sort of active narration. They imply that they do not have a clear internal representation of what they want to say: "*Before, I had a clear idea that I needed to say such and such, and now I want to start, but there is nothing there in front of me, just emptiness*" (Luria, 1970, p. 208).

Luria hypothesizes that patients with this form of aphasia are suffering from impairment of the inner dynamic schema of an utterance, as a result of which "*general thought does not get embodied in an inner speech schema, and does not go beyond a general, unformulated intention*" (Ibid) and thus cannot serve as the basis for constructing an utterance. In Luria's opinion, this impairment is engendered by the breakdown of inner speech, which he, after L.S. Vygotsky (1987), considers a derivative of external speech, differing from it in structure and functions. According to this point of view, inner speech is directly tied to the abbreviation of an extensive utterance into a general "sense schema" and the expansion of the general "sense schema" into a full utterance (see about Vygotsky's and Luria's notion of "inner speech" and its role in the construction of an utterance in Akhutina, 1975 R, 1978/ 2003a).

Similar thought about the presence of inner speech scheme of the utterance was expressed by a well-known philosopher and literature theorist M. Bakhtin:

> When we construct our speech, we always start with a picture of the whole utterance, both in the form of a certain genre schema, and in the form on an individual speech intention. We do not string words together, we do not move from word to word, but instead we seem to fill in the whole with the requisite words (Bakhtin, 1979 R, p. 266).

T. Akhutina who extensively studied dynamic aphasia assumes that in dynamic aphasia genre schemata are being disintegrated, and as a result patient is unable to produce and maintain the program of utterance (Akhutina, 1989/2012 R, 2007, p. 45). Modern researchers confirming the presence of the syndrome of dynamic aphasia and difficulties in verbal planning, do not relate them to inner speech disorders (Costello de Lacy, Warrington, 1989; Robinson, Blair and Cipolotti, 1998; Robinson, Shallice and Cipolotti, 2005; Bormann T. et al., 2008).

The extent to which utterance planning is disrupted may vary: in severe cases, patient cannot and does not attempt to initiate speech; in milder forms, the impairment may be almost undetectable to an outside observer, and only manifest itself when there is a need to plan a relatively extensive utterance. In the works of A.R. Luria and his followers (Luria, 1947/1970; Luria and Tsvetkova, 1968; Akhutina, 1975/2008 R) the increase of difficulty to formulate an utterance in patients with dynamic aphasia depending on the complexity of the planning, is described. Tasks are ranged from 0 (zero difficulty) to 3 (maximum difficulty): short answers in dialogue (0), long answers in dialogue (1-2), narration of simple events depicted in picture sequences (1), narration of content depicted in one "story-picture" (2), narration of content depicted in a picture of landscape (3), retelling (1-3), narration on a given topic (3). Here is an example of a narration on the topic "The North" by a patient with a PhD in geography, who has been to the north multiple times:

> ... (long pause) «There are bears in the north... which I bring to your attention». Let us also see the story created by patient Buk. on the basis of picture "The letter from the front" (Prof. Luria and me studied this case of dynamic aphasia):

The boy is reading a letter..... (More details, please!) The soldier is listening to him.... The girl is listening.... The woman is listening.... The girl is listening.... (What has happened? Tell altogether.) The joy [is] on these faces... (And what has happened?) The interesting letter... (From where, do you think?) From the front... (To whom?) To woman... (Now tell all together in details) The boy is reading a letter, the soldier is listening to him, the little girl is listening to him, the woman is listening to him, the girl is listening to him. The joy [is] on the faces.

While all the types of aphasia described above occur as a result of lesions of the frontal portion of the brain, all the remaining forms of aphasia occur after damage to the posterior portions of the dominant hemisphere's cortex. The frontal portions of the brain provide the "morphological basis for programming and implementing behavioral acts varying in complexity" (Poliakov, 1966). These operations act on the basis of successive synthesis, that is, integration of excitation in sequential, successively organized series (Luria, 1966, see also Sechenov, 1953). In contrast, posterior brain regions are perceptual and gnostic and perform their functions on the basis of simultaneous synthesis, that is, integration of excitation in simultaneous groups. When participating in motor acts, posterior portions of the brain monitor the performance of actions, and provide adjustment and differentiation. In terms of Jakobson-Luria, the anterior operations provide *combining elements in syntagmatic units* and the posterior operations provide *selection of elements out of paradigms* (Jakobson, 1964; Luria, 1964, 1976).

Let us consider now those forms of aphasias that occur when the posterior portions of the left hemisphere's cerebral cortex are damaged.

Sensory Aphasia

Sensory aphasia syndrome (Wernicke's aphasia) occurs in the case of damage to the posterior third of the upper-temporal gyrus. The mechanism of this type of aphasia is a deficit of phonemic hearing in the absence of elementary hearing deficits (Luria, 1970, pp. 104-135).

Impairment of phonemic perception is seen primarily in speech perception and evokes impaired understanding and phenomena of alienated word meaning, when patients can repeat (imitate) the pronunciation of a word, but cannot understand its meaning. In severe cases, patients with sensory aphasia perceive other people's speech as inarticulate noise; in mild cases, they have difficulty only in recognizing "oppositional phonemes": (b-p, m-m', etc.).

Careful assessment shows that patients with sensory aphasia can not repeat individual sounds. This symptom is often accompanied by substitution of oppositional phonemes (like *b – p*, *d–t*). The problem with repetition is more severe if patient is asked to delay the repetition by 10 or 15 seconds.

Words repetition is also difficult. Patients can distort the word making literal paraphasias (kolos – golos) or verbal paraphasias ("eyes" instead of "glasses"). The same errors are evident in naming. Sometimes patients can not remember their own names or addresses. It is important that verbal prompting usually does not help to find the name; this symptom is not seen in aphasias due to parietal lobe lesions.

Comprehension of verbal instructions strongly depends on context; it is often more a result of guessing than of genuine speech comprehension. Writing and reading abilities usually are severely disturbed.

Expressive speech of these patients is relatively less impaired. In more severe cases, the patients' speech becomes unintelligible and turns into "word salad." But even when aphasic impairments are severe, certain frequently-used words, the pronunciation of which does not require special phonetic analysis, and that have long been automated into speech motor programs can be pronounced without error. An example of such set phrases could be such expressions as: "you know . . .," "I mean. . . .". Though limited in content, these expressions may be pronounced with normal intonation". In mild cases patients exhibit only word finding difficulty and make literal and verbal paraphasias. And while lexical aspect of speech in patients with sensory aphasia is severely disrupted, syntax is only secondarily disturbed. Errors are most often seen if two synonyms have different government – in such cases patients may use one synonym but produce a phrase in accordance with the other synonym government ("a girl shouts with him" instead of "she quarrels with him" or "she shouts at him").

A.R. Luria (1970) and E.S. Bein (1957 R) note that the meaning of suffix of the word could be understood whereas the meaning of the root cannot. Thus when the word "kolokol'chik" (bell) is presented ("kolokol" is a root, "chik" is a suffix that often conveys diminutive meaning) patient says: "*something small, but do not know what*".

Luria stated that in patients with sensory aphasia semantic aspect of speech is profoundly disturbed, the unity of sound and meaning disintegrates, he explained it by "general inconstancy of phonemes and phonemic sequences" (ibid, p. 125). He wrote: "*Underlying this syndrome is a phonemic hearing disorder as a result of which the auditory image of a word is easily lost, and all that remains of its meaning is the general "semantic sphere" to which its belongs*" (ibid, p. 134). However the statement about the connection between loss of phonemic hearing and problems in auditory comprehension and naming was disputed by some Russian and Western authors. Thus, Bloomstein and her colleagues (1977) have shown that comprehension disturbances in sensory aphasia only weakly correlate with the degree of phonemic hearing deficiency. Similar data was obtained by E.P. Kok (1965a), one of A.R. Luria's coworkers. She has found that "alienation" of words' meanings is highly correlated (0.73) with phonemic hearing disturbance and with naming difficulties (0.55), whereas phonemic hearing disturbance and naming difficulties correlate at the border of statistical significance (0.43). Explaining these facts E.P. Kok supposed that "alienation" of words' meanings has the dual nature: it could be connected either with phonemic hearing disturbance or with word level defect. In the translation of "Traumatic aphasia" (1970) unlike the original (1947) A.R. Luria wrote that "*the "alienation" of word meanings may arise at different stages in the auditory recognition of words*" (ibid, p. 137) and that in temporal lobe damage one could see different levels of integration of auditory processes disturbances (Luria, 1970, p.139). Considering massiveness of the disturbances in sensory aphasia, one could assume that in this case not only phonemic level, but also the level of words is disturbed, namely phonological form of words, disturbance of which (without the pronounced deficits of phonemic hearing) is typical for acoustic-mnestic aphasia.

Acoustic-mnestic Aphasia

This syndrome can appear as a stage in recovery from sensory aphasia or as a separate syndrome. As a separate syndrome acoustic-mnestic aphasia occurs when there is a lesion in the middle and inferior portions of the left temporal lobe. Luria (1970) wrote that it was characteristic of these cases that in the initial period following injury there was no severe disruption of phonemic hearing accompanied by the usual total agraphia and inability to communicate verbally. The primary defect is the disturbance of auditory memory that manifests itself in forgetting words, difficulties to remember long sentences or to recall several words. The *instability of the auditory images of words* (lexemes) can sometimes lead to the "alienation" of word meaning.

Discussing the mechanism of acoustic-mnestic aphasia Luria reminds that the posterior-inferior portion of the left temporal lobe is the newest part of temporal area. It consists of the posterior portion of Brodmann's area 21 and the adjacent portion of area 37. Luria wrote: "There is probably some basis for the idea that area 37 plays an important role in the coordination of functions between the auditory and visual analyzers" (ibid, p. 136). This idea has a theoretical and empirical support (Goldberg, 1990; Tsvetkova, 1975). Following A.R. Luria N.G. Kalita, the student of L.S. Tsvetkova, showed that patients with acoustic-mnestic aphasia cannot evoke a visual image associated with a given word (Tsvetkova, 1975; Kalita, 1974 R; see also Luria, 1966, pp. 118-119).

Psycholinguistic analysis of naming disorders in patients with acoustic-mnestic aphasia showed that two aspects of word meaning – referential and significative (categorical) – are disturbed differently in the speech of these patients. The connection between an image and a word (referential meaning) is disturbed in cases of acoustic-mnestic aphasia, whereas the hierarchical concept network (significative meaning) is disturbed primarily in patients with semantic aphasia (Akhutina, 1994 R /2003c; Akhutina, Glozman, 1995).

Semantic Aphasia

This form of aphasia occurs due to the lesion of the parietal-occipital (or more accurately, parietal-temporal-occipital) areas of the left cerebral hemisphere. Semantic aphasia is usually seen within a syndrome that also includes disorders of space orientation, constructive apraxia, and acalculia. Speech impairment in semantic aphasia manifests itself in difficulties finding words and understanding logical-grammatical constructions.

A.R. Luria has hypothesized that the mechanism underlying this form of aphasia involves defective simultaneous synthesis. As Luria wrote: "*both the naming difficulty and the impairment of the comprehension of complex grammatical constructions arise from <u>a profound disruption of the semantic epistructure of words</u>*..." (Luria, 1970, p. 228, underlining it corresponds to italics Luria). Patient understands details of what is said, but cannot combine them into a single integrated picture. Thus, for example, patient understands meanings of words "father" and "brother," but the meaning of "father's brother" is beyond him. At the same time, disruption of simultaneous synthesis leads to the impairment of the significative (categorical) meaning of the word. As Luria writes, "the primary image represented by a word, i.e., its specific "relatedness to an object" (referential meaning – authors) remains intact. But the system of relationships centered about the word is profoundly impaired" (Luria, 1970, p. 228). Speaking about this Luria refers to L.S. Vygotsky who pointed out to different origins of these different aspects of meaning: "relatedness to an object" (Vygotsky's term) is being mastered as soon as child pronounces his/her first words; categorical meaning of a word appears when words' meanings comprise a system (conceptual framework), it is a part of this system and may be identified in terms of its place in the system (Vygotsky, 1988, chapter 7).

Recent research confirms that the meaning of a word that designates a concrete object is stored in two coordinate systems: (1) in a formal logic-based hierarchical system of categorical meanings, and (2) in a visual image "gallery of generalized images" associated with the referential meaning of the word. Members of the "gallery of generalized images" are grouped according to the principle of "family resemblance" around their prototypes (Rosh, 1975). The degree of typicality determines how easy it is to operate with the given concept. For example, if we ask subjects to evaluate the truth of the propositions: "A crow is a bird" and "A chick is a bird" it will take less time to verify the first proposition than the second, which names a nontypical category member (Rosh et al., 1976). As for scientific concepts, members of hierarchical system of categorical meanings, they show another effect, namely the effect of the distance between categories (Collins & Quillian, 1969, 1975). The experiments on lexical recognition and naming of a word have shown that two types of meaning representation—perceptual and conceptual—are activated at differing rates (Flores d'Arcais, Schreuder, and Glazenborg, 1985).

Modern neuroimaging studies also demonstrate different contributions of temporal and temporal-parietal-occipital areas in word retrieval. Left hemisphere temporal areas (BA 19, BA 27, and BA 20) participate in matching the sequences of speech sounds transiently stored in a temporary buffer (Wernicke's area) to the phonological form of words stored in lexical long-term memory. Areas that include posterior superior temporal/inferior parietal cortex (BA 39) constitute "core semantic regions" that can be distinguished in comparison of activation areas during semantic categorization on words vs. phoneme detection (Demonet et al., 2005).

A.R. Luria correlates the damage to the temporal-parietal-occipital junction, and in particular BA 39, with the syndrome of semantic aphasia. The breakdown of the hierarchical system of categorical meanings (conceptual framework) leads to the disruption of the normally automatic retrieval of words and as a result patients start to experience difficulty finding words, take long time to search for the word they want, or replace it with verbal paraphasias. On the surface, disturbances of expressive speech experienced by patients with semantic aphasia are similar to difficulties of patients with acoustic-mnestic aphasia, but careful observation reveals differences both in the symptoms and in the mechanisms of these difficulties. Thus, patients with semantic aphasia respond readily to hints, while for patients with damage to temporal areas of the cortex hints, sometimes even very extensive ones, are not helpful.

Another confirmation of Luria's understanding of naming deficits in different forms of aphasia was found in the experimental study targeted at analyzing the retention of categorical meanings of words and referential meanings. Categorical classification (either of words or of objects), retrieval of words with a given meaning (*apple : fruit = dress* : *???*) were the most difficult for the patients with semantic aphasia (Akhutina and Malakhovskaia, 1985 R; Akhutina, 2003c). To analyze the ability to use referential meanings T.V. Akhutina with her student N.V. Komolova developed an experimental methodology based on the idea that underlying such meaning is a generalized image-template, which is used to segment the continuum of real phenomena. In this experiment, subjects were asked to view schematic depictions of animals (cats, dogs, foxes, bears) whose features changed smoothly along a single continuum, and to divide them into groups. In addition to this perceptual classification they used verbal classification in which words were to be placed in groups not on the basis of generic-specific categories, but on the basis of whether they referred to one or another object (in particular, the words: *pussycat*, *kitty*, *to mew and to purr*, had to be distinguished from *puppy*, *cub*, *to bark*, *to grawl* or *Brer*, *vixen*, *intoed*). The difficulties of this verbal classification task and the task of continuum segmentation, which were intercorrelated for these tasks but not correlated with defects in performing tasks involving categorical meanings, was greatest for patients with acoustic-mnestic aphasia (Akhutina, 1994 R/2003c; Akhutina, Glozman, 1995).

Second component of the syndrome of semantic aphasia are difficulties understanding logical-grammatical constructions. Patients with semantic aphasia can easily grasp meaning of simple sentences. However they have difficulties comprehending "a two word construction which cannot be understood without recognizing their grammatical relationship" (Luria, 1970, p. 230). Examples of such constructions are: "brother of father", "a circle is under the cross", "less bright" and so on. To designate these constructions Luria after 1975 used the term "reversible constructions", proposed by D. Slobin (1966). The patient with semantic aphasia Lev Zasetsky, a hero of Luria's romantic essay "The man with a shattered world" (1987), wrote in his diary about how he was trying to understand the utterance "*an elephant is bigger than a fly*»:

> I realized that a fly is small and an elephant is big but to understand these words and answer the question, whether a fly is smaller or bigger than an elephant, I for some reason could not. The main problem was that I could not understand what does the word "smaller" (or "bigger") refer to – a fly or an elephant" (Luria, 1987, citation page is necessary).

In the same vain this patient had difficulties understanding reversible active and passive utterances. Comparative analysis of construction, understanding, and verification of such sentences in patients with efferent motor, acoustic-mnestic, and semantic aphasia, as well as understanding of such sentences by Russian-speaking children 3-5 years of age is presented in the book by T.V. Akhutina (1989 R). Similar data on difficulties in understanding reversible structures in patients with conductive aphasia (with close localization of the deficit) were obtained by Berndt & Caramazza (1981).

Afferent Motor Aphasia

This form of aphasia is caused by damage to the lower portions of the postcentral area. In severe cases, motor problems are so bad that patients cannot produce a single articulate sound. When they try to repeat one or another sound, they move their lips and tongue, and puff out their cheeks, but do not hit on the articulation required. In mild cases, patients merely slip into similar articulation patterns. Writing errors due to difficulties in differentiation of letters that correspond to the sounds close in pronunciation could be more persistent. Usually, patient's actual speech, especially pronunciation of certain well-mastered set phrases, suffers less than the arbitrary repetition of individual sounds.

The primary deficit, which is the basis for this form of aphasia and the whole syndrome of non-verbal and verbal deficiencies, is connected to the afferent aspect of motor processes. The important role of feedback in motor control was demonstrated by Russian physiologists L.A Orbeli, P.K. Anokhin, and N.A. Bernstein. Their works, especially "*The construction of movement*" (Bernstein, 1947 R), have become a theoretical foundation for the distinction of the two types of motor aphasia: in efferent motor aphasia dynamic component of articulation is impaired, and in afferent motor aphasia posture of articulatory apparatus is suffering (Luria, 1980, pp. 143- 147, 152-153). Well known aphasiologists P. Shinn and Sh. Blumstein (1983) write about the first syndrome: "*Broca's aphasics seemed to be able to reach the articulatory configuration for the appropriate place of articulation. However, the dynamic aspects of speech production seemed to be impaired*". About the syndrome of afferent motor aphasia A.R. Luria wrote: "*The disturbance of differentiations among similar articulatory positions is one of the most characteristic symptoms of this form of aphasia*" (ibid, p. 153) and noted that "*these disorders differ from those seen in premotor lesions in that the articulation difficulty is unaccompanied by any sign that the dynamics of speech processes have been disturbed*" (ibid, p. 152). Though this type of aphasia is close to apraxias seen in inferior frontal-parietal area damage, and therefore could be considered as a positional apraxia of the speech organs, none the less the deficit is not limited to the purely executive level of pronunciation. The syndrome also includes pronounced writing and reading disturbances. Explaining the syndrome of afferent motor aphasia Luria wrote that "*the difficulty of the latter lies almost completely in mastering the schemata of articulatory movements*" (ibid, p. 154). The loss of generalized articulatory schemata affects not only articulation but also writing and reading. The main writing problem is sound awareness disturbance. Thus when writing a dictation of sounds the patient repeats the sound and only after having found a word that starts with this sound: "T, t, t.... Tanya (name of the patient)" she is able to write the letter. This method of writing is being used by patients with afferent motor aphasia for many years, whereas patients with other types of aphasia use it as temporary help.

There is an opinion that afferent motor aphasia is close to conduction aphasia (see for example, Goodglass, Kaplan, 1994, p. 86). Luria himself pointed out that the main symptom of conduction aphasia – difficulty repeating sounds and words in right order–can be seen in different syndromes and it appears in voluntary forms of speech. Luria wrote:

> In some cases it appears as a mild form of acoustic-gnostic disturbance, in others as a defect of verbal articulation, and in still others as what Goldstein has described as a disturbance of the "abstract attitude" necessary for the voluntary repetition of words spoken by others (Luria, 1970, p. 245).

His coworker E.P. Kok has described three patients with conduction aphasia connected with instability of the auditory images of words (Kok, 1965b). The neuropsychologists from S.Peterburg explained mechanism of conduction aphasia by disorders of operational memory (Tonkonogii et al., 1965). In *Traumatic aphasia* Luria has described a patient Sukh. With parietal lobe syndrome who had stable problems to repeat and write words maintaining correct order of the sounds (p. 429-430) and mentioned patients with such symptoms with lesions to the left temporal lobe (p. 140, 292). Different mechanisms that cause the symptoms of conduction aphasia were described by western researchers (cp. Dubois et al., 1964; Shallice, Warrington, 1977; Tzortis, Albert, 1974).

To summarize the description of different components of speech/ language ability disturbed in different forms of aphasia we present the Figure 8.1. The comparison of Lurian and Western aphasia classification is represented in Figure 8.2, one can see relations of aphasias distinguished in both classifications.

	Disorders of expressive speech				**Disorders of speech reception**		
	Dynamic 1	Agrammatical (dynamic 2)	Efferent	Afferent	Semantic	Acoustic-mnestic	Sensory
Utterance planning	■						
Grammatical structuring		■	■				
Construction of a syllabic schema of the phrase			■				
Kinesthetically guided selection of sound				■			
Semantic based selection of word					■		
Selection of word form (lexeme)						■	■
Phonemic control of speaker's output							■

Figure 8.1. The disorders of language production components in different forms of aphasia from Ryabova

Source: Akhutina (2003).

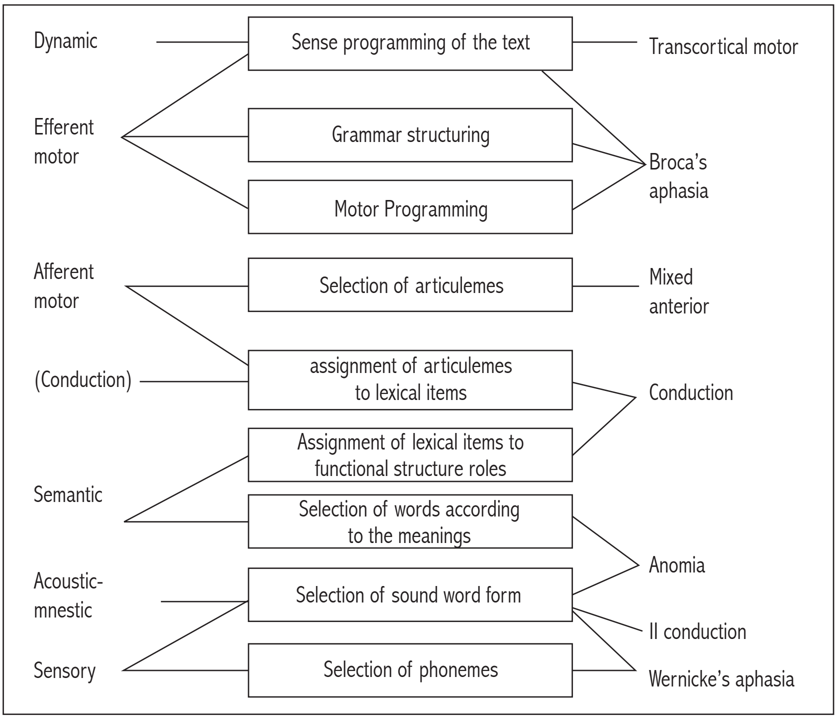


Figure 8.2 Aphasia Classification in Russian and Western Neurolinguistics

Source: Akhutina, T. V. (1989/2012). Porozhdenie rechi. Neyrolingvisticheskiy analiz sintaksisa Language production: Neurolinguistic analysis of syntax. Moscow: Moscow University Press. (4th ed.).Moscow: URSS. P. 99.

Thus we have completed the discussion of A.R. Lurian classification of aphasias. The understanding of the notion of "syndrome" suggested by Luria, allows using in syndrome analysis of speech disturbances data on the status of non-verbal functions which are often easier to qualify than the speech deficits. Thus in the case of motor speech deficits qualification of the type of aphasia based on speech alone could be difficult. Analysis of praxis allows assuming which type of motor aphasia – afferent, efferent, or combined – is seen in a given patient. The involution of the speech deficits allows confirming the diagnosis.

Thus A.R. Lurian neuropsychology offers a wide array of tools for psychological qualification of the deficit:

1. System neuropsycholgical analysis of speech and other higher mental functions;
2. Monitoring the dynamic changes of the syndrome;
3. Determination of the external compensatory techniques.

This array of A. R. Lurian neuropsychology is much richer then the simple statement of the “double dissociation of functions”, its utilization allows making analysis of aphasia syndromes more precise.

References

Akhutina, T. V. (1975/2002). *Neirolingvisticheskii analiz dinamicheskoi afazii* [The neurolinguistic analysis of dynamic aphasia]. Moscow: Moscow University Press. 2nd edition: Moscow: Terevinf.

Akhutina,T.V. (1989/2012). *Porozhdenie rechi. Neyrolingvisticheskiy analiz sintaksisa* [Language production: Neurolinguistic analysis of syntax]. Moscow: Moscow University Press. 4th edition: Moscow: URSS.

Akhutina, T.V. (2003a). ‘The role of inner speech in the construction of an utterance’. *Journal of Russian and East European Psychology* 41 (3/4): 49-74. Russian ed. Akhutina (1975), the first English ed. (1978).

Akhutina T.V. (2003b). ‘Is agrammatism an anomaly?’. *Journal of Russian and East European Psychology* 41(3-4): 75-95. The first English edition (1991).

Akhutina T.V. (2003c). ‘The structure of the individual mental lexicon from the standpoint of L.S. Vygotsky’s ideas’. *Journal of Russian and East European Psychology* 41 (3-4): 115-128. Russian ed. (1994).

Akhutina T. V. (2007). ‘Vygotsky-Luria-Leontiev’s School of Psycholinguistics: The Mechanisms of Language Production’. In *Language in Action: Vygotsky and Leontievian Legacy Today*. Eds: R. Alanen, S. Pöyhönen. Newcastle, UK: Cambridge Scholars Publishing. Pp. 32-56.

Akhutina T.V., Glozman J.M. (1995). 'Neurolinguistic study of semantics'. *Aphasiology* 9(2): 143-152.

Akhutina, T.V., and Malakhovskaia, E.V. 1985. [The Significative Word Meaning in Aphasia]. Vestn. Mosk. Un-ta. Ser. 14, *Psikhologiia*, no. 1, pp. 29–38.

Akhutina, T.V., Melikyan, Z.A., Mikadze, Y.V., Mervis, J.E., Bisoglio, J., & Goldberg, E. (In Press). History of Neuropsychology in Russia. In W.B. Barr & L. Bieliauskas (Eds). *Oxford Handbook on the History of Clinical Neuropsychology*. New York : Oxford University Press.

Bakhtin, M.M. (1979). *Estetika slovesnogo tvorchestva* [The Aesthetics of Verbal Creativity]. Moscow: Iskusstvo. Translation: Mikhail Bakhtin (1986). Speech genres and other late essays, ed. C. Emerson and M. Holquist. Austin.

Bein E.S. (1957). O nekotorykh osobennost'akh smyslovoi struktury slova i grammaticheskogo stroya rechi pri aphasiyakh [On some features of word meaning structure and grammatical construction of speech in aphasias]. *Vop. Psikhol.*, no. 4.

Berndt R.S., Caramazza A. (1981). '*Syntactic Aspects of Aphasia*', ed. M.I. Samo. / Acquired Aphasia. New York: Academic Press.

Blumstein S.E., Baker E., Goodglass H. (1977). 'Phonological factors in auditory comprehension in aphasia'. *Neuropsychologia*, 15.

Bormann T., Wallesch CW, Blanken G. (2008). Verbal planning in a case of 'Dynamic Aphasia': an impairment at the level of macroplanning. *Neurocase*, 14(5):431-50.

Collins A.M. & Quillian, M.R. (1969). Retrieval time from semantic memory. *J. of Verbal Learning and Verbal Behavior, vol. 8*, pp. 240-248.

Collins A.M. & Loftus E.F. (1975). A spreading-activation theory of semantic processing. *Psychological Review, vol. 82*, pp.407-428.

Costello de Lacy A., Warrington E.K. (1989). 'Dynamic aphasia: the selective impairment of verbal planning'. *Cortex 25*(1): 103-114.

Demonet, J.-F., Thierry G., and Cardebat D. (2005). 'Renewal of the Neurophysiology of Language: Functional Neuroimaging'. *Physiology Review* 85: 49–95. doi:10.1152/physrev.00049.2003.

Dick F., Dronkers N., Pizzamiglio L., Saygin A.P., Small S.L., & Wilson S.. Language and the brain. In M. Tomasello & D.I. Slobin, (Eds.) *Beyond Nature-Nurture: Essays in honor of Elizabeth Bates*. New Jersey: Erlbaum, 2005, pp. 237-260

Dubois J.H., Hecaen R., Angelergues A., Maufras de Chatelier, and Marcie P. (1964). 'Etude neurolinguistique de l'aphasie de conduction'. *Neuropsychologia* 2: 9-44.

Flores d'Arcais, G.B; Schreuder, R.; and Glazenborg, G. 1985. Semantic Activation During Recognition of Referential Words. *Psychol. Res., vol. 47*, no. 1, pp. 33–50.

Goodglass H., Kaplan E. (1994). *The assessment of aphasia and related disorders*. Philadelphia: Lea and Febiger.

Jakobson, R. (1964). 'Towards a Linguistic Typology of Aphasic Impairments. Disorders of language'. *Ciba Foundation Symposium*. London.

Goldberg E. (1990). '*Contemporary Neuropsychology and the Legacy of Luria*'. Hillside-London: Lawrence Erlbaum.

Kalita, N.G. 1974. 'K voprosu o prirode narusheniia nazyvaniia pri akustiko-mnesticheskoi afazii' [On the question of nature of picture naming impairments in acoustic-mnestic aphasia]. *Psikhologicheskie issledovaniia, vol. 6*. pp. 31–42. Moscow.

Kok E.P. (1965a). 'Korrel'atsia simptomov visochnoi afazii' [The corelation of the symptoms of temporal lobe aphasia]. [*Questions of Psychiatry and Neuropathology*]. Leningrad, vol. XI: 132-135.

Kok E.P. (1965b). 'K probleme provodnikovoi afazii" [On the problem of conduction aphasia]. *J. of Neuropathol. and Psychiatry, 12*: 1777-1779. In Russian.

Luria A.R. (1964). 'Factors and forms of aphasia'. *Ciba Foundation Symposium*. London.

Luria A.R. (1965). 'Vygotsy and problem of localization of functions'. *Neuropsychologia* 3: 387-392.

Luria, A. R. (1966). *Human Brain and Psychological Processes* (Harper & Row).

Luria A.R. (1970). *Traumatic aphasia*. (The Hague: Mouton). Russian ed. Luria (1947).

Luria, A. R. (1973). *The working brain*. (New York, NY: Basic Books).

Luria A.R. (1976). *Basic problems of neurolinguistics* (The Hague: Mouton).

Luria, A. R. (1980). *Higher cortical functions in man* (New York, NY: Basic Book).

Luria, A. R. (1987). The Man with a Shattered World. (Harvard University Press).

Luria, A. R., Tsvetkova L.S. (1968). The mechanism of 'dynamic aphasia.' *Foundation of Language*, *4*: 296-307.

Robinson G, Blair and Cipolotti L. (1998). 'Dynamic aphasia: an inability to select between competing verbal responses?' *Brain. Jan;121* (Pt 1):77-89.

Robinson G, Shallice T, Cipolotti L. (2006). 'Dynamic aphasia in progressive supranuclear palsy: a deficit in generating a fluent sequence of novel thought'. *Neuropsychologia* 44(8):1344-60.

Rosch, E. 1975. Cognitive Representations of Semantic Categories. *J. Experiment. Psychol. General*, *vol. 104*, pp. 192–233.

Rosch, E.; Simpson, C.; and Miller, R.S. 1976. Structural Bases of Typicality Effects. J. Experiment. *Psychol: Human Perception and Performance*, *no. 2*, pp. 491–502.

Ryabova (Akhutina) T.V. (2003). 'Mechanism of Speech Production Based on the Study of Aphasia'. *Journal of Russian and East European Psychology* 41(3-4): 12-32.

Sechenov, I.M. (1953). *Izbrannye proizvedeniia* [Selected Works]. Moscow.

Shallice T., Warrington E.K. (1977). 'Auditory-verbal short-term memory impairment and conduction aphasia'. *Brain and Language* 4(4): 479–491.

Shinn P., Blumstein Sh. (1983). 'Phonetic disintegration in aphasia: acoustic analysis of spectral characteristics for place of articulation.' *Brain and Language*, *20*: 90-114.

Slobin D.I. (1966). Grammatical transformation and sentence comprehension in childhood and adulthood.' *J. of Verbal learning & Verbal Behavior, 5*: 219-227.

Tonkonogii I.M., Tsukerman I.I., Schklovskii V.M. (1965). 'Conduction aphasia and disorders of operational memory'. *Zh. Neuropathol. and Psychiatry, 12*: 1773-1776. In Russian.

Tsvetkova L.S. (1975). 'The naming process and its impairment.' Foundation of language development, ed. E.H. Lennenberg and E. Lennenberg. N.Y.: Academic Press. Pp. 31-48.

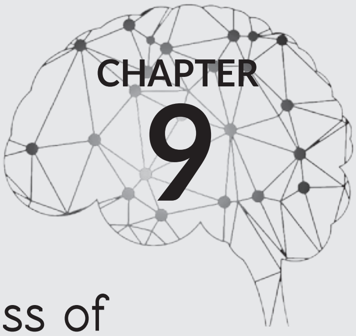
Tzortzis, C. and Albert, M.L. (1974). 'Impairment of memory for sequences in conduction aphasia'. *Neuropsychologia* 12: 355-366.

Vygotsky, L. S. (1988). *The collected works of L. S. Vygotsky*. Vol. 1: Problems of general psychology, including the volume Thinking and speech, R. W. Rieber and A. S. Carton (eds.). New York: Plenum Press.

Vygotsky, L. S. (1995). 'Problema razvitiya i raspada vysshikh psikhicheskikh funktsii' [The problem of development and disintegration of higher mental functions]. In *Problemy defek- tologii (Problems of defectology)* (pp. 404–418). Moscow: Prosveshchenie

Vygotsky, L. S. (1997a). *The collected works of L. S. Vygotsky*. Vol. 3: *Problems of the theory and history of psychology*. Edited by R. W. Rieber & J. Wollock. (London, UK: Plenum Press).

Vygotsky, L. S. (1997b). *The collected works of L. S. Vygotsky*. Vol. 4: *The history of the development of the higher mental functions*. Ed. R. W. Rieber. (New York, NY: Plenum Press).



CHAPTER 9

Tactile activity and success of learning at younger school children

Elena Karimulina
Natalia Zvereva

Introduction

The study is devoted to the problem of development of natural and higher mental functions (according to L.S. Vygotsky) in tactile sphere. The investigation was focused on some points: to reveal features of tactile manual preferences of boys and girls of primary school age with different advances in learning; to reveal features of tactile memory with boys and girls with a different structure of manual domination; to study distribution of achievements in tactile, visual and acoustic storing with boys and girls with different advances in learning. Object of research: boys and girls of 7-10 years, pupils of primary school having different progress in learning. Material of research: 90 boys and 90 girls divided into 4 groups depending on advances in learning. Methods of research: estimation of manual preferences (questionnaire “Annette”); estimation of manual tactile preferences (updating), estimation of tactile, visual and acoustic memory (author’s development of method for stimulus storing. The received materials allow more differentiated approach to using of a tactile modality during teaching in primary school. We can suppose the specific development of natural and higher mental functions in tactile sphere.

The first thesis from the theory of Lev Vygotsky, which is important for the formation of the problem of present study, is theseparation of all mental functions according to their level in natural and social, spontaneous and higher, direct and mediated. In this respect tactile memory and gnosis (including voluntary) occupy special place in comparison with other higher mental functions. Tactile cognitive activity is less of all connected with speech in one’s individual experience. It has more pronounced (basic) connection with immediate feelings, with data and sensory representations, and occupies an important place in providing overall homeostasis.

Lev Vygotsky elaborated an idea of two lines of mental function development – natural and cultural (cultural-historical). Natural line reflects maturation of function according to biological development, cultural line – mediated by sign, experience of social communication. If to go to the contrary , we can define “natural” function as less mediated (by sign) and speech, less circled in communication process, including transfer of social experience, less included in control and planning of behavior (natural – means spontaneous). Visual and audial functions become more mediated by speech or signs (gestures?) in the ontogenesis, more voluntary and regulated – i.e. higher form Vygotsky’s point of view. Tactile function in this respect “lags behind”, it doesn’t pass through mediation by gesture and speech (or this process goes in much smaller volume).

Lev Vygotsky advanced formula “training leads the development”, which is correct for distant analyzing systems (vision, hearing), the fact of mediating by speech supports that hypothesis. Tactile sensory system here comes in special state – intensity of early development in early childhood and practically full unlessens in school education system. Exception – cases of deficit development (innate or early acquired absence or gross vision pathology). Level of development of “unclaimed”, “untrained” function in school education process can be interesting for differentiation of children.

Third statement is the Vygotsky’s idea of “a great meaning of comparative method of normative/non-normative child investigation for the whole history of cultural development”. Comparing children with educational difficulties in their activities relying on tactile modality, we can see special way of higher mental functions formation in norm and pathology, in successfully and unsuccessfully educating children (Vygotsky, 1997,1998).

In this work tactile activity is understood as a tactile preference (asymmetry) and voluntary tactile memory (we have not considered involuntary forms). The idea to evaluate manual preferences was dictated by gained information about high frequency of occurrence of left-sided signs in problem children (including children with educational difficulties). In this regard, question about tactile activity lateralization also seems to be important (Zvereva, 2007).

Hypothesis

1. In the light of Vygotsky’s ideas, tactile memory efficiency seems to be lower than visual and audial memory efficiency in children in the same tasks.

2. Tactile memory efficiency has connection with educational level of children: there is straight connection of tactile memorization efficiency and success of education level. The higher the learning – the higher the efficiency of tactile memorization, the lower the learning – the lower the efficiency of tactile memorization.

3. Indices of tactile memorization reflect the level of learning more accurate and reliable, than auditory and visual memory indices (by virtue of solicitation of tactile function in school education process).

4. There is a connection between tactile memorization and manual preferences features in object palpation. Left-sided manual preference and mixed type of preference connected with low efficiency of tactile memorization.

Materials of study

90 boys and 90 girls aged form 7 to 10, 2 years. All children were subdivided into 4 groups by learning success level: 1 level (high success) – children learn well in core subjects; 2 level (middle success) – children learn good in core subjects, allow individual errors; 3 level (low success) – children learn the curriculum satisfactory, but they have learning difficulties in some subjects, 4 level – children of correctional class, they have learning difficulties expressed by a number of subjects.

In progress of present study were solved following tasks step by step:

- Evaluation of tactile manual preference of boys and girls of primary school age.
- Investigation of tactile manual preference distribution among boys and girls of primary school age with different learning success.
- Assessment of tactile memory efficiency in boys and girls of primary school age with different profile of manual dominance.
- Assessment of tactile memory efficiency in boys and girls of primary school age with different learning success in comparing with efficiency of visual and audial memorization.

Methods

1. Evaluation of genera manual preference was conducted using Annet Hand Preference Questionnaire (AHPQ) and evaluation of tactile preference also was conducted.

2. Experimental method of tactile, audial and visual memory assessment

Method of tactile memory assessment

Vulnerable memorization of tactile stimuli was investigated in tasks in their subsequent recognition among distractors by classical scheme of experimental recognition “yes – no”. As stimulus material used equal wooden rounded plates with different surfaces. Each subject was offered to memorize row of stimuli (8 plates with different surfaces) and then recognize them among mixed stimuli with distractors (4 plates with closed to stimuli, but not the same surfaces).

Visual control was excluded. The criterion of memorization efficiency was number of mistakes in stimuli recognition, and also their quality: mistakes of stimuli missing and false recognition of stimuli.

The same scheme used for study of visual (pictures) and audial (syllables) memory. Tactile and other kinds of memory studied only in strong right-handed and left-handed, ambidexters were excluded, as well as children from correctional classes (4 level of learning success).

Results of study

Study of tactile manual preference of boys and girls of primary school age showed, that subjects subdivided by three groups in accordance with manual preferences: dominance of right features, dominance of left features, with symmetrical features by tactile features. Figure 9.1 shows following data: most children prefer right hand, but there was differences.

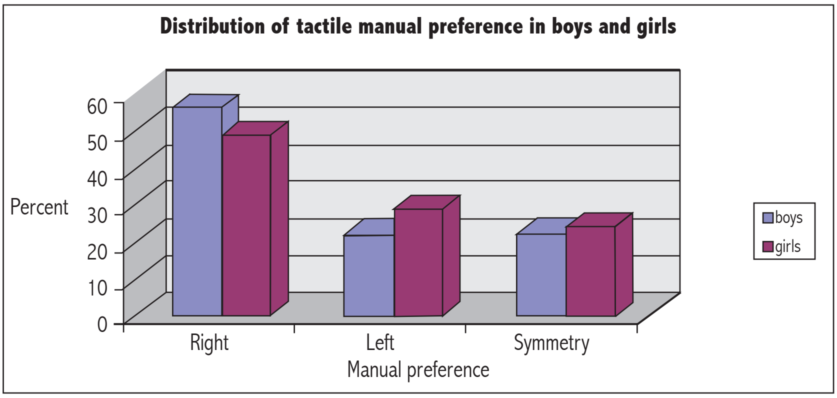


Figure. 9.1. Distribution of tactile manual preference in boys and girls (in percent).

Source: Prepared by authors.

Among boys 56% of subjects prefers right hand for palpation and identification of the object. Among girls – 49% of subjects. In the group of left hand dominance more girls than boys (29 % of girls, 22% of boys). Group of symmetry presented approximately equal number of boys and girls. In comparison of different variants of manual dominance (AHPQ data) with preference of hand by tactile function we can notice, that there is some correlation of handedness degree and disturbance of laterality features in tactile system.

Right-handed prefer right hand for recognition object by palpation (63 %–in boys, 58 %–in girls). Left-handed children frequently, then other children speak about preference of left hand in palpation: "strong" left-handed – 25% of boys, 40 % of girls. Comparing different variants of hand dominance with tactile self-esteem showed correlation of handedness degree with tactile manual preference, Right handed boys (AHPQ data) prefers right hand in 73 % for tactile identification of object. Right-handed girls (AHPQ data) in 63%. There is a correlation of handedness degree and tactile preference of hand in palpation of object, right-handed children prefer right hand, left-handed prefer left hand or both hands, although in this case correlation seems to be not so expressed. Nonconformity of leading hand and tactile manual preference was noted only among "strong" left-handed (60 % of boys and girls).

Tactile manual preference occurred to be non-equal in groups of children of different learning success. These results one can see on Figure 9.2.

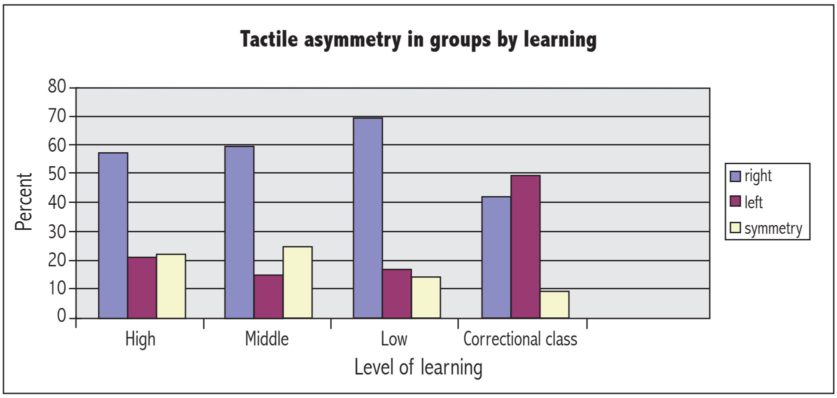


Figure 9.2. Tactile asymmetry in groups by learning (in % of in-group occurrence).

Source: Prepared by authors.

As expressed by level of achievement, preference of right hand was among children with 1 (high) level – 57%, with 2 (middle) – 60%, 3 (low) – 69%, 4 (correctional class) – 42%. Preference of left hand had: 1 group – 21%, 2 group – 17%, 3 group – 15 %, 4 group – 49 %. Other children in noted groups didn't have distinct tactile manual preference.

Study of tactile memory in these groups of subjects showed next. Were detected statistically significant distinctions in indexes of voluntary memorization depending on gender of subjects: boys made more mistakes, then girls (0, 33 and 0, 20).

Accordance of voluntary visual, audial (syllables) and tactile efficiency to learning efficiency presented on Figure 9.3.

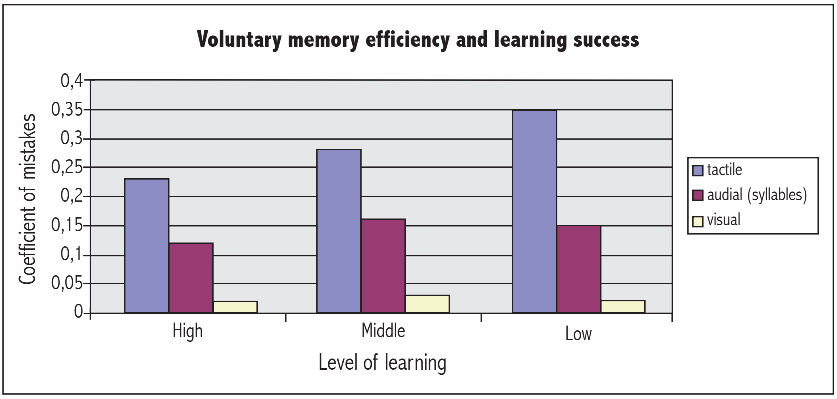


Figure 9.3 Voluntary memory efficiency and learning success (coefficient of mistakes).

Source: Prepared by authors.

Efficiency of tactile memorization in children with high level of learning success occurred to be higher comparing with same in children with low level. Distinctions are statistical significant (p ≤0.05). Children with low level of learning success occurred to have more coefficient of mistakes (average – 0, 35 mistakes), children with middle level – intermediate (average – 0, 28 mistakes), and children with high level – the lowest number of mistakes (average – 0, 23 mistakes).

Comparison of tactile memorization efficiency and lateral dominance profile showed that in general number of mistakes, right-handed children and left-handed children (AHPQ data) didn't differ. Analysis of difference among groups in dependence of type of mistakes showed more differentiating pattern. According to literature data, missing (what is there in Russian original?) stimuli mistakes are more connected with memorization process (trail-generation), and false recognition of feature mistakes point on paucity of criticism and control. Group of left-handed showed statistically significant dominance of number of failure feature recognition mistakes over number of mistakes of stimuli missing (p<0.05). In group of right-handed there were no distinctions of quality of mistakes made.

Children with low learning skills are less trained and exercised in tactile cognitive functions in general. Tactile cognitive functions occur to be on the decline in comparing with other functions (vision, hearing). Obtained data allows us more to develop a more differentiated approach to the issue of using of tactile modality in early school learning process and recommend using of tactile mediation for harmonization of personal development and educational process optimization. Through a combination of association links, which are based on a tactile modality, both in traditional and special (classes of correction).

Conclusions

1. Efficiency of tactile memorization as special mental function is lower, than efficiency of visual and audial memory. These results are corresponding to the ideas of Vygotsky about leading role of learning processes in the formation of mental functions in ontogenesis.

2. Successful learning (which leads development) has a positive impact on untrained function: the higher is a learning skill of a child, the higher is the tactile memory efficiency index.

3. Children with low learning skill showed lowest productivity of tactile memorization. Difference in audial and visual memorization is less expressed in same groups of children.

4. There exists noticeable ambiguity of distribution of right and left tactile manual preferences in groups with different learning success. The peculiarity of early school age children distribution by tactile manual preference for boys and girls was also found. The trend of gender differences in tactile memorization task performance was marked.

References

Vygotsky, L.S. (1997). Volume 4: The History of the Development of the Higher Mental Functions. In R.W. Reiber (Ed.). *The Collected Works of L.S. Vygotsky.* New York: Plenum Press.

Vygotsky, L.S. (1998). Volume 5: Child Psychology. In C. Ratner (Ed.). *The Collected Works of L. S. Vygotsky.* New York: Plenum Press.

Zvereva, N. (2007). Tactile Activity and Success at Training of Younger Schoolchildren / *17th EECERA annual conference exploring Vygotsky's ideas: crossing borders.* Prague, Czech Republic 29th August – 1st September, 2007, p.269.