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Same, same but different: Cognitive and neural mechanisms underlying basic subprocesses of reading in younger and older adults

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Eidesstattliche Erklärung

Hiermit erkläre ich an Eides statt,

- dass ich die vorliegende Arbeit selbstständig und ohne unerlaubte Hilfe verfasst habe,
- dass ich mich nicht bereits anderwärts um einen Doktorgrad beworben habe
- und keinen Doktorgrad in dem Promotionsfach Psychologie besitze
- und dass ich die zugrunde liegende Promotionsordnung vom 08.08.2016 kenne.

Berlin, den 20. April 2017 Eva Fröhlich

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Summary

The complexity of reading may seem astonishing given the ease with which most individuals use it every day up to old age. Especially for older people, reading is not only one of their favorite leisure time activities but it helps them to maintain functional independence thus contributing essentially to life quality. Despite extensive research on the developing and younger reader, very little is known about the impact of age on sublexical, orthographic, phonological and lexico-semantic processing which constitute the central subprocesses of reading. This is even more astonishing, considering that reading relies not only on the integration of these four subprocesses but additionally on successful memory operations (e.g., working and episodic memory) which are known to decline with age. Therefore, the aim of the present dissertational project was to investigate cognitive and neural mechanisms underlying central subprocesses of single word recognition and reading in younger and older adults. For this purpose, I reviewed literature and conducted three empirical studies with different groups of younger and older adults using hierarchical diffusion modeling, functional magnetic resonance imaging (fMRI) and structural equation modeling. The main results indicated: 1) a relative stability of reading processes across the lifespan both at the behavioral as well as the neural level with orthographic and lexico-semantic processing being the most robust subprocesses; 2) despite the maintenance, age-related differences in brain activation specific to all four subprocesses and 3) a reliable contribution of working memory functions to sublexical, orthographic, phonological and lexico-semantic processing in older adults and reliable influences of both working and episodic memory operations on sentence comprehension in younger and older adults. Possible underlying mechanisms accounting for these findings may lie in older adults' disadvantage in inhibiting and/or activating optimal processing routes, in updating and constructing situation models needed for text comprehension, as well as in age-related decline of cognitive processes supporting reading (e.g., attention, executive functioning).

Zusammenfassung

Wir lesen jeden Tag problemlos Wörter und Texte. Diese Fähigkeit scheint auch im Alter gut erhalten zu bleiben. Dies ist umso erstaunlicher, betrachtet man die Komplexität des Leseprozesses. Gerade ältere Menschen nutzen das Lesen nicht nur als bevorzugten Freizeitvertreib, es hilft ihnen vor allem ihre funktionelle Unabhängigkeit zu bewahren und trägt somit wesentlich zur Sicherung der Lebensqualität bei. Gemessen an der Bedeutung des Lesens für ältere Menschen, wissen wir überraschend wenig über den Einfluss des Alterns auf die vier zentralen Subprozesse des Lesens: sublexikalische, orthographische, phonologische und lexiko-semantische Verarbeitung. Dabei beruht erfolgreiches Lesen auf funktionierenden episodischen und Arbeitsgedächtnisprozessen, die jedoch von kognitivem Altern betroffen sind. Das Hauptziel der vorliegenden Dissertation liegt darin, die den Subprozessen der Einzelworterkennung und des Lesens zugrundeliegenden kognitiven und neuronalen Mechanismen von jüngeren und älteren Erwachsenen zu untersuchen. Nachdem ich zunächst die relevante Literatur in einer Übersichtsarbeit zusammengefasst habe, habe ich drei empirische Studien mit jungen und älteren Teilnehmern durchgeführt. Folgende Methoden- und Analyseverfahren wurden dabei verwendet: Hierarchische Drift-Diffusionsmodellierung, funktionelle Magnetresonanztomographie (fMRT) und Strukturgleichungsmodellierung. Die Ergebnisse dieser Untersuchungen deuten auf eine relativ hohe Stabilität der Subprozesse des Lesens im Alter hin. Dabei scheint vor allem die orthographische und lexiko-semantische Verarbeitung vor Alterungsprozessen bewahrt zu bleiben. Dies konnte sowohl mittels behavioraler als auch neuronaler Daten gezeigt werden. Dennoch lassen sich für alle vier zentralen Subprozesse spezifische altersbedingte Unterschiede in den neuronalen Aktivierungsmustern feststellen. Ein weiteres zentrales Ergebnis zeigte, dass das Arbeitsgedächtnis wesentlich zur sublexikalischen, orthographischen, phonologischen und lexiko-semantischen Verarbeitung beiträgt. Darüber hinaus konnten signifikante Einflüsse des episodischen und des Arbeitsgedächtnisses auf das Lesen von Sätzen in beiden Altersgruppen

festgestellt werden. Als mögliche Erklärungsansätze für die Ergebnisse dieser Dissertation werden zum einen altersbedingte Nachteile bei der Inhibierung und/oder Aktivierung optimaler Verarbeitungswege herangezogen. Zum anderen könnten Unterschiede in der Flexibilität bei der Konstruktion und Aktualisierung von Situationsmodellen die Ergebnisse junger und älterer Erwachsener erklären. Letztendlich spiegelt sich vermutlich auch in den Teilprozessen des Lesens der Abbau allgemeiner kognitiver Fähigkeiten (z.B. Aufmerksamkeit und exekutive Funktionen) wider.

List of Original Publications & Submitted Manuscripts

1) Froehlich, E., & Jacobs, A. M. (2016). Verändert sich Lesen im Alter? Alterseffekte in der visuellen Worterkennung [Does reading change with age? A review of aging effects on visual word recognition]. *Lernen und Lernstörungen*, *5*, 95-109. http://dx.doi.org/10.1024/2235-0977/a000130

2) Froehlich, E., Liebig, J., Ziegler, J. C., Braun, M., Lindenberger, U., Heekeren, H. R., & Jacobs, A. M. (2016). Drifting through basic subprocesses of reading: A hierarchical diffusion model analysis of age effects on visual word recognition. *Frontiers in Psychology*. 7:1863. http://dx.doi.org/10.3389/fpsyg.2016.01863

3) Froehlich, E., Liebig, J., Morawetz, C., Ziegler, J. C., Braun, M., Heekeren, H. R., & Jacobs, A. M. (under revision). Same, same but different: Processing words in the aging brain. *Neuroscience*

4) Froehlich, E., Düzel, S., Brandmaier, A. M., Ziegler, J. C., Braun, M., Heekeren, H. R., & Jacobs, A. M. (under revision). Age-related differences in the subprocesses of reading and sentence comprehension: The impact of working and episodic memory. *Psychology and Aging*

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1. Theoretical and Empirical Background

For most individuals, reading is an integral part of everyday life, a routinely and automatized activity which is effortlessly performed well into old age. In fact, reading is not only one of the most popular leisure activities of older people, it also helps them to maintain their functional independence thus contributing significantly to life quality (Meyer & Pollard, 2006). Identifying and consequently promoting factors that support successful reading in (later) life bears the possibility of generating positive transfer effects to other cognitive domains that are affected by aging (e.g., Demoulin & Kolinsky, 2016). Yet, despite extensive research on the developing and younger readers, both at the behavioral as well as the neural level (e.g., Booth et al., 2004; Braun et al., 2015; Frith et al., 1998; Jacobs & Grainger, 1994; Liebig et al., 2017; Martin et al., 2015; Oganian et al., 2016; Price, 2012; Turkeltaub et al., 2003; Ziegler et al., 2001a,b, 2008; Zoccolotti et al., 2008), there is a lack of studies investigating reading and visual word recognition in aging adults, especially with respect to neural correlates of the central subprocesses of reading (i.e., sublexical, orthographic, phonological and lexico-semantic processing) as well as within transparent orthographies, such as German. This deficiency is even more astonishing considering the following: On the one hand, older adults have a life-long expertise in processing and comprehending written words, sentences and texts resulting in, for instance, a superior vocabulary (Verhaeghen, 2003). On the other hand, reading and visual word recognition also rely on the successful execution of perceptual-attentional processes, memory functions and other higher cognitive processes (Hofmann & Jacobs, 2014; Jacobs, 2001; Jacobs & Ziegler, 2015; Just & Carpenter, 1992; Perry et al., 2007, 2010, 2013), which decline with age (e.g., Craik, 1994; Hedden & Gabrieli, 2004; Kramer & Kray, 2006; Lindenberger et al., 2008; Salthouse, 2003, 2009). It is not yet known how these age-related alterations in cognitive functions affect word recognition in the aging individual. Therefore, the aim of the present dissertation is to investigate age-related differences in the central subprocesses of single word recognition and reading at the behavioral as well as the neural level. This investigation will include those cognitive processes that support successful reading with a particular focus on memory functions, such as working and episodic memory (WM and EM, respectively).

For this purpose, I will first present the current status of research regarding single word recognition in younger and older adults and refer to relevant computational models of reading. I will then give a short overview of neural correlates of reading, neurocognitive aging as well as of the interrelationships between memory processes, reading and aging. In the final part of the introduction, I will describe the research questions addressed in this dissertation, the general methodology applied and give a brief summary of the studies conducted. Chapters 2 to 5 contain the studies as published (studies 1 and 2) or as they have been submitted (studies 3 and 4). Finally, in Chapter 6, I will discuss findings from all four studies and relate them to present and future research.

1.1. Reading as a Multicomponent Activity

1.1.1. Principles and central measures of visual word recognition

Successful reading depends on the integration of several complex processes such as pattern recognition and letter identification, integrating letters to form lexical units, grapheme-phoneme conversion, whole word recognition, morpho-syntactic, lexico-semantic and global text comprehension processes as well as the assimilation of aesthetic and emotional aspects of words and texts (e.g., Coltheart et al., 2001; Jacobs, 2011; Perry et al., 2007, 2010, 2013). Especially the latter processes rely heavily on the accurate execution of the basic operations, that is, on single word recognition. Not surprisingly, visual word recognition constitutes the main basis for fluid reading (Grainger & Jacobs, 1996; Jacobs &

Ziegler, 2015). In fact, the importance of single word recognition for the development of central cognitive and psycholinguistic concepts has been compared to that of the cell in biology (Balota et al., 2004).

Visual word recognition, or lexical access, is based on several fundamental processes, that are repeated in the brain each time a word is read. Whenever a written stimulus is encountered, a basic (word) form representation is calculated which is subsequently matched with abstract representations stored in long-time memory. The best fit is then selected for identification of the written word (Grainger & Jacobs, 1996). Thus, orthographic, phonological and semantic characteristics of words emerge only from this non-linear, dynamic interaction between physical stimulus and brain (Jacobs & Graf, 2005).

The main paradigms employed to investigate visual word recognition are the lexical decision task, the naming task and the perceptual identification task (Jacobs & Grainger, 1994). In the perceptual identification task participants have to identify a word which is presented for only a few milliseconds and subsequently masked (e.g., Ratcliff et al., 1989). As this paradigm promotes fast guesses (e.g., Ziegler et al., 1998) and therefore obstructs interpretation of results, its application in word recognition research is currently dwindling (New et al., 2006). In word naming tasks, participants are asked to read out loud a presented word or pseudoword. In lexical decision tasks, participants have to decide whether the presented stimulus is a word or a pseudoword. While naming mainly taps processes that are related to phonology, lexical decision predominantly measures the accuracy and the speed of lexical access. Paap et al. (1987) recommend explicitly the use of the lexical decision task as standard paradigm for investigating visual word recognition.

Central measures connected to visual word recognition are word frequency, word length and orthographic neighborhood which influence the speed of word identification in both naming and lexical decision (e.g., Andrews, 1989, 1992; Braun et al., 2009; Forster &

Shen, 1996; Grainger & Jacobs, 1996; Hauk & Pulvermüller, 2004; Juphard et al., 2006; New et al., 2006; Weekes, 1997; Zoccolotti et al., 2008). While manipulations of word frequency and orthographic neighborhood are generally thought to affect lexical access (e.g., Balota et al., 2004; Bysbaert et al., 2011; Grainger & Jacobs, 1996 but Spieler & Balota, 2000), manipulations of word length probably influence sublexical processes (e.g., Allen et al., 1993).

1.1.2. The basic subprocesses of reading in (late) adult life

Visual word recognition, the most basic and central process of reading (*cf.* section *1.1.1. Principles and central measures of visual word recognition*) is typically divided into sublexical, orthographic/lexical, phonological and lexico-semantic processing (Ziegler et al., 2008). Sublexical processing comprises letter recognition and integration of letters into larger sublexical units. Orthographic processing corresponds to whole word recognition. Phonological processing deals with grapheme-phoneme conversion, while in lexico-semantic processing meaning is assigned to a string of letters. These subprocesses have been successfully implemented in computational models of reading (*cf.* section *1.2.1. Computational models of reading*) in interactive activation or parallel processing approaches (Coltheart et al., 2001; Grainger & Jacobs, 1996; Harm & Seidenberg, 1999; Hofmann & Jacobs, 2014; Perry et al., 2007; Plaut et al., 1996; Zorzi et al., 1998) and have also been replicated on the neural level (*cf.* section *1.3.1. Neural correlates of reading*). To date, it remains an open question how these subprocesses are affected by age, which is astonishing given the importance of reading in everyday life of (older) adults. Even though a number of studies investigated behavioral age-related effects on sublexical, orthographic and semantic processing in an isolated manner, a systematic approach examining all four subprocesses within one sample is still missing.

A relatively consistent finding concerns age-related differences at the sublexical level. Older adults have been observed to respond more slowly in letter detection or letter matching tasks than younger adults (Allen et al., 1991; Guttentag & Madden, 1987; Madden et al., 2007) and show a pronounced word length effect (e.g., Allen et al., 1991, 1993; Whiting et al., 2003). Yet, comparable word length effects in younger and older adults have also been reported (e.g., Allen et al., 1993, experiment 3). One general problem of these findings is that results are exclusively based on the mere comparisons of mean response times (RTs) between these age groups or on the application of Brinley plots, respectively. Thus, one cannot differentiate whether age-related differences occur due to differences in sublexical processing or are simply the result of perceptual encoding difficulties in older adults as has been previously suggested (e.g., Aberson & Bouwhuis, 1997; Allen et al., 1991, 1993). To circumvent this problem, Thapar et al. (2003) used diffusion modeling (*cf.* section *1.2.2. Computational models of decision making*) to investigate age-related effects on letter discrimination. With larger estimates for the decision time (*t*) as well as smaller estimates for the information uptake or drift rate (*v*), their results actually point towards both of those possibilities.

At the orthographic processing level, a number of studies examined age-related differences using the lexical decision task and manipulating word frequency and/or orthographic neighborhood. While older and younger adults do not seem to differ with regard to word frequency (e.g., Allen et al., 1991, 1993, experiments 1 and 2; Allen et al., 2004; Balota & Ferraro, 1996; Bowles & Poon, 1981; Caza & Moscovitch, 2005; Cohen-Shikora & Balota but see Allen et al., 1993, experiment 3; Stadtlander, 1995; Tainturier et al., 1989; Taler & Jarema, 2007), age-related differences seem to prevail when researching orthographic neighborhood effects (Balota et al., 2004; Robert & Mathey, 2007). Yet, when applying diffusion modeling to data obtained in a lexical decision task as has been done in the study of

Ratcliff et al. (2004a), drift rates (*v*) of younger and older adults did not differ even though the decision time did (*t*), suggesting preservation of orthographic processing over the life span.

Although it is known that phonological representations are automatically activated during silent reading even in highly skilled readers (e.g., Braun et al., 2009, 2015; Briesemeister et al., 2009; Ziegler & Jacobs, 1995), research on age-related effects on phonological processing during visual word recognition is sparse. Age-related slowing has been observed in silent pseudoword reading (e.g., Bush et al., 2007; Madden, 1989; Stadtlander, 1995), which requires successful phonological recoding (e.g., Coltheart et al., 2001; Jacobs et al., 1998; Perry et al., 2007; Taylor et al., 2012). However, a phonological decision task (*cf.* Bergmann & Wimmer, 2008; Kronbichler et al., 2007) that requires participants to explicitly engage in phonological rather than in orthographic processing has not been applied to older adults.

Analyzing mean RTs obtained in semantic decision tasks, older adults have been reported to respond more slowly than younger adults (Lustig et al., 2003; Spaniol et al., 2006) or show similar performance levels across age groups (Daselaar et al., 2003). The latter result has also been observed for drift rates (*v*) when data from a semantic decision task had been subjected to diffusion modeling (Spaniol et al., 2006).

In summary, findings from previous behavioral research points towards a preservation of orthographic and possibly semantic processing over the lifetime, whereas sublexical and phonological processing seem to be prone to age-related effects. However, as already mentioned, most of the findings were obtained by mere comparisons of mean correct RTs neglecting information that can be derived from incorrect response times, accuracy data and their underlying distributions (*cf.* section *1.2.2. Computational models of decision making*). Additionally, as reading is more than just the sum of its component processes, investigating only one of the subprocesses or failing to consider higher-order comprehension processes may give an incomplete picture about age-related effects on visual word recognition and reading. Moreover, the vast majority of the above mentioned studies tested English native speakers using English stimulus material. Yet, English as opposed to German has a rather inconsistent orthography, which may possibly lead to different strategies in language processing and word recognition (e.g., Das et al., 2011; Ziegler & Goswami, 2005, 2006).

1.2. Computational Models of Reading and Decision Making

1.2.1. Computational models of reading

Computational models of (word) reading were originally developed to capture the complexity of this everyday activity, i.e., the multitude of processes involved, the interaction of these processes as well as their individual contributions to word recognition and reading. By adhering to standards for developing and evaluating cognitive models, these computational models ought to postulate verifiable or falsifiable hypotheses and preferably clarify all processing steps between input and output stimuli (Jacobs & Grainger, 1994).

An important step towards meeting these demands was the introduction of the interactive activation model (IAM; McClelland & Rummelhart, 1981). Based on previous word recognition models, it allowed to simulate the process of word recognition from the feature to the letter to the word layer and – because of its architecture – could account for neural mechanisms such as connectivity and interactivity (Hofmann & Jacobs, 2014). In recent years, IAMs have been further developed and extended. Current prominent representatives in the field of computational models of reading are, amongst others, the Connectionist Dual-Process Model (CDP++; Perry et al., 2007, 2010), the Multiple Read-Out Model (MROM; Grainger & Jacobs, 1996) and its extension featuring phonological units (MROM-p; Jacobs et al., 1998) as well as the Associative Read-Out Model (AROM;

Hofmann et al., 2011). While the CDP++ is based on a connectionist dual route architecture, i.e., on a lexical (orthographic) and a non-lexical (phonological) pathway, the MROM consists of three layers of interacting processing units: Words are positively identified in lexical decision as soon as the activation of a single word node (μ) or the summed lexical activity (σ) reaches a certain decision criterion. Stimuli receive a no-response when a temporal deadline (T) is reached before the aforementioned two processes reach their respective response criterion. The AROM extends the MROM by adding a semantic layer, in which (long-term memory) associations between words are accounted for. One of the advantages of IAMs is the range of psycholinguistic effects they can explain, for instance word length, word sequence, word frequency and orthographic neighborhood effects, and their connection to neuroanatomical and neuroimaging data (Hofmann & Jacobs, 2014).

1.2.2. Computational models of decision making

Basing conclusions about cognitive processes exclusively on the analysis of mean correct response times neglects valuable information, such as incorrect response times, their respective distributions and accuracy data. Moreover, response time analysis can neither differentiate between several processing components, for instance visual encoding and processing of stimuli (Nazir et al., 1991; O'Regan & Jacobs, 1992), nor does it provide any information about decision strategies (Grainger & Jacobs, 1996; Wagenmakers et al., 2008) preceding the actual decision making process. Yet all these factors contribute to performance in a decision task.

In 1978, Ratcliff addressed these general issues by introducing diffusion models for analyzing two-alternative forced choice tasks. Similar to the MROM/AROM (*cf.* section *1.2.1. Computational models of reading*), a diffusion model conceptualizes the decision making process as a continuous sampling of information. This information accumulates over time and a response is given as soon as one of two decision thresholds is reached.

Incorporating a wider set of data, i.e., correct and incorrect RTs, their distributions as well as accuracy data, four parameters are described in the original model: a non-decision time (*t*) which corresponds to the time needed for stimulus encoding, configuration of task-related working memory, preparation and execution of motor response; a decision threshold (*a*), which represents the amount of information required for making a decision; a drift rate (*v*), which indicates the speed of evidence accumulation over time reflecting processing efficiency; and lastly a starting point (*z*), which maps potential a priori biases (Ratcliff, 1978; Voss et al., 2013). The starting point (*z*) is often set to .5, meaning that no preferences for one of the response options is assumed. Interpreting the other three parameters is fairly straight forward. Large parameter estimates for the non-decision time (*t*) are thought to reflect stimulus encoding difficulties whenever response preparation requires little effort (e.g., a simple button press). Large estimates for the decision threshold (*a*) represent a more conservative decision style while fast but consequently less accurate guesses result in small estimates, thus, accounting for the commonly observed speed-accuracy tradeoff. Finally, large estimates for the drift rate (*v*) signify faster information processing (Oganian et al., 2016; Ratcliff & Smith, 2010; Voss et al., 2013). Diffusion modeling has been applied to data from a variety of tasks, such as letter discrimination (Thapar et al., 2003), lexical decision (Ratcliff et al., 2004a) and semantic decision (Spaniol et al., 2006).

One of the drawbacks of diffusion modeling is, however, that it requires a relatively large number of data points per participant (Ratcliff & Tuerlinckx, 2002). Moreover, statistical inference is restricted to the specific sample not allowing for the investigation of interindividual differences (Vandekerckhove et al., 2011; Voss et al., 2013). By combining the advantages of diffusion models and hierarchical models (Gelman & Hill, 2007), Vandekerckhove et al. (2011) proposed a novel approach: the use of hierarchical diffusion models. Applying hierarchical diffusion modeling to decision data allows for estimating diffusion parameters in individuals even with only a small number of data points, making it an ideal method in fields such as psycholinguistics and reading, where it is not always possible to generate a large number of stimuli due to careful matching and multiple controls (Jacobs et al., 2015).

1.3. The Reading Brain and the Aging Brain

1.3.1. Neural correlates of reading

The reading brain needs to successfully integrate the sublexical, orthographic, phonological and lexico-semantic information of written words (*cf.* section *1.1.2. The basic subprocesses of reading in (late) adult life*). Previous research has identified functionally separable brain regions that are systematically linked to these four different types of information processing of words (e.g., Price, 2012; Welcome & Joanisse, 2012). For instance, neuroanatomical circuits associated with sublexical and orthographic processing consist of the left inferior and middle occipital gyri (IOG and MOG, respectively) and left ventral occipito-temporal regions (vOT), while phonological and lexico-semantic processes additionally recruit left inferior parietal, lateral temporal and bilateral frontal systems (e.g., Braun et al., 2015; Cavalli et al., 2016; Glezer et al., 2016; Jobard et al., 2003; McNorgan et al., 2015; Price, 2012; Schurz et al., 2014; Welcome & Joanisse, 2012).

The left vOT circuit seems to be particularly important when processing written stimuli. It comprises the fusiform gyrus (FG) and the inferior temporal gyrus (ITG); the latter including the so-called visual word form area (VWFA; Dehaene et al., 2002). Although being extensively researched, the specific function and the role of the vOT in reading is still a matter of ongoing debate (e.g., Cohen & Dehaene, 2004; Glezer & Riesenhuber, 2013; Kronbichler et al., 2007; Price & Devlin, 2003, 2011; Richardson et al., 2011; Schurz et al., 2014). Left inferior parietal regions associated with phonological and lexico-semantic processing include the supramarginal and angular gyrus (SMG, ANG), left lateral temporal regions comprise the superior temporal and the middle temporal gyri (STG, MTG). Bilateral regions consistently implicated in the frontal circuit are the inferior frontal gyrus (IFG) including opercular and triangular parts as well as the precentral and the middle frontal gyrus (PRG, MFG; e.g., Binder et al., 2009; Jobard et al., 2003; Joubert et al., 2004; Martin et al., 2015; McNorgan et al., 2015; Newman & Joanisse, 2011; Richlan et al., 2009). Recently, the right cerebellum as well as the bilateral supplementary motor area (SMA) have been identified as being consistently activated in the reading system of adult readers (Martin et al., 2015).

During reading acquisition, the neural reading network undergoes developmental changes as reading proficiency increases. A wealth of research has been dedicated to this neural development (e.g., Booth et al., 2004; Houdé et al., 2010; Liebig et al., 2017; Martin et al., 2015; Olulade et al., 2013; Turkeltaub et al., 2003). Many of these studies compared normally developing readers to poor readers or readers with dyslexia (e.g., Bach et al., 2010; Boros et al., 2016; Monzalvo et al., 2012; Shaywitz et al., 2007; van der Mark et al., 2009). Although behavioral studies indicate that increasing age impacts reading and some of its subprocesses (e.g., Allen et al., 1991; Thapar et al., 2003; Ziegler et al., 2014) there is an apparent lack of research investigating the neural changes within the reading network in old(er) age accompanying these age-related behavioral findings. To tackle this, the first step towards analyzing age-related differences in reading would be to systematically investigate and describe neural correlates of reading in older adults per se, including all four subprocesses. To my knowledge this has not yet been done: A negligence even more astonishing given the importance of reading in everyday life for older adults.

1.3.2. Neural correlates of cognitive aging

The age-related decline of cognitive functions such as memory operations and executive processes (i.e., the inhibition of irrelevant information, simultaneously handling multiple information, accurately manipulating information within working memory, and monitoring episodic memory operations; Cabeza & Dennis, 2013) has been undisputed (e.g., Craik, 1994; Hasher & Zacks, 1988; Lindenberger et al., 2008). These functions in concert with perceptual-attentional processes are needed to successfully recognize words (e.g., Jacobs, 2001; Jacobs & Ziegler, 2015; Just & Carpenter, 1992; Perry et al., 2007, 2010, 2013). So far, very little is known about age-related differences in neural correlates associated with single word recognition. It has been hypothesized, that age-related changes primarily occur within regions that are not typically linked to core language processing circuits, but to cognitive functions prone to age-related decline (e.g., Cho et al., 2012; Wingfield & Grossman, 2006).

The most prominent brain region consistently implicated in executive functions, working and episodic memory is the prefrontal cortex (PFC), which has also been found to be strongly affected by age-related changes in volume, structure and functional brain response (e.g., Lindenberger et al., 2013). However, despite these changes, some older adults show "youth-like" cognitive performance. Consequently, several mechanisms have been proposed to explain successful cognitive aging, for instance, maintenance, compensation and selection (e.g., Cabeza, 2002; Lindenberger, 2014; Reuter-Lorenz & Cappell, 2008).

Older adults who maintain high levels of cognitive performance are more likely to resemble younger adults in brain structure as well as functional brain response than older adults who show a marked decline in cognitive performance (e.g., Nagel et al., 2011). Successful compensation takes place when high levels of cognitive performance are linked with increases in brain activity or connectivity in older adults (e.g., Cabeza & Dennis, 2013).

Selection refers to the ability of some older adults to select an age-robust processing route from a formerly large pool of neural resources to successfully perform a given task (Lindenberger, 2014).

Declines in the behavioral performance of older adults together with recruitment of additional brain regions have been ascribed to dedifferentiation (Grady, 2012; Sugiura, 2016) or attempted compensation (Cabeza & Dennis, 2013; Reuter-Lorenz & Cappell, 2008). From the dedifferentiation perspective, the increase in neural activity is thought to reflect the reduced functional specialization of brain networks as neural representations become less distinct with increasing age (e.g., Carp et al., 2011; Li et al., 2001).

Given the evidence for neurocognitive aging and its underlying proposed mechanisms, age-related differences in reading are hardly interpretable without drawing on at least one of these theories. Yet, age-related differences in neural correlates of reading have scarcely been discussed within this framework. It remains an open question whether age affects sublexical, orthographic, phonological and lexico-semantic processing in a unitary, holistic way or whether different mechanisms apply to the different subprocesses of reading.

1.4. Memory Processes in Reading and Aging

1.4.1. Memory functions and aging

Aging is a highly individual process that is marked by a decrement in neurochemical, anatomical and functional brain resources, which in turn affects mechanisms supporting WM and EM (Lindenberger et al., 2008). Memory performance has been found to decline with age (e.g., Craik, 1994; Lindenberger et al., 2008; Salthouse, 2003). However, the magnitude as well as the onset of the decline seem to depend on the type of memory function as well as on the type of data used (cross-sectional vs. longitudinal). For instance, while WM and EM show a roughly similar life-long decline, performance in autobiographical memory appears to be stable across the lifespan (e.g., Grady & Craik, 2000; Hedden & Gabrieli, 2004; Salthouse, 2003). Furthermore, cross-sectional studies found the decline in both WM and EM performance starting as early as in the 20s. However, results from longitudinal studies, which control for possible cohort effects, indicate a relatively stable EM performance up until approximately 60 years of age – only then does the decline seem roughly similar for both cross-sectional and longitudinal data (e.g., Hedden & Gabrieli, 2004; Rönnlund et al., 2005; Siegel, 1994). Additional factors contributing to the magnitude of the decline in memory operations are task complexity and specific processing demands (e.g., Craik, 1994; Salthouse et al., 1989; Siegel, 1994). More specifically, while late-life WM performance seems to depend on age-related slowing and decrements in inhibitory control, reductions in EM performance have been associated with age-related changes in WM and perceptual speed (e.g., Borella et al., 2011; Head et al., 2008; Hertzog et al., 2003). Despite this ample research about age-related declines in memory functions and their well-known supportive roles for successful reading (*cf.* sections *1.4.2. Working memory, aging and reading*, *1.4.3. Episodic memory, aging and reading*), it is currently still an open issue how age-related declines in WM and EM specifically affect the subprocesses of reading, especially at the single word level.

1.4.2. Working memory, aging and reading

The importance of WM for reading has been well established (e.g., Baddeley et al., 1985; Daneman & Carpenter, 1980; Daneman & Merikle, 1996). One of its key functions is the maintenance and updating of surface, text-based and situation models (Borella et al., 2011; Zwaan, 2015). Individual differences in reading comprehension have been suggested to be the result of differences in WM capacity (Daneman & Carpenter, 1980; Daneman & Merikle, 1996). Readers with high WM capacities, as assessed by reading span, for example, are notably faster at dissolving lexical ambiguities encountered in sentences than those with small WM capacities (Miyake et al., 1994). A meta-analysis of both child and adult data indicates that differences in reading comprehension with respect to WM differences depended on the modality of the WM task administered (e.g., visuo-spatial vs. verbal) as well as on its complexity and demands towards other (underlying) cognitive processes (e.g., attentional control; Caretti et al., 2009). Moreover, the predictive power of WM on text comprehension is also determined by the task with which the latter is measured (*cf.* DeDe et al., 2004).

Studies investigating age-related differences in text comprehension suggest a decline in accessing surface or text-based levels of representation but no notable difference has been observed between younger and older adults in situation model processing (Radvansky & Dijkstra, 2007). Furthermore, in (poetry) reading WM is a necessary qualification for integrating words and text aspects (e.g., phonological, syntactic and lexico-semantic) to derive meaning and to keep lexical building blocks activated (Jacobs & Willems, 2017). Importantly for the present work, studies applying multivariate approaches to separate the influence of declining cognitive processes in older adults on text comprehension found ambiguous results concerning WM. It has been reported both as the single direct contributor to age-related differences in comprehension performance (Borella et al., 2011; Van der Linden et al., 1999), exerting only a direct influence for sentence and text comprehension yet not for online syntactic processing (DeDe et al., 2004) and as having no explicit effect on language performance (Kwong See & Ryan, 1995). The latter study found age-related differences in text comprehension to be predicted by age-related changes in processing speed (PS) and inhibitory control processes whereas the former studies proposed only an indirect influence of PS and inhibition efficacy through directly contributing to age-related changes in WM (*cf.* Borella et al., 2011; Van der Linden et al., 1999).

1.4.3. Episodic memory, aging and reading

However, focusing solely on WM as the only memory function promoting successful text comprehension seems to neglect the importance of EM for word recognition and reading. Neurobiological evidence from functional connectivity analyses indicates that readers with high WM capacities may benefit from their ability to form elaborate event representations. These are partly based on the engagement of EM systems which activate and integrate information of previously experienced events or schematic abstractions (Newman et al., 2013). Further support for a “shared” contribution of WM and EM to reading was provided by Frick et al. (2011) who observed significant correlations between reading irregular words as measured by the National Adult Reading Test (NART; Nelson, 1982; Nelson & Willison, 1991) and both verbal EM and WM measures. Despite these findings, surprisingly little research has been dedicated to the investigation of the interplay of EM processes and reading and to the effects of age-related decline in EM on word recognition and reading.

At the behavioral level, findings from word recognition studies suggest that individual exposure to words, i.e., personal experience with written and spoken language, influences the speed of lexical access: Word frequency effects were found to be greater for subjective than for objective frequency measures, and when objective frequency measures were adapted to specifically fit the mental lexicons of the cohort in question (Balota et al., 2004; Dorot & Mathey, 2010). At the neural level, engagement of the FG, a region reliably implicated to be of central importance for word processing (*cf.* section *1.3.1. Neural correlates of reading*), has been linked to recognition performance with higher activation indicating better EM performance (Mei et al., 2010). Similarly, in semantic decision tasks, better recognition performance lead to increased activity in the hippocampal complex, a brain structure consistently associated with EM (e.g., DeQuervain & Papassotiropoulos, 2006; Otten et al., 2001; Wagner et al., 1998). Furthermore, during poetry reading, brain regions associated with

EM seem to be particularly engaged (Jacobs, 2015; Zeman et al., 2013). Consequently, it has been suggested that this activity may greatly depend on the formation of and preference for mental simulation during reading due to the individual personal experiences of the readers (Jacobs & Willems, 2017).

Given the empirically and theoretically close relationship between WM, EM and reading, it is as yet an open question how these memory functions affect sublexical, orthographic, phonological and lexico-semantic processing as well as sentence comprehension, particularly (but not exclusively) in older adults.

1.5. Research Questions and Hypotheses

The overall aim of this dissertational project was to investigate the four basic subprocesses of reading in older and younger adults as well as the cognitive and neural mechanisms underlying successful word recognition and reading. For this purpose, I reviewed existing literature (study 1) and conducted three empirical studies (studies 2 – 4). The review focused on summarizing age effects on central measures of visual word recognition, such as frequency, word length and orthographic neighborhood thus providing an overview of the current research. However, my search of the literature mainly yielded information on sublexical and orthographic processing. Therefore, the objective of study 2 was to systematically investigate the impact of age, not only on sublexical and orthographic, but also on phonological and lexico-semantic processing by applying a hierarchical diffusion modeling approach to a very large behavioral data set. To explore neural correlates associated with age-related effects on the four basic subprocesses of reading, a third study was conducted using functional magnetic resonance imaging (fMRI). Finally, based on results from study 3, study 4 concentrated on the contribution of memory processes to successful word recognition, which are clearly marked by an age-related cognitive decline. In the following, research questions and related hypotheses are described in more detail.

1.5.1. Study 1: Verändert sich Lesen im Alter? Alterseffekte in der visuellen Worterkennung [Does reading change with age? A review of aging effects on visual word recognition]

Research question 1: Do younger and older adults differ with respect to central measures of visual word recognition?

This question was based on the inconclusive findings regarding age-related effects on word frequency, word length and orthographic neighborhood and their theoretical implication for successful sublexical and lexical processing as described in section *1.1.1. Principles and central measures of visual word recognition*. Well-established tasks to investigate these central measures of visual word recognition are lexical decision, naming and perceptual identification (Jacobs & Grainger, 1994; *cf.* section *1.1.1. Principles and central measures of visual word recognition*). As effects of word length and orthographic neighborhood differ across these three paradigms, we focused on results obtained within lexical decision making. The lexical decision task is not only the most popular task of these three tasks, but it is explicitly recommended as a standard task for researching visual word recognition (Paap et al., 1987). Thus, the aim of the review was, firstly, to give an overview over the existing literature on age-related effects on visual word recognition found during lexical decision making under consideration of potential confounds such as vocabulary or years of education. Secondly, its objective was further to provide a starting point for further research using multimethod approaches to systematically investigate age-related effects in visual word recognition and reading. Due to the nature of this work, no hypotheses were brought forward.

1.5.2. Study 2: Drifting through Basic Subprocesses of Reading: A Hierarchical Diffusion Model Analysis of Age Effects on Visual Word Recognition

Research Question 2a**:** What is the impact of age on the four basic subprocesses of reading?

Research Question 2b**:** Which model parameters are affected by age?

Research Question 2c: Can reading proficiency account for previously reported inconsistent age-related findings during visual word recognition?

With the exception of age-related effects on word frequency, results from the review were rather mixed and could not, as yet, answer the question whether younger and older adults process written words differently. Besides, the review focused on sublexical and lexical/orthographic measures, thus providing no information with regard to age-related effects in phonological and semantic processing. As described in section *1.1.2. The basic subprocesses of reading in (late) adult life* there is little research on phonological processing in aging adults while for semantic processing findings are somewhat inconclusive. Moreover, the majority of results is based on the analysis of mean correct RTs and/or accuracy rates, which poses difficulties in interpreting these results as older adults are known to respond more slowly than younger adults (Salthouse, 1996) and this may therefore mask subtle processing differences. To circumvent this problem, diffusion models have been introduced (e.g., Ratcliff, 1978, 2008; Ratcliff et al., 2004a,c; *cf.* section *1.2.2. Computational models of decision making*). Applying a diffusion modeling approach to the data has the additional advantage of disentangling processes such as the decision threshold (a), the time needed to make a decision (t) and the speed of information uptake (v), which may be affected by age. The aim of study 2 was to systematically investigate the impact of age on the four basic subprocesses of reading and to identify model parameters affected by age. Additionally, as older adults tend to show greater behavioral heterogeneity than younger adults (e.g., Baltes & Lindenberger, 1997; De Frias et al., 2007; Lindenberger, 2014; Nagel et al., 2011) the older age group was divided into two proficiency groups to account for this increased variance. Based on previous findings, it was hypothesized:

Hypothesis 2a: Non-decision time (*t*) in older adults is longer than in younger adults.

Hypothesis 2b: The decision threshold (*a*) is higher in older adults than in younger adults.

Hypothesis 2c: Drift rates (*v*) are lower in older adults than in younger adults within sublexical processing.

Hypothesis 2d: Drift rates (*v*) of younger and older adults do not differ within orthographic and lexico-semantic processing.

Hypothesis 2e: Drift rates (*v*) of older adults might be lower than those of younger adults in phonological processing.

1.5.3. Study 3: Same, same but different: Processing words in the aging brain

Research Question 3: What are the similarities and differences in brain activation associated with the subprocesses of reading in healthy younger and older adults? Do the results in fact imply (in)stability of these processes across the lifespan?

Results from study 2 suggested age-related slowing in the speed of information uptake in sublexical and phonological processing, while in orthographic and lexico-semantic processing, highly skilled older readers outperformed younger adults. Less skilled older readers, however, were slowest in all four subprocesses. From these findings alone, it is impossible to tell whether the observed age-related differences originate from age-related differences specific to these subprocesses or possibly from differences in functions supporting the component processes of reading (e.g., memory operations, executive functioning). Keeping this in mind and given the importance of reading in everyday life for older adults, it is astonishing that despite the large number of studies investigating neural correlates associated with the subprocesses of reading in the developing and younger brain (e.g., Booth et al., 2004; Cavalli et al., 2016; Liebig et al., 2017; Martin et al., 2015; Price, 2012; Welcome & Joanisse, 2012), only few studies have focused on brain activity patterns of these subprocesses in healthy older readers. An investigation systematically examining and describing sublexical, orthographic, phonological and lexico-semantic processing within one sample is still missing. The aim of the study was therefore to investigate similarities and differences in the neural correlates associated with the four central subprocesses of reading and to describe these associations in the aging brain.

Hypothesis 3a: Given the fact that reading performance in general is relatively well maintained over the lifespan, older and younger adults were expected to recruit a similar set of brain regions associated with sublexical, orthographic, phonological and lexico-semantic processing.

Hypothesis 3b: If the subprocesses of reading were indeed stable over the life span then no age-related differences should be observed in terms of accuracy rates as well as within the core regions of the neural reading network. Rather age-related differences should occur in brain regions consistently associated with cognitive functions supporting reading, for instance WM and EM.

Hypothesis 3d: If the subprocesses of reading themselves are affected by age, then we would expect age-related differences within core reading regions. However, as cognitive aging is marked by a decline in executive functions and memory operations, we would still assume to find age-related differences in regions associated with these processes.

1.5.4. Study 4: Age-related differences in the subprocesses of reading and sentence comprehension: The impact of working and episodic memory

Research Question 4: How do WM and EM influence the subprocesses of reading and sentence comprehension in younger and older adults?

This study was motivated by two major findings. Firstly, whereas reading performance seems to be relatively stable over the lifespan (e.g., Cohen-Shikora & Balota, 2016; de Beni et al., 2007), WM and EM are prone to age-related decline (e.g., Hedden & Gabrieli, 2004). Secondly, a subset of the results from study 3 implicated age-related activation differences during single word processing in brain structures usually engaged in memory processes during orthographic, phonological and lexico-semantic processing. Using multivariate approaches, it has been shown that age-related changes in WM seem to influence age-related differences in text comprehension. Age-related changes in WM in turn are thought to be mediated by the impact of age on inhibitory control processes and PS (e.g., Borella et al., 2011; Van der Linden et al., 1999). Yet, very little is known about the impact of WM on single word recognition, i.e., on the four central subprocesses of reading. The same holds true for EM, although there is evidence that suggests an active involvement of EM processes in reading (e.g., Frick et al., 2011; Mei et al., 2010; Newman et al., 2013). Therefore, study 4 aimed at investigating the influence of WM and EM on the four subprocesses of reading and reading in general in younger and older adults by applying a structural equation modeling approach. The following hypotheses were put forward:

Hypothesis 4a: Younger adults respond faster in tasks tapping the four subprocesses of reading as well as in two tasks measuring PS, and outperform older adults in memory performance.

Hypothesis 4b: WM and EM are thought to significantly contribute to sentence reading and possibly to single word reading.

Hypothesis 4c: PS, WM and EM should correlate with each other, as should the four subprocesses of reading.

Hypothesis 4d: The four subprocesses of reading (i.e., sublexical, orthographic, phonological and lexico-semantic) are assumed to predict sentence reading performance.

Hypothesis 4e: Due to relatively stable reading performance across the life span, little or no age-related differences are expected with regard to the influence of the four central subprocesses of reading on sentence reading.

Hypothesis 4f: In accordance with previous studies using structural equation modeling, an age-related difference was assumed for the influence of WM and EM on sentence comprehension, yet no such assumption could be made for word reading due to the lack of data.

1.6. General Methodology

1.6.1. Study 1 – Review

To identify potential studies for the review, an extensive literature search was conducted covering databases such as PubMed, Science Direct, Google Scholar, Isi Web of Knowledge, DIMDI, MEDLINE, PsycINFO and PsychNET. Key words used included the English and German terms *aging, old age, elderly, older/younger adults, visual word recognition, reading, lexical decision, lexical access, neural correlates, fMRI, PET, MEG, frequency, word length, orthographic neighborhood, review* as well as *meta-analyses*. Additionally, reference sections of relevant literature were scanned for further studies regarding the topic. This procedure led to the identification of 16 studies, which had been published until January 2014.

1.6.2. Experimental samples (studies 2 – 4)

Studies 2 to 4 of this dissertational work employed mixed-model designs with age as between-subjects variable and task as within-subjects variable. Due to the methodology (measurement of response times, accuracy rates and BOLD-signal) all studies were conducted in a laboratory setting at Freie Universität Berlin (study 3) or at Charité Campus, Berlin (studies 2 and 4). Subsamples from the Berlin Aging Study II cohort (BASE-II; Bertram et al., 2014) of 1,807 and 1,532 participants (younger adults: 384/309; older adults: 1,423/1,223) were recruited in studies 2 and 4, respectively. Twenty-five younger and 58 older adults participated in study 3. All participants were German native speakers, right-handed, and had normal or corrected-to-normal vision. None of the participants had a history of reading difficulties or language impairment, neurological disease, psychiatric disorders or a history of head injuries. Prior to testing, participants gave written informed consent and received financial compensation. Studies 2 and 4 were approved by the Ethics Committee of the Max Planck Institute for Human Development, study 3 by the Ethics Committee of the Freie Universität Berlin.

1.6.3. Tasks (studies 2 – 4)

In order to assess sublexical, orthographic, phonological and lexico-semantic processing in study 2 to 4, we administered four two-alternative forced decision tasks, each tapping one of these specific subprocesses of reading. In all of these tasks participants had to give a yes response in case a target stimulus was presented and a no response in case a non-target was shown. In the letter identification task, participants were asked to indicate whether a string of letters contained the letter *r* (target) or not (sublexical processing). In the lexical decision task participants had to judge whether a word (target) or a pseudohomophone was presented (orthographic processing). In the phonological decision task participants were shown a pseudohomophone (target) or a pseudoword (phonological processing) and in the semantic decision task participants had to indicate whether the presented stimulus was a living object (target) or not (lexico-semantic processing). For each task, we carefully selected 40 targets and 40 non-targets. To control for confounding linguistic variables and to ensure comparability of results, words and word-based stimuli were matched for (base) word frequency, item length, number of orthographic neighbors and bigram frequency based on the dlex database (dlexDB; Heister et al., 2011) norms for German words. To measure overall reading ability, a computerized sentence comprehension task (*cf.* Bergmann & Wimmer, 2008; Wimmer et al., 2010) was employed in studies 2 and 4. In this task, participants had to judge whether each of a total of 77 successively presented sentences was meaningful or not. Sentence length as well as its morpho-syntactic complexity increased over the course of the task. In study 4, we also measured WM performance by administering a spatial updating task, a letter updating task and a number-n-back task. EM performance was assessed by means of a scene encoding task, a verbal learning and recognition task, a face-profession task and an object location memory task (*cf.* Düzel et al., 2016). Additionally, four measures of processing speed were obtained by conducting a multi-source interference task (*cf.* Bush & Shin, 2006), a digit symbol substitution test (*cf.* Wechsler, 1997) and a basic pattern recognition task for which participants had to indicate whether a string of tilted slashes pointed in the same direction (target; e.g. /////) or not (e.g., ///\/).

1.6.4. Data analysis (studies 2 – 4)

To analyze response times and accuracy rates in studies 2 to 4, we applied a mixed-effects modeling approach (Baayen et al., 2008). This approach permits the inclusion of several random factors, therefore allowing the modeling of random variance in participants as well as in items, making its application particularly suitable for linguistic research. RTs were analyzed by way of linear mixed-effects regression, accuracy using logistic mixed-effects regression. Memory, sentence comprehension and processing speed scores obtained in study 4 were analyzed using independent t-tests. All analyses were run in R version 3.3.0 (R Core Team, 2015).

In study 2, data was additionally analyzed using a hierarchical diffusion modeling approach (Vandekerckhove et al., 2011). As described in section *1.2.2. Computational models of decision making*, this relatively novel approach combines the advantages of both diffusion models (e.g., Ratcliff, 1978; Ratcliff & McKoon, 2008; Ratcliff & Rouder, 1998) and hierarchical models (e.g., Gelman & Hill, 2007). For each of the four tasks assessing the subprocesses of reading, we created a model in which the parameters non-decision time (t), decision threshold (a), with the upper threshold being the correct response and the lower threshold being the incorrect response, as well as drift-rate (v) were estimated for all participants simultaneously. Parameters were estimated using a Bayesian approach, posterior distribution was approximated by means of Markov chain Monte-Carlo sampling (*cf.* Kruschke, 2015). Model convergence was assured by visually inspecting the traces of the posterior distribution and by calculating Gelman-Rubin statistics (Gelman & Rubin, 1992). The Python (version 3.5.1; Python Software Foundation, https://www.python.org/) toolbox HDDM (version 0.6.0; Wiecki et al., 2013) was used for fitting the hierarchical diffusion models to the data and for performing Bayesian hypotheses testing.

To investigate age-related differences in neural correlates of reading, study 3 employed fMRI. fMRI, as a non-invasive measure, makes it possible to indirectly assess brain activity by detecting changes occurring in the blood oxygen level (BOLD; Logothetis & Wandell, 2004; Ogawa et al., 1990) providing at the same time good spatial and temporal resolution. Despite the advantages this methodology offers, conclusions about cognitive processes involved are often drawn from reverse inference and should be judged with care, for instance by considering the task setting used (Hutzler, 2014; Poldrack, 2011). In addition to the four tasks tapping the subprocesses of reading, in the third study of the dissertational work the basic pattern recognition task served as an explicit baseline task. SPM12 software (revision 6685; Statistical Parametric Mapping, Wellcome Department of Imaging Neuroscience, University College London, UK, 2014) running in a Matlab 2016a (Mathworks Inc., Natick, MA, USA) environment was used for preprocessing and statistically analyzing MRI data. Preprocessing of functional images included slice timing correction, realignment, co-registration and spatial normalization. At the subject level, data was statistically analyzed by first constructing a GLM modeling the block onsets of each task with a canonical hemodynamic response function and including the six realignment parameters as regressors of no interest in the model space. Subsequently, subject-specific contrast images (reading task > baseline task) were calculated and entered into a second-level group by task flexible factorial design analysis with subject serving as a random effect.

In study 4, we used structural equation modeling (SEM) to investigate the influence of WM, EM and processing speed on the subprocesses of reading and sentence comprehension in younger and older adults. Prior to conducting SEM analyses, we performed confirmatory factor analyses (CFA) to assess qualities of the measurement models, to identify the multigroup baseline model and to evaluate cross-group metric and scalar equivalence (*cf.* Brown, 2006; Byrne, 2008; Steinmetz, 2014; Weiber, 2014). Due to the non-normal distribution of the data, the robust maximum likelihood estimator was applied for all analyses. Missing data was handled using a full information maximum likelihood approach. Model fit was assessed by means of chi-square tests, root mean square error of approximation (RMSEA), on the comparative fit index (CFI) and the standardized root mean square (SRMR; Brown, 2006). All models were tested in R using the “lavaan”-package (Rosseel, 2012).

The next four chapters (sections 2 – 5) will contain the review (study 1) and the three empirical studies (studies 2 – 4). A brief summary of each of the studies is provided below (section *1.7. Summary of Studies*).

1.7. Summary of Studies

1.7.1. Study 1: Verändert sich Lesen im Alter? Alterseffekte in der visuellen Worterkennung [Does reading change with age? A review of aging effects on visual word recognition]

This study addressed the first research question: Do younger and older adults differ with respect to central measures of visual word recognition? This study was motivated by seemingly inconsistent and sparse findings regarding age-related differences with respect to word frequency, word length and orthographic neighborhood effects. Therefore, this review was intended to summarize studies researching age-related differences in visual word recognition. To do so, we focused on the above-mentioned variables which are typically used to investigate lexical and sublexical processing, respectively. A total of sixteen studies were identified, with the majority of studies researching word frequency effects (15 studies), followed by word length effects (6) and orthographic neighborhood effects (3). Especially the age-equivalent effects of word frequency seem to point towards a preservation of lexical processes up into old age. However, findings regarding orthographic neighborhood effects suggest possible age-related differences in lexical activation and inhibition processes. Age-related effects on word length are ambiguous, but may imply differences between older and younger adults in sublexical processing. The review also revealed an apparent lack of studies investigating neural correlates of aging readers as well as of studies employing transparent orthographies, such as German.

1.7.2. Study 2: Drifting through Basic Subprocesses of Reading: A Hierarchical Diffusion Model Analysis of Age Effects on Visual Word Recognition

Study 2 focused on the following research questions: What is the impact of age on the four basic subprocesses of reading? What model parameters are affected by age? Can reading proficiency account for previously reported inconsistent age-related findings during visual word recognition? To answer these questions, we applied hierarchical diffusion modeling to a large sample of 1,807 participants (young, *N* = 384; old, *N* = 1,423) who performed four two-alternative forced choice tasks, each tapping one of the four central subprocesses of reading (i.e., sublexical, orthographic, phonological and lexico-semantic processing). As older adults typically show greater behavioral heterogeneity in performance than younger adults, we additionally grouped older adults into high- and low-performing readers. The model-guided approach allowed us to differentiate between age-related differences in non-decision time, decision threshold and speed of information uptake. Longer non-decision times as well as more conservative decision thresholds were observed for the older sample. However, speed of information uptake differed as a function of age group, reading performance and task. While high-performing older adults outperformed younger adults at the speed of information uptake in orthographic and lexico-semantic processing, both groups of older adults showed age-related disadvantages in sublexical and phonological processing. In fact, low-performing older adults showed the slowest information uptake in all four subprocesses. Relating these findings to computational models of word recognition, we discussed potential inefficiencies of older adults in temporal sampling and activation and/or inhibition processing. Furthermore, our results implicated the need for more research regarding the topic, especially at the neural level.

1.7.3. Study 3: Same, same but different: Processing words in the aging brain

Study 3 revolved around the similarities and differences in brain activation patterns of healthy younger and older adults. Using fMRI, we investigated whether central subprocesses of reading (i.e., sublexical, orthographic, phonological and lexico-semantic) are in fact affected by age. For this purpose, 20 younger (range 22 – 35 years) and 38 older (range 65 – 76 years) adults participated in a series of four decision tasks specifically assessing these subprocesses (i.e., letter identification task, lexical, phonological and semantic decision task), while their brain activation was being recorded. Our results showed that younger and older adults engaged an identical set of reading-related brain regions, indicating a preservation of neural circuits associated with component processes of reading across the lifespan. However, at the same time, we observed age-related differences within these circuits despite an age-equivalent behavioral performance, which led us to conclude that despite the similarities, age indeed impacts the subprocesses of reading. The marked increase of the BOLD signal in older adults was especially noticeable during phonological and orthographic processing, possibly because of older adults' disadvantage in neurally suppressing a non-optimal processing route. Moreover, outside reading-related brain regions, older adults displayed distinct frontal midline activation, pointing towards a stronger involvement of memory operations, attentional processes and executive functions in older adults during single word recognition.

1.7.4. Study 4: Age-related differences in the subprocesses of reading and sentence comprehension: The impact of working and episodic memory

The aim of study 4 was to investigate the influence of WM and EM on the subprocesses of reading and sentence comprehension as a function of age. To do so, 309 younger (range 23 – 39 years) and 1,223 older adults (range 60 – 84 years) participated in a set of WM and EM tasks tapping different memory modalities (e.g., verbal, numerical, or figural-spatial). Furthermore, participants performed four decision tasks addressing sublexical, orthographic, phonological and lexico-semantic processing and finally completed a sentence comprehension task. Additionally, to account for age-related differences in PS, four simple speed measures were obtained. We then combined latent variables of PS, WM, EM, sublexical, orthographic, phonological and lexico-semantic processing as well as sentence comprehension into a multigroup structural equation model. The results showed that WM/EM contributed significantly to sentence comprehension regardless of age. However, while both memory functions seem to be supportive for older adults, for younger adults this beneficial effect was limited to WM. In contrast, the influence of EM on sentence comprehension was negative for the younger age group. At the subprocess level, we found age-related differences in the association of EM with orthographic processing yet no reliable effects of EM on any of the four subprocesses in neither younger nor older adults. For the latter group WM was identified to positively contribute to sublexical, orthographic, phonological and lexico-semantic processing. Regardless of age, the subprocesses of reading were reliably associated with sentence comprehension (with the exception of phonological processing in younger adults). Yet, an impact of age was only identified for lexico-semantic processing. The findings were attributed to compensational mechanisms due to age-related declines in memory functions, selection processes of choosing an optimal processing route, as well as age-related differences in response strategies and the construction and updating of situation models.

2. Verändert sich Lesen im Alter? Alterseffekte in der visuellen Worterkennung [Does reading change with age? A review of aging effects on visual word recognition]

This chapter has been published as (see Appendix A.1. for an extended abstract in English):
Froehlich, E., & Jacobs, A. M. (2016). Verändert sich Lesen im Alter? Alterseffekte in der visuellen Worterkennung [Does reading change with age? A review of aging effects on visual word recognition]. *Lernen und Lernstörungen*, *5*, 95-109.
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2.1. Fokus der Übersichtsarbeit

Lesen ist eine für die moderne Gesellschaft unentbehrliche Tätigkeit, die unseren Alltag in einem solchen Maße durchdringt, dass ihre Ausübung automatisch und selbstverständlich erscheint (Heine et al., 2012). Einmal gelernt, vertrauen wir darauf, bis an unser Lebensende problemlos lesen zu können. Dieses Selbstverständnis relativiert sich jedoch mit dem Wissen, dass erfolgreiches Lesen auf dem Zusammenspiel zahlreicher komplexer Prozesse beruht: Muster- und Buchstabenerkennung, Integration einzelner Buchstaben zu größeren lexikalischen Einheiten, Zuordnung dieser Buchstabengruppen zu bestimmten Lauten, Ganzworterkennung, morpho-syntaktische, semantische und globale Textverständnisprozesse, sowie reflektive oder ästhetische Vorgänge (Jacobs, 2011). Letztere, höhere Verarbeitungsprozesse der geschriebenen Sprache, können jedoch nur dann fruchtbar ins Spiel kommen, wenn die zugrunde liegende visuelle Worterkennung optimal funktioniert. Die visuelle Worterkennung bildet demnach die Basis für flüssiges Lesen (Grainger & Jacobs, 1996). Tatsächlich wird der Untersuchung des einzelnen Wortes bei der Entwicklung zentraler Konzepte in der kognitiven Psychologie und Psycholinguistik eine so hohe Bedeutung zugeschrieben, dass sie mit der Bedeutung der Zelle in der Biologie verglichen wird (Balota et al., 2004).

Die Frage nach den Faktoren, die beim Leseerwerb eine Rolle spielen, ist über verschiedene Sprachen hinweg intensiv untersucht und dokumentiert worden (z.B. Frith et al., 1998; Seymour et al., 2003; Ziegler et al., 2010; Zoccolotti et al., 2008). Ähnlich verhält es sich mit der Entwicklung von Leseprozessen bis ins junge Erwachsenenalter, wobei neben dem Verhalten sowohl die mit dem Lesen assoziierten Blickbewegungen als auch Gehirnaktivierungen erfasst wurden (z.B. Dehaene et al., 2002; Grainger & Holcomb, 2009; Kliegl et al., 2012; Price, 2012). Angesichts der Tatsache, dass Lesen eine Fertigkeit ist, bei der zwar einerseits auf eine lebenslange Expertise im Umgang mit Sprache und Texten zurückgegriffen wird, andererseits aber auch kognitive Prozesse im Spiel sind, die sich mit zunehmendem Alter verschlechtern (z.B. das Arbeitsgedächtnis; Lindenberger et al., 2008), ist es in diesem Kontext erstaunlich, dass systematische Untersuchungen der Leseprozesse im hohen Alter bis heute kaum existieren, obwohl dieser Missstand schon vor 17 Jahren betont wurde (Aberson & Bouwhuis, 1997).

Ziel dieser Arbeit ist es, einen Überblick über die Untersuchungen zur visuellen Worterkennung im Alter und damit zum derzeitigen Forschungsstand bereitzustellen. Hierfür werden zunächst die Grundlagen und Effekte der visuellen Worterkennung, danach das methodische Vorgehen dieser Arbeit dargestellt. Anschließend werden die Ergebnisse zur untersuchten Thematik hinsichtlich ihrer Kausalität und in Hinblick auf mögliche Implikationen für zukünftige Forschungsarbeiten diskutiert.

2.1.1. Grundlagen der visuellen Worterkennung

Hinter der visuellen Worterkennung verbergen sich zahlreiche elementare Vorgänge, die sich in ihrem Ablauf bei jedem gelesenen Wort wiederholen. Vereinfacht zusammengefasst, wird bei jeder Betrachtung eines Wortes im Gehirn zunächst eine Repräsentation der visuellen Wortform (re-)konstruiert, welche als Basis für komplexe Wechselwirkungen mit gespeichertem Sprachwissen dient (Grainger & Jacobs, 1996). Aus dieser nonlinearen, dynamischen Interaktion zwischen äußerer Reizung und Gehirn entstehen so erst die orthographischen, phonologischen oder semantischen „Worteigenschaften“ kontextabhängig in Analogie zur Funktionsweise von Computermodellen der Muster- und Worterkennung (Jacobs & Graf, 2005).

Zusammengefasst beruht Lesen, dessen Grundlage die visuelle Worterkennung darstellt, auf zentralen, visuellen, orthographischen, phonologischen, morphosyntaktischen, und semantischen Prozessen sowie deren Interaktion mit Arbeits- und Langzeitgedächtnis. Just und Carpenter (1980) bemerken jedoch treffend, dass es deutlich einfacher ist, sich auf diesen Punkt zu einigen, als eine konkrete Spezifizierung der Eigenschaften der jeweiligen Subprozesse, deren Zusammenspiel und deren Auswirkungen auf das Leseverhalten festzulegen. Zur systematischen Bewältigung dieser Aufgabe wurden verschiedene Formate von Worterkennungsmodellen entwickelt, die in Jacobs und Grainger (1994) erstmalig formal spezifiziert wurden. Grundsätzlich sollte jedes Modell der Muster- bzw. Worterkennung Hypothesen über die Funktionen der beteiligten Prozesse aufstellen und diese mittels geeigneter Paradigmen, möglichst multimethodal verifizieren oder falsifizieren (Jacobs & Grainger, 1994; Jacobs & Hofmann, 2013). Auf kognitiver Ebene gab es in der Vergangenheit zahlreiche Versuche, visuelle Worterkennung zu modellieren. Populäre Modelle sind z.B. die Gruppen der Zwei-Pfad-Modelle (z.B. Dual Route Cascaded Model [DRC]; Coltheart et al., 1993, 2001; Connectionist Dual Process Model [CDP]; Perry et al., 2007, 2010; Zorzi et al., 1998) und der interaktiven Aktivationsmodelle (IAMs; McClelland & Rumelhart, 1981; MROM; Grainger & Jacobs, 1996). Allgemein gehen Zwei-Pfad-Modelle davon aus, dass Wörter über eine lexikalische Route (Ganzworterkennung) oder über eine nicht-lexikalische (phonologische) Route erlesen werden. IAMs postulieren, dass ein bestimmtes lexikalisches Aktivierungsniveau überschritten werden muss, um ein Wort erfolgreich zu erkennen, wobei orthographische (Grainger & Jacobs, 1996), phonologische (Jacobs et al., 1998), und semantische (Hofmann et al., 2011) Repräsentationen zusammenwirken, jedoch kein zweiter sublexikalischer Pfad im Spiel ist. Während Zwei-Pfad-Modelle eher zur Erklärung von Aneignungs- und Produktionsprozessen des Lesens herangezogen werden, betrachten IAMs die Worterkennung als einen Spezialfall der Mustererkennung. Der Konzeption beider Modelltypen gemeinsam ist, dass sie die Leseleistungen in den in der Tabelle 2.1 genannten Worterkennungsparadigmen erklären und vorhersagen sollen.

Tabelle 2.1

Gängige Paradigmen zur Untersuchung der visuellen Worterkennung

Häufig verwendete Standardtests zur Untersuchung der visuellen Worterkennungsleistung sind die perzeptive Identifikationsaufgabe, die Benennungsaufgabe und die lexikalische Entscheidungsaufgabe (Jacobs & Grainger, 1994), die sich in gleicher Weise zur Erfassung von behavioralen und hirnelektrischen/neurofunktionalen Daten eignen (Jacobs & Ziegler, 2014).

Perzeptive Identifikationsaufgabe

In der perzeptiven Identifikationsaufgabe wird den Probanden für einige Millisekunden ein Wort auf einem Bildschirm präsentiert und anschließend maskiert, z.B. durch das Einblenden von Symbolzeichen (Ratcliff et al., 1989). Anschließend soll der Proband angeben, welches Wort er gerade gesehen hat. Die Interpretation der Ergebnisse ist insofern schwierig, als dass der Anteil korrekt identifizierter Wörter von der Gesamtzahl präsentierter Wörter auch durch das Erraten des Wortes auf Grund einiger erkannter Buchstaben zustande gekommen sein kann (Ziegler et al., 1998). Die perzeptive Identifikationsaufgabe war eines der ersten Paradigmen, das zum Studium der visuellen Worterkennung herangezogen wurde. Sie wird heutzutage jedoch wegen o.g. Nachteile eher selten verwendet (New et al., 2006).

Lexikalische Entscheidungsaufgabe

Bei der lexikalischen Entscheidungsaufgabe wird den Versuchspersonen eine einzelne Buchstabenfolge auf einem Bildschirm gezeigt. Diese Buchstaben bilden entweder ein Wort oder haben keine Bedeutung. Die Aufgabe des Probanden besteht darin, so schnell wie möglich zu entscheiden, ob es sich um ein Wort oder handelt oder nicht. Das Augenmerk liegt hier primär auf der Messung der Reaktionszeit der korrekten Antworten, welche als Indikator der Zugriffszeit auf das hypothetische mentale Lexikon gilt, sekundär auf der Fehlerrate. Es wird angenommen, dass die Reaktionszeit sowohl von der Aktivierungszeit individueller Wortrepräsentationen, als auch der Aktivierungszeit globaler Repräsentationen abhängt (Grainger & Jacobs, 1996). Meist werden bei der lexikalischen Entscheidungsaufgabe neben den Wörtern Kunstwörter (aussprechbare Buchstabenfolgen ohne Bedeutung, die den Regeln der Orthographie folgen; z. B. mume, Kall) und/oder Pseudohomophone (aussprechbare Buchstabenfolgen, die wie existierende Wörter klingen, jedoch nicht den Regeln der Orthographie folgen; z.B. Baan, Meis) eingesetzt. Letztere als Nicht-Wörter zu kategorisieren, führt zu längeren Reaktionszeiten als das Ablehnen der Kunstwörter, am schnellsten werden Wörter identifiziert (z.B. Ziegler et al., 2001a). Die lexikalische Entscheidungsaufgabe ist die am häufigsten eingesetzte Methode zur Untersuchung der visuellen Worterkennung (Norris, 2009).

Tabelle 2.1 (Fortsetzung)

Einfache Wortbenennungsaufgabe
Bei der einfachen Wortbenennungsaufgabe wird den Probanden auf einem Bildschirm ein einzelnes Wort präsentiert, das diese so schnell und so korrekt wie möglich laut benennen sollen. Da normal lesende Erwachsene dies zum großen Teil fehlerfrei beherrschen, wird die Zeit, die vom Zeitpunkt der Präsentation des Wortes bis zum Einsetzen der Antwort verstreicht als kritisches Maß erhoben. Im Fokus der Benennungsaufgabe stehen die Eigenschaften des zu benennenden Wortes bzw. wie dessen Charakteristika das laute Vorlesen begünstigen oder aber verzögern (Spieler & Balota, 2000). Alternativen zur Wortbenennungsaufgabe sind Bildbenennungsaufgaben, bei denen statt eines Wortes ein Bild präsentiert wird und von denen angenommen wird, dass sie die Leichtigkeit des Zugangs zu phonologischen Repräsentationen symbolisieren ohne orthographische Prozesse oder Graphem-Phonem-Kopplungen zu aktivieren (z.B., Glaser, 1992; Ziegler et al., 2008).
Erhebung von Blickbewegungsdaten
Werden Blickbewegungsdaten erhoben, besteht ein typisches Experiment aus der Präsentation einzelner Sätze oder Textpassagen, in denen ein bestimmtes Zielwort eingebettet wurde (z. B. Dambacher et al., 2006; Kliegl et al., 2004; Nuthmann et al., 2006; Risse & Kliegl, 2011). Um die Entwicklung von Theorien und Lesemodellen voranzutreiben, werden Blickbewegungsmessungen zunehmend beim „natürlichen“ Lesen ganzer Texte durchgeführt (Radach et al., 2012), und auch die Leseforschung unter Einsatz von EEG-Messungen tendiert zu „natürlicheren“ Lesetests (Dimigen et al., 2011; Hutzler et al., 2007).

2.1.2. Effekte von Frequenz, Wortlänge und orthographischer Nachbarschaft

In den gängigen Paradigmen zur Untersuchung der visuellen Worterkennung (vgl. Tabelle 2.1) werden typische Variablen der visuellen Worterkennung wie zum Beispiel Wortfrequenz, Wortlänge und Frequenz bzw. Dichte der orthographischen Nachbarschaft (Tabelle 2.2) gezielt manipuliert, um die Auswirkungen auf Reaktionszeiten, Blickbewegungen sowie elektro- und neurophysiologische Korrelate (i.e. EEG und fMRT) zu beobachten und Rückschlüsse über die zugrunde liegenden Prozesse zu ziehen (siehe Appendix A.2. für eine Betrachtung der Effekte von Frequenz, Wortlänge und orthographischer Nachbarschaft auf Blickbewegungen, EEG sowie neuronale Korrelate).

Während unabhängig vom verwendeten Paradigma hochfrequente Wörter schneller identifiziert werden als niederfrequente (Benennungsaufgabe: z.B., Balota & Chumbley, 1984; Zoccolotti et al., 2008; lexikalische Entscheidungsaufgabe: z.B., Braun et al., 2009;

Hauk & Pulvermüller, 2004; perzeptive Identifikationsaufgabe: z.B., Broadbent, 1967), zeigen sich bei der Wortlänge deutliche Abhängigkeiten von Aufgabentyp und Stimulusmaterial auf die Geschwindigkeit der Worterkennung. In der perzeptiven Identifikationsaufgabe werden sowohl inhibitorische (d.h. zunehmende Wortlänge erschwert die Identifizierung des Wortes; z.B., McGinnies et al., 1952) als auch Nulleffekte, also keine Einflüsse unterschiedlicher Wortlängen, festgestellt (z.B. Howes & Solomon, 1951). In der Benennungsaufgabe treten ebenfalls inhibitorische Wortlängeneffekte auf, allerdings sind sie für Wörter schwächer ausgeprägt als für Kunstwörter (z.B., Juphard et al., 2006; Zoccolotti et al., 2008) oder bleiben auf Kunstwörter beschränkt (Weekes, 1997). Auf lexikalische Entscheidungen scheint die Wortlänge, zumindest im Englischen, einen sehr differenzierten Einfluss zu haben: Während die Worterkennung bei drei- bis fünfbuchstabigen Wörtern mit steigender Wortlänge begünstigt wird, zeigt sich bei fünf- bis achtbuchstabigen Wörtern kein Einfluss der Wortlänge auf die Wortidentifizierung. Wörter mit acht bis dreizehn Buchstaben werden mit steigender Wortlänger hingegen langsamer erkannt (New et al., 2006; aber Hauk & Pulvermüller, 2004). Werden Wortlänge und Frequenz gemeinsam variiert, lässt sich sowohl in der lexikalischen Entscheidungsaufgabe als auch in der Benennungsaufgabe ein stärkerer Längeneffekt für nieder- als für hochfrequente Wörter beobachten (Balota et al., 2004). Mit zunehmender Lesefertigkeit wird dieser Effekt kleiner (Zoccolotti et al., 2008).

Eine hohe orthographische Nachbarschaftsdichte verlangsamt im Regelfall die visuelle Worterkennung in perzeptiven Identifikationsaufgaben (z.B. Carreiras et al., 1997; aber Grainger & Jacobs, 1996), wirkt aber beschleunigend bei der Benennungsaufgabe (z.B., Andrews, 1989, 1992) und der lexikalischen Entscheidungsaufgabe (Andrews, 1989; Forster & Shen, 1996). Für letztere Paradigmen ist dieser faszilitatorische Effekt vor allem bei niederfrequenten Wörtern stark ausgeprägt (Andrews, 1992; Forster & Shen, 1996). Bei

Kunstwörtern dagegen verlangsamt eine hohe Anzahl orthographischer Nachbarn die lexikalische Entscheidung (Andrews, 1989; Forster & Shen, 1996).

Tabelle 2.2

Zentrale Variablen zur Untersuchung der visuellen Worterkennung

Wortfrequenz/Frequenzeffekt
Die objektive Wortfrequenz stellt eine statistische Größe dar, die angibt wie häufig ein bestimmtes geschriebenes Wort in einer Auswahl von Texten vorkommt (Howes & Solomon, 1951). Diese Texte werden in Datenbanken gesammelt und sollen eine möglichst repräsentative Abbildung der Sprache darstellen. Häufig verwendete Datenbanken im Deutschen sind die Celex (Baayen et al., 1993), die dlexDB (Heister et al., 2011) und die SUBTLEX-DE (Brysbaert et al., 2011), wobei letztere auf Untertiteln von Filmen und Serien basiert und von den Datenbanken die höchste Vorhersagekraft für Reaktionszeiten aufweist. Wörter, die häufig vorkommen, werden über die lexikalische Route verarbeitet, d.h. bereits bekannte und oft gelesene Wörter werden mit bereits vorhandenen Repräsentationen visueller Wortformen abgeglichen; Das Auslautieren und Zusammenfügen einzelner Buchstaben bzw. Silben wie es z.B. sehr seltene Wörter oder Kunstwörter erfordern, ist für eine erfolgreiche Worterkennung nicht (mehr) nötig. Die Wortfrequenz wird als wichtigstes Maß für den lexikalischen Zugriff betrachtet (z.B. Balota et al., 2004; Brysbaert et al., 2011).
Wortlänge/Wortlängeneffekt
Die Wortlänge kann sich sowohl auf orthographische Einheiten (Anzahl der Buchstaben) als auch auf phonologische Einheiten (Anzahl der Phoneme, Silben) beziehen (New et al., 2006). Sie wird häufig als sublexikalisches Maß bezeichnet, da einzelne Buchstaben bzw. Silben statt des ganzen Wortes betrachtet werden; Allen et al., 1993). Vom Wortlängeneffekt wird im Allgemeinen gesprochen, wenn die Anzahl der Buchstaben bzw. Silben eine Auswirkung auf die Reaktionszeiten bzw. die Fehlerraten hat.
Orthographische Nachbarschaft/Orthographischer Nachbarschaftseffekt
Unter orthographischer Nachbarschaft versteht man die Anzahl von Wörtern gleicher Länge, die sich anhand eines Buchstabens unterscheiden (Coltheart et al., 1977), z.B. sind *Hals, Hans* und *Laus* orthographische Nachbarn des Wortes *Haus.* Orthographische Nachbarschaftseffekte beschreiben demnach die Auswirkungen der Anzahl (Dichte) orthographischer Nachbarn auf die Reaktionszeiten bzw. die Fehlerraten (z.B. Andrews, 1989; Forster & Shen, 1996), können sich aber auch auf Einflüsse der Frequenz der orthographischen Nachbarn beziehen (z.B. Grainger & Jacobs, 1996; Grainger et al., 1989). Nachbarschaftseffekte sind im Regelfall auf der Ganzwortebene verortet (z.B. Grainger & Jacobs, 1996; aber Balota & Spieler, 2000). Zum Beispiel postulieren IAMs, dass bei der visuellen Präsentation eines Wortes orthographisch ähnliche Wörter, also Nachbarn, ebenfalls aktiviert werden und miteinander konkurrieren. Wörter mit höherfrequenten Nachbarn erhalten auf Grund der stärkeren Aktivierung ihrer Nachbarn eine stärkere Inhibition als solche Wörter mit keinen bzw. nur wenigen Nachbarn. Besitzt ein Wort eine hohe Nachbarschaftsdichte, erhöht sich die Gesamtaktivierung und die Worterkennung erfolgt im Regelfall schneller.

Besitzt ein Wort höherfrequente orthographische Nachbarn, wirkt sich dies nachteilig auf seine Identifikation aus (z.B. Grainger & Jacobs, 1996). Auch bei lexikalischen Entscheidungen werden mehrheitlich inhibitorische Effekte der Nachbarschaftsfrequenz beobachtet (z.B. Spanisch: Carreiras et al., 1997; Niederländisch: Grainger, 1990; Französisch: Grainger & Jacobs, 1996; aber Englisch: Forster & Shen, 1996). Dagegen scheint bei der Benennungsaufgabe eine hohe Nachbarschaftsfrequenz eher förderlich für die Worterkennung zu sein (z.B. Grainger, 1990). Eine detailliertere Betrachtung der Effekte von orthographischer Nachbarschaftsdichte und -frequenz findet sich in der Übersichtsarbeit von Andrews (1997).

2.1.3. Selektionskriterien

Diese Übersichtsarbeit konzentriert sich auf Studien, deren Ergebnisse mit dem meistverwendeten Paradigma der Worterkennungsforschung, der lexikalischen Entscheidungsaufgabe, gewonnen wurden. Abgesehen von Platzgründen, beruht unser Entschluss, auf Studien zu verzichten, die die perzeptive Identifikations- oder Benennungsaufgabe einsetzen, bezüglich ersterer Aufgabe darauf, dass dieses Paradigma die Probanden zu komplexen Rateprozessen verleitet. Dies erschwert die Interpretation der Ergebnisse (New et al., 2006) – auch wenn Computersimulationsmodelle vorliegen, die diese Rateprozesse erklären können (Ziegler et al., 1998). Die Nichtberücksichtigung der Benennungsaufgabe ist vor allem der Tatsache geschuldet, dass sie neben lexikalischen auch nicht-lexikalische Prozesse erfasst, weswegen Paap et al., (1987) ausdrücklich die lexikalische Entscheidungsaufgabe als Standard zur Untersuchung der Worterkennung empfehlen. Vorliegende Übersichtsarbeit folgt diesem Hinweis und betrachtet ausschließlich Studien, die funktional hauptsächlich die Ebenen der Wortverarbeitung bzw. des –verständnisses ansprechen und nicht die der Wortproduktion. Ebenso wurden Blickbewegungsstudien von einer weiteren Betrachtung ausgeschlossen, da sie für Modelle der Einzelworterkennung nur begrenzt verwertbar sind (Balota et al., 2004).

Um zu klären, ob vor allem sublexikalische oder lexikalische Prozesse durch das Altern beeinträchtigt werden (vgl. Tabelle 2.2), wurden bei der Auswahl der Studien ausschließlich diejenigen berücksichtigt, die Längen-, objektive Frequenz-, oder orthographische Nachbarschaftseffekte auf die Reaktionszeit untersucht haben.

Dementsprechend werden auch nur die auf diese Faktoren bezogenen Ergebnisse berichtet, unabhängig von weiteren Untersuchungsebenen dieser Studien. Fehlerraten werden in dieser Arbeit explizit nicht betrachtet, da sie in den Originalarbeiten kaum bzw. gar nicht diskutiert und vorhandene Effekte zum Teil auf die Besonderheiten des Versuchsaufbaus der Studie attribuiert werden (z.B. Bush et al., 2007). Darüber hinaus ist bei den Fehlerraten die Ergebnislage besonders uneinheitlich. Eine angemessene Darstellung ist aus Platzgründen nicht möglich. In die Arbeit miteinbezogen wurden nur solche Ergebnisse, die von gesunden, nicht-dyslektischen Probanden stammen. Die Altersspanne aller berücksichtigten Versuchspersonen beträgt 17 bis 88 Jahre, wobei die jüngeren Probanden im Schnitt ein Alter von 21,9 Jahren aufweisen, die älteren eins von 70,5 Jahren.

2.1.4. Abgrenzung dieser Übersichtsarbeit

Während eine Reihe von Übersichtsarbeiten vorliegen, die Auswirkungen von Alterungsprozessen in Bezug auf Textverständnis, Sprachperzeption und Sprachverständnis diskutieren (z.B. Abrams & Farrell, 2011; Burke & Shafto, 2008; Meyer et al., 1993; Thornton & Light, 2006), existiert lediglich eine Übersichtsarbeit, die Einzelwortlesen im Alter thematisiert (Allen et al., 1995). Allen et al. (1995) berichten von insgesamt 7 Studien (5 lexikalische Entscheidungsstudien; 2 Benennungsstudien, eine davon unveröffentlicht), die Frequenzeffekte im Alter untersucht haben. Die aktuelle Übersichtsarbeit unterscheidet sich von der älteren Arbeit Allens et al. (1995), abgesehen von der größeren Aktualität, dadurch, dass sie neben behavioralen auch eine erste neuronale Studie mit diesem Schwerpunkt und zusätzlich zu Frequenzeffekten auch Längen- und orthographische Nachbarschaftseffekte berücksichtigt.

2.2. Methodik

Für diese Übersichtsarbeit wurde eine Literaturrecherche in den Datenbanken von PubMed, Science Direct, Google Scholar, Isi Web of Knowledge, DIMDI, MEDLINE, PsycINFO und PsycNET durchgeführt. Folgende Schlagwörter wurden dafür verwendet: Altern (*aging*), Alter (*old age*), ältere Menschen/Senioren (*elderly*), ältere/jüngere Leser (*older/younger readers*), visuelle Worterkennung (*visual word recognition*), Lesen (*reading*), lexikalische Entscheidung (*lexical decision*), lexikalischer Zugriff (*lexical access*), neuronale Korrelate (*neural correlates*), fMRI, PET, MEG, Worthäufigkeit (*frequency*), (Wort-)Länge (*word length*), orthographische Nachbarschaft (*orthographic neighborhood*), Übersichtsarbeit (*review*) und Meta-Analyse (*meta-analysis*). Die Suche wurde sowohl auf Englisch als auch auf Deutsch durchgeführt. Zusätzlich wurden die Bibliografien der als relevant eingestuften Artikel durchgesehen. Diese Übersichtsarbeit berichtet über die Ergebnisse von insgesamt 16 Studien, die bis einschließlich Januar 2014 publiziert waren.

2.3. Ergebnisse

2.3.1. Alters- und Frequenzeffekte auf die Reaktionszeit

Die Ausprägung des Frequenzeffekts in Abhängigkeit vom Alter wurde in den Studien dieser Übersichtsarbeit mit Abstand am häufigsten thematisiert (Tabelle 2.3). Dabei reagierten in den 15 relevanten Untersuchungen jüngere Teilnehmer grundsätzlich schneller als ältere Probanden; auf häufig auftretende Wörter wurde schneller geantwortet als auf seltene.

Tabelle 2.3

Zusammenfassung der empirischen Untersuchungen zu Alters- und Frequenzeffekten auf Reaktionszeiten

Studie	Sprache	Durchschnittsalter (Spannweite)	Stichprobe	Jahre formaler Bildung	Wortschatz	Alterseffekt
Bowles & Poon (1981)	Englisch	Jü: 21 J. (17-28) Ä: 74 J. (62-82)	Jü: 21 Ä: 22	Jü = A (13 J. vs. 13 J.)	Jü = Ä (WAIS)	Jü = Ä
Tainturier et al. (1989)	Französisch	Jü: 28 J. (20-33) Ä: 67 J. (62-77)	Jü: 19 Ä: 20	Jü = Ä (laut Autoren; keine Angabe)	keine Angabe	Jü = Ä
Allen et al. (1991)	Englisch	Jü:19,2 J. (17-22) Ä: 69,9 J. (60-77)	Jü: 24 Ä: 24	Jü < Ä (13,3 J. vs. 16,9 J.)	Jü < Ä (WAIS-R)	Jü = Ä
Allen et al. (1993) Experiment 1	Englisch	Jü: 20,4 J. (18-29) Ä: 69,2 J. (61-76)	Jü: 20 Ä: 20	Jü < Ä (13,3 J. vs. 15,9 J.)	Jü < Ä (WAIS-R)	Jü = Ä
Allen et al. (1993) Experiment 2	Englisch	Jü: 20,3 J. (19-23) Ä: 69,7 J. (62-77)	Jü: 20 Ä: 20	Jü < Ä (13,5 J. vs. 16,1 J.)	Jü < Ä (WAIS-R)	Jü = Ä
Allen et al. (1993) Experiment 3	Englisch	Jü: 18,6 J. (k.A.) Ä: 70,0 J. (k.A.)	Jü: 20 Ä: 20	Jü < Ä (12,7 J. vs. 14,5 J.)	Jü < Ä (WAIS-R)	Jü = Ä Jü > Ä*
Stadtlander (1995)	Englisch	Jü: 19,2 J. (k.A.) Ä: 67,0 J. (k.A.)	Jü: 15 Ä: 15	Jü < Ä (13 J. vs. 16 J.; absolute Werte)	Jü < Ä (WAIS-R; absolute Werte)	Jü = Ä

Tabelle 2.3 (Fortsetzung)

Studie	Sprache	Durchschnittsalter (Spannweite)	Stichprobe	Jahre formaler Bildung	Wortschatz	Alterseffekt
Balota & Ferraro (1996)	Englisch	Jü: 20,1 J. (18-28) Ä: 69,1 J. (62-80)	Jü: 48 Ä: 48	keine Angabe	Jü = Ä (WAIS-R)	Jü < Ä
Allen et al. (2002)	Englisch	Jü: 21,8 J. (18-35) Ä: 72,6 J. (61-88)	Jü: 20 Ä: 20	Jü < Ä (14,5 J. vs. 15,9 J.)	Jü < Ä (WAIS-R)	Jü = Ä
Whiting et al. (2003)	Englisch	Jü: 23,6 J. (20-29) Ä: 65,0 J. (62-70)	Jü: 12 Ä: 12	Jü = Ä (15,7 J. vs. 16,8 J.)	Jü = Ä (WAIS-R)	Jü = Ä
Allen et al. (2004)	Englisch	Jü: 22,2 J. (17-43) Ä: 71,1 J. (60-87)	Jü: 96 Ä: 97	Jü < Ä (14 J. vs. 15,2 J.)	Jü < Ä (WAIS-R)	Jü = Ä
Balota et al. (2004)	Englisch	Jü: 20,5 J. (k.A.) Ä: 73,6 J. (k.A.)	Jü: 30 Ä: 30	Jü = Ä (14,9 J. vs. 15,1 J.)	Jü < Ä (Shipley)	Jü < Ä**
Caza et al. (2005)	Englisch	Jü: 23,3 J. (21-28) Ä: 72,9 J. (67-78)	Jü: 15 Ä: 15	Jü = Ä (15,5 J. vs. 15,1 J.)	Jü = Ä (Mill Hill)	Jü = Ä
Bush et al. (2007)	Englisch	Jü: 24,5 (18-30) Ä: 73,9 (59-84)	Jü: 20 Ä: 19	Jü: keine Angabe Ä: 14,8 J.	keine Angabe	Jü = Ä
Taler & Jarema (2007)	Englisch	Jü: 26,8 (k.A.) Ä: 75,0 (k.A.)	Jü: 10 Ä: 11	Jü = Ä (14,8 J. vs. 14, 5 J.)	keine Angabe	Jü = Ä

*Reaktionszeiten der jüngeren Teilnehmer wurden denen der älteren angepasst, um die altersbedingte Verlangsamung in der Reaktion zu berücksichtigen;
**gilt nur für die gemeinsame Betrachtung von lexikalischer Entscheidungsaufgabe und Wortbenennungsaufgabe; Ä = Ältere; Jü = Jüngere; J = Jahre.

Es ist jedoch die Interaktion dieser beiden Faktoren, die Aufschluss darüber gibt, ob sich der Frequenzeffekt im Alter verändert. Lässt sich keine signifikante Interaktion zwischen Alter und Frequenz beobachten, wie es bei 12 Studien der Fall war, unterscheiden sich jüngere und ältere Probanden bezüglich des Frequenzeffektes nicht: beide Kohorten reagieren gleichermaßen schneller auf hoch- als auf niederfrequente Wörter (z.B., Allen et al., 2002; Bowles & Poon, 1981; Caza & Moscovitch, 2005; Tainturier et al., 1989). In zwei Studien, die von einer solchen Interaktion berichten, zeigten ältere Erwachsene einen größeren Frequenzeffekt als jüngere Erwachsene (Balota et al., 2004; Balota & Ferraro, 1996). Während Balota und Ferraro (1996) mit abnehmender Frequenz bei Älteren einen stärkeren Reaktionszeitzuwachs fanden als bei jüngeren Erwachsenen, führen Balota et al. (2004) ihr Resultat, dass ausschließlich auf der gemeinsamen Betrachtung von lexikalischer Entscheidungs- und Wortbenennungsaufgabe beruht, nicht weiter aus. Für die lexikalische Entscheidungsaufgabe allein fanden die Autoren keine Interaktion von objektiver Frequenz und Alter. Eine Besonderheit stellt die Studie von Allen et al. (1993) dar. Nachdem die Autoren eine Anpassung der Reaktionszeiten der jüngeren Teilnehmer an die der älteren vorgenommen hatten, fanden sie einen stärkeren Frequenzeffekt für jüngere im Vergleich zu älteren Erwachsenen (Teilexperiment 3). Bei der Betrachtung der untransformierten Reaktionszeiten trat zunächst kein Unterschied bezüglich der Frequenzeffekte zwischen den älteren und jüngeren Probanden auf.

2.3.2. Alters- und Wortlängeneffekte auf die Reaktionszeit

Wortlängeneffekte in Abhängigkeit vom Lebensalter wurden in sechs Studien systematisch betrachtet (Tabelle 2.4). Erwartungskonform reagierten jüngere Probanden schneller als ältere, kurze Wörter wurden schneller identifiziert als längere.

Tabelle 2.4

Zusammenfassung der empirischen Untersuchungen zu Alters- und Wortlängeneffekten auf Reaktionszeiten

Studie	Sprache	Durchschnittsalter (Spannweite)	Stichprobe	Jahre formaler Bildung	Wortschatz	Alterseffekt
Allen et al. (1991)	Englisch	Jü: 19,2 J. (17-22) Ä: 69,9 J. (60-77)	Jü: 24 Ä: 24	Jü < Ä (13,3 J. vs. 16,9 J.)	Jü < Ä (WAIS-R)	Jü < Ä
Allen et al. (1993) Experiment 1	Englisch	Jü: 20,4 J. (18-29) Ä: 69,2 J. (61-76)	Jü: 20 Ä: 20	Jü < Ä (13,3 J. vs. 15,9 J.)	Jü < Ä (WAIS-R)	Jü = Ä Jü < Ä*
Allen et al. (1993) Experiment 2	Englisch	Jü: 20,3 J. (19-23) Ä: 69,7 J. (62-77)	Jü: 20 Ä: 20	Jü < Ä (13,5 J. vs. 16,1 J.)	Jü < Ä (WAIS-R)	Jü = Ä Jü < Ä*
Allen et al. (1993) Experiment 3	Englisch	Jü: 18,6 J. (k.A.) Ä: 70,0 J. (k.A.)	Jü: 20 Ä: 20	Jü < Ä (12,7 J. vs. 14,5 J.)	Jü < Ä (WAIS-R)	Jü = Ä
Whiting et al. (2003)	Englisch	Jü: 23,6 J. (20-29) Ä: 65,0 J. (62-70)	Jü: 12 Ä: 12	Jü = Ä (15,7 J. vs. 16,8 J.)	Jü = Ä (WAIS-R)	Jü < Ä
Balota et al. (2004)	Englisch	Jü: 20,5 J. (k.A.) Ä: 73,6 J. (k.A.)	Jü: 30 Ä: 30	Jü = Ä (14,9 J. vs. 15,1 J.)	Jü < Ä (Shipley)	Jü = Ä**

*Reaktionszeiten der jüngeren Teilnehmer wurden denen der älteren angepasst, um die altersbedingte Verlangsamung in der Reaktion zu berücksichtigen;

**gilt nur für die gemeinsame Betrachtung von lexikalischer Entscheidungsaufgabe und Wortbenennungsaufgabe; Ä = Ältere; Jü = Jüngere; J = Jahre.

Die kritische signifikante Interaktion von Wortlänge und Alter wurde in zwei Untersuchungen beobachtet (Allen et al., 1991; Whiting et al., 2003). Dabei war der Wortlängeneffekt bei der älteren Kohorte ausgeprägter als bei der jüngeren, d.h. die Reaktionszeiten der älteren Erwachsenen nahmen mit zunehmender Wortlänge stärker zu als die der jüngeren Erwachsenen. In zwei Studien konnten keine gemeinsamen Effekte von Wortlänge und Alter festgestellt werden (Allen et al., 1993, Teilexperiment 3; Balota et al., 2004). Wie schon bei den Frequenzeffekten wies die Studie von Allen et al. (1993) ambivalente Ergebnisse auf. Während bei der Analyse der untransformierten Reaktionszeiten keine Interaktion von Wortlänge und Alter nachgewiesen wurde, zeigten sich nach Anpassung der Reaktionszeiten der jüngeren Teilnehmer an die der älteren in den Teilstudien 1 und 2 stärkere Effekte der Wortlänge für ältere Erwachsene im Vergleich zu jüngeren Erwachsenen.

2.3.3. Alterseffekte und Effekte der orthographischen Nachbarschaft auf die Reaktionszeit

In lediglich drei Studien wurde der Einfluss von Alter auf orthographische Nachbarschaftseffekte untersucht (Tabelle 2.5), entweder mittels der Nachbarschaftsdichte (Balota et al., 2004; Stadtlander, 1995) oder aber der Nachbarschaftsfrequenz (Robert & Mathey, 2007; Stadtlander, 1995). Unabhängig von der Operationalisierung reagierten in allen drei Untersuchungen jüngere Erwachsene schneller als ältere. Während Stadtlander (1995) sowohl bei jüngeren als auch bei älteren Probanden weder einen Einfluss der Nachbarschaftsdichte noch der –frequenz feststellen konnte, berichten Balota et al. (2004) sowie Robert und Mathey (2007) von schwächeren Effekten der Nachbarschaftsdichte bzw. –frequenz bei älteren im Vergleich zu jüngeren Studienteilnehmern: Auf Wörter mit einer hohen Anzahl orthographischer Nachbarn reagierten ältere Erwachsene weniger schnell als jüngere Erwachsene; Wörter mit einer hochfrequenten Nachbarschaft wiesen ausschließlich bei jüngeren Erwachsenen längere Antwortzeiten auf als Wörter mit einer niedrigen Nachbarschaftsfrequenz, bei Älteren zeigte sich dieser Effekt nicht. Wie schon bei den

Frequenzeffekten bezieht sich das Ergebnis von Balota et al. (2004) ausschließlich auf die gemeinsame Betrachtung von lexikalischer Entscheidungs- und Wortbenennungsaufgabe.

2.3.4. Alterseffekte und Frequenz- bzw. Wortlängeneffekte auf den zerebralen Blutfluss

Es konnte lediglich eine Arbeit identifiziert werden, in der die neuronalen Auswirkungen des Alterns auf Frequenz- und Längeneffekte systematisch untersucht wurden (Tabelle 2.6); bezüglich der orthographischen Nachbarschaft konnte keine Studie gefunden werden.

Mittels Positronen-Emissions-Tomographie untersuchten Whiting et al. (2003) systematische Veränderungen des regionalen zerebralen Blutflusses von jüngeren und älteren Probanden, die in Zusammenhang mit Veränderungen der Reaktionszeiten auf Grund von Frequenz- und Wortlängenmanipulationen auftraten. Die Forscher konzentrierten sich dabei auf den linken inferioren Okzipitalkortex (Brodmann-Areal 17) und den linken inferioren Temporalkortex (Brodmann-Areal 37), da diese Hirnregionen zuvor als sensitiv für differenzielle Alterseffekte identifiziert wurden (Madden et al., 2002).

Ausschließlich bei älteren Probanden zeigte sich ein deutlicher Frequenzeffekt sowohl im Brodmann-Areal 17, 18 sowie im Brodmann-Areal 37 der linken Hemisphäre. Je langsamer die Reaktion auf nieder- im Vergleich zu hochfrequenten Wörter ausfiel, um so höher war die Hirnaktivität in den o.g. Hirnregionen.

Tabelle 2.5

Zusammenfassung der empirischen Untersuchungen zu Alterseffekten und Effekten der orthographischen Nachbarschaft auf Reaktionszeiten

Studie	Sprache	Durchschnittsalter (Spannweite)	Stichprobe	Jahre formaler Bildung	Wortschatz	Alterseffekt
Stadtlander (1995)	Englisch	Jü: 19,2 J. (k.A.) Ä: 67,0 J. (k.A.)	Jü:15 Ä: 15	Jü < Ä (13 J. vs. 16 J.; absolute Werte)	Jü < Ä (WAIS-R; absolute Werte)	Jü = Ä
Balota et al. (2004)	Englisch	Jü: 20,5 J. (k.A.) Ä: 73,6 J. (k.A.)	Jü: 30 Ä: 30	Jü = Ä (14,9 J. vs. 15,1 J.)	Jü < Ä (Shipley)	Jü > Ä*
Robert & Mathey (2007)	Französisch	Jü: 20,9 J. (18-25) Ä: 67,8 J. (61-79)	Jü: 27 Ä: 27	Jü = Ä (13,2 J. vs. 13,2 J.)	Jü < Ä (Mill Hill)	Jü > Ä

*gilt nur für die gemeinsame Betrachtung von lexikalischer Entscheidungsaufgabe und Wortbenennungsaufgabe; Ä = Ältere; Jü = Jüngere; J = Jahre

Tabelle 2.6

Zusammenfassung der empirischen Untersuchungen zu neurologischen Alterseffekten und Frequenz- und Wortlängeneffekten (zerebraler Blutfluss)

Studie	Sprache	Durchschnittsalter (Spannweite)	Stichprobe	Jahre formaler Bildung	Wortschatz	Alterseffekt
Whiting et al. (2003)	Englisch	Jü: 23,6 J. (20-29) Ä: 65,0 J. (62-70)	Jü: 12 Ä: 12	Jü = Ä (15,7 J. vs. 16,8 J.)	Jü = Ä (WAIS-R)	Jü < Ä

Ä = Ältere; Jü = Jüngere; J = Jahre

Ein Zusammenhang von Wortlänge und zerebralem Bluttfluss konnte ebenfalls ausschließlich bei älteren Probanden nachgewiesen werden. Im Brodmann-Areal 17 war die Hirnaktivität um so höher, je weniger Einfluss die Wortlänge auf die Reaktionszeiten ausübte. Wie schon bei der Frequenz zeigten jüngere Probanden keine systematisch von der Wortlänge abhängigen Aktivierungen.

2.4. Diskussion

Insgesamt konnten 16 (Teil-)Studien identifiziert werden, welche altersabhängige Frequenz-, Längen- und orthographische Nachbarschaftseffekte auf Verhaltens- und neurokognitiver Ebene untersucht haben. Dabei zeigte sich eine gewisse Variabilität in den Ergebnissen, auf deren mögliche Ursachen im Folgenden näher eingegangen werden soll.

2.4.1. Ursachen der Variabilität der Ergebnisse

Die Variabilität der Ergebnisse bezüglich der Auswirkungen des Alterns auf die visuelle Worterkennungsleistung kann unterschiedliche Ursachen haben. Zum einen besteht ein generelles Problem in Bezug auf die Vergleichbarkeit unterschiedlicher Studien. Erstens in Bezug auf die Prämissen, nach denen die Versuchspersonen selektiert wurden. Während einige Forschergruppen bewusst ältere und jüngere Probanden wählen, deren Wortschatz vergleichbar ist (z.B. Balota & Ferraro, 1996), betonen andere Forschergruppen das natürliche Ungleichgewicht zugunsten der älteren Probanden (z.B. Allen et al., 1995). Zweitens zeigen Ältere generell langsamere Reaktionen als jüngere Erwachsene, was in den statistischen Auswertungsverfahren explizit berücksichtigt wurde (z.B. Allen et al., 1993) oder keine besondere Beachtung fand (z.B. Bowles & Poon, 1981; Tainturier et al., 1989). Drittens fehlen in einigen Artikeln Angaben zu Variablen, die die Ergebnisse beeinflussen könnten, z.B. zur Messung des Wortschatzes der Versuchspersonen, die Zeit ihrer formalen

Schulbildung und Angaben zur Sehschärfe (vgl. Tabellen 2.3 bis 2.6). Gerade die Relevanz der Sehschärfe bei Untersuchungen von Alterseffekten wird mehrfach betont (z.B., Baltes & Lindenberger, 1997; Daffner et al., 2013). Aberson und Bouwhuis (1997) gehen gar davon aus, dass Alterseffekte beim Textlesen gänzlich in der Abnahme der Sehschärfe im Alter begründet liegen. Sehschärfe als potentieller Einflussfaktor sollte daher in jeder Untersuchung zur visuellen Worterkennung erhoben bzw. kontrolliert werden, vor allem, da sich der Abbau von Seh- und Hörfähigkeit ab einem Alter von 70 Jahren nochmals beschleunigt (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994).

Zudem divergiert das mittlere Alter der Studienteilnehmer sowohl bei den jüngeren als auch bei den älteren Erwachsenen stark. Die jüngste Stichprobe findet sich in der Studie von Allen und Kollegen (1993; 18,6 Jahre), die älteste Stichprobe der jungen Erwachsenen bei Tainturier et al. (1989; 28 Jahre). Die Spanne bei den älteren Erwachsenen ist zwar durchaus mit der der jüngeren vergleichbar (Durchschnittsalter bei Whiting et al., 2003: 65 Jahre; Taler & Jarema, 2007: 75 Jahre), hat aber gravierendere Folgen, da Altern per se ein sehr heterogener Prozess ist: Während einige ältere Menschen bis ins hohe Alter ein hohes kognitives Funktionsniveau aufweisen, treten bei anderen kognitive Defizite zutage. Sowohl Umwelteinflüsse als auch genetische Faktoren beeinflussen die im Alter stetig zunehmenden Unterschiede in der individuellen kognitiven Leistung (Lindenberger et al., 2008) und tragen dazu bei, dass die Varianz der Ergebnisse bei Älteren deutlich größer ist als bei jüngeren Probanden.

Darüber hinaus wurden die in dieser Übersichtsarbeit ausgewerteten Studien in Englisch und Französisch durchgeführt. Jedoch unterscheiden sich die Sprachen bezüglich der Tiefe ihrer Orthographien und können somit unterschiedliche Verarbeitungsstrategien bei den Versuchspersonen hervorrufen (Das et al., 2011; Ziegler & Goswami, 2005, 2006). Da jedoch die Mehrzahl der in dieser Übersichtsarbeit aufgeführten Studien auf Englisch durchgeführt wurden, spielt dieser Aspekt zumindest hier eine wohl eher untergeordnete Rolle.

2.4.2. Frequenzeffekte

In 12 der hier aufgeführten Untersuchungen konnten keine unterschiedlich ausgeprägten Frequenzeffekte für jüngere und ältere Studienteilnehmer nachgewiesen werden. Lediglich zwei Studien berichteten von stärkeren Frequenzeffekten für ältere im Vergleich zu jüngeren Erwachsenen, wobei eine der beiden Studien dieses Ergebnis lediglich bei gemeinsamer Betrachtung von Wortbenennungsaufgabe und lexikalischer Entscheidungsaufgabe findet. Eine Studie berichtet zunächst keine differentiellen Alterseffekte; nach der Anpassung der Reaktionszeiten der jüngeren Teilnehmer an die der älteren jedoch von einem stärkeren Frequenzeffekt für junge Erwachsene als für ältere.

Allen et al. (1995) weisen darauf hin, dass ein ausgeprägterer Frequenzeffekt für ältere Versuchspersonen die Folge des vergleichbaren Wortschatzes der jüngeren und älteren Probanden sein könnte. Normalerweise wird davon ausgegangen, dass mit steigendem Alter der Wortschatz wächst (Verhaeghen, 2003) und dass das wiederholte Sehen von Wörtern zu deren schnellerer automatischer Verarbeitung und Bedeutungszuweisung beiträgt (Borowsky & Besner, 1993). Unterscheiden sich Ältere und Jüngere bezüglich ihres Wortschatzes nicht, besteht die Gefahr weniger kompetente ältere Leser im Vergleich zu jüngeren zu untersuchen. Da weniger kompetente Leser einen stärkeren Frequenzeffekt als kompetente produzieren (Frederiksen, 1978), könnte dies das Ergebnis von Balota & Ferraro (1996) erklären. Jedoch finden z.B. Bowles und Poon (1981), Caza et al. (2005) sowie Whiting et al. (2003) keine Interaktion von Alter und Frequenz, obwohl sie den Wortschatz der älteren und jüngeren Probanden kontrollieren.

Des Weiteren kann die Anzahl der Jahre formaler Bildung ebenfalls die Ausprägung des Frequenzeffekts beeinflussen: Personen, mit einer geringen Anzahl an Jahren formaler Bildung zeigen einen ausgeprägteren Frequenzeffekt als solche mit einer hohen (Tainturier et al., 1992). Dies könnte die Ergebnisse von Allen et al. (1993; Teilexperiment 3) erklären. Darüber hinaus scheint diese Tatsache allerdings auf die große Mehrzahl der hier betrachteten Studien nicht zuzutreffen. In 12 Studien, die Frequenzeffekte im Alter untersuchten, wird keine Interaktion dieser beiden Variablen gefunden, obwohl in sechs dieser Studien ältere Erwachsene einen Bildungsvorsprung gegenüber jüngeren Erwachsenen aufweisen (z.B. Allen et al., 1991, 2002, 2004; Stadtlander, 1995). In den beiden Studien, die einen stärkeren Frequenzeffekt für ältere im Vergleich zu jüngeren Erwachsenen finden, verfügen die Altersgruppen dagegen über eine vergleichbare Anzahl an Bildungsjahren (Balota et al., 2004) bzw. fehlt diese Angabe (Balota & Ferraro, 1996).

Auch die Spekulation Balotas et al. (2004), dass die stärkeren objektiven Frequenzeffekte bei älteren Erwachsenen auf die verwendeten Frequenznormen zurückzuführen sind, erscheint vor dem Hintergrund der Vielzahl von Studien, die trotz der Verwendung objektiver Frequenznormen keine Interaktion von Frequenz und Alter gefunden haben wenig plausibel. Insgesamt sprechen die Ergebnisse zum Frequenzeffekt eher dafür, dass die visuelle Wortverarbeitung auf der lexikalischen Ebene, also dem Bereich der Ganzworterkennung, bis ins hohe Alter intakt und in ihrer Ausprägung konstant bleibt.

2.4.3. Längeneffekte

In dieser Übersichtsarbeit wurden sechs Studien identifiziert, die Wortlängeneffekte in Abhängigkeit vom Alter untersuchten. Dabei wurde in zwei Studien ein stärkerer Längeneffekt für ältere als für jüngere Probanden gefunden, in zweien ein identischer. Zwei weitere Studien berichten zunächst von vergleichbaren Längeneffekten für jüngere und ältere

Probanden, nach der Transformation der Reaktionszeiten jedoch ebenfalls von stärkeren Längeneffekten für ältere Erwachsene im Vergleich zu jüngeren.

Nach den Annahmen der Zwei-Pfad-Modelle weisen Längeneffekte auf eine serielle, sublexikalische Lesestrategie hin, z.B. rufen seltene Wörter, die eher mittels der phonologischen Route erlesen werden, Längeneffekte hervor, wobei die Größe des Längeneffekts das Ausmaß der sublexikalischen Verarbeitung widerspiegelt (z.B. Coltheart et al., 2001; Perry et al., 2007, 2010). Da in den hier genannten Studien sowohl junge als auch ältere Leser Längeneffekte, speziell auch bei niederfrequenten Wörtern zeigen, scheinen bei beiden Altersgruppen sublexikalische Leseprozesse per se intakt zu sein. Die hier vorliegende Auswertung, speziell unter Berücksichtigung der Ergebnisse von Allen et al. (1993) nachdem sie die Reaktionszeiten der jüngeren den der älteren Studienteilnehmer angepasst haben, legt jedoch nahe, dass ältere Erwachsene stärker von sublexikalischen Stimuluseigenschaften beeinflusst werden als jüngere. Whiting et al. (2003) sehen dies in den Eigenschaften der eingesetzten Stimuli begründet. So könnten längere und mehrsilbige Stimuli bei älteren Studienteilnehmern zu einer stärkeren Belastung der Wahrnehmung führen. Wenn man jedoch bedenkt, dass Allen et al. (1991, 1993) mit kürzeren und einsilbigen Stimuli ebenfalls stärkere Längeneffekte bei älteren Erwachsenen finden, kann dies nicht die alleinige Erklärung für dieses Phänomen sein.

Alles in allem ist die Ergebnislage bezüglich der Wortlängeneffekte im Alter ambivalent. Es scheint sich jedoch eine Tendenz abzuzeichnen, dass Wortlänge ältere Erwachsene stärker beeinflusst als jüngere, Wortlängeneffekte sich also mit dem Alter verändern.

2.4.4. Orthographische Nachbarschaftseffekte

Nur drei Studien konnten im Rahmen dieser Übersichtsarbeit identifiziert werden, in denen die Ausprägung des Nachbarschaftseffekts in Abhängigkeit vom Alter untersucht wurde. Da Stadtlander (1995) weder einen Haupteffekt der Nachbarschaftsdichte noch der -frequenz nachweisen konnte, werden nachfolgend lediglich die Ergebnisse der beiden verbleibenden Studien diskutiert. Die geringe Anzahl an Untersuchungen zu Alterseffekten in Abhängigkeit von der orthographischen Nachbarschaft kann durchaus in der komplexen Natur dieser Variable begründet liegen. So sind die zu erwartenden Effekte von Nachbarschaftsdichte und –frequenz gegensätzlich. Während eine hohe Nachbarschaftsdichte von Wörtern zu einer beschleunigten Reaktion führt, bedingt eine hohe Nachbarschaftsfrequenz eine langsamere Antwort (Andrews, 1997). Dieses Antwortmuster scheint sich jedoch über die Lebensdauer hinweg zu verändern: Ältere Studienteilnehmer zeigen im Vergleich zu jüngeren Probanden eine deutlich geringere Beschleunigung ihres Antwortverhaltens auf Wörter mit hoher Nachbarschaftsdichte (Balota et al., 2004), die inhibitorischen Effekte der Nachbarschaftsfrequenz scheinen bei älteren Erwachsenen nicht aufzutreten (Robert & Mathey, 2007).

Beide Effekte können anschaulich mit dem MROM (vgl. Abschnitt *2.1.1 Grundlagen der visuellen Worterkennung*) erklärt werden. Innerhalb dieses Modells entsteht der faszilatorische Effekt einer hohen Nachbarschaftsdichte hauptsächlich über die lexikalische Aktivierung, die durch die Anzahl orthographischer Nachbarn generiert wird (Grainger & Jacobs, 1996). Weisen ältere Erwachsene im Vergleich zu jüngeren einen geringeren Einfluss der orthographischen Nachbarschaftsdichte auf, deutet dies auf eine verminderte lexikalische Aktivierung bei älteren Studienteilnehmern hin.

Ähnlich schlussfolgern Robert und Mathey (2007) bezüglich des Nachbarschaftsfrequenzeffektes. Im IAM oder dem MROM erhalten Stimuli mit höherfrequenten Nachbarn eine stärkere Inhibition und werden daher langsamer erkannt (Grainger & Jacobs, 1996). Die Größe des Nachbarschaftsfrequenzeffektes gilt dabei als Indikator für die Effizienz der visuellen Worterkennung. Aus dem Vorliegen des Nachbarschaftsfrequenzeffekts für jüngere Erwachsene und dessen gleichzeitiger Abwesenheit bei älteren, folgern Robert und Mathey (2007), dass mit zunehmendem Alter der inhibitorische Effekt der höherfrequenten Nachbarn nachlässt und gleichfalls Aktivierungseffizienz abnimmt. Außerdem stehen diese Ergebnisse in Einklang mit der Inhibitions-Defizit-Hypothese, die altersbedingte kognitive Veränderungen in ineffizienter Reizunterdrückung verortet (z.B. Zacks & Hasher, 1997).

Insgesamt sprechen die im Rahmen dieser Übersichtsarbeit ermittelten Ergebnisse zur orthographischen Nachbarschaft dafür, dass sowohl Effekte der Nachbarschaftsdichte als auch der Nachbarschaftsfrequenz über die Lebensspanne nicht stabil bleiben.

2.4.5. Neuronale Effekte

In Hinblick auf die Generalisierbarkeit der Ergebnisse sei kritisch angemerkt, dass im Rahmen dieser Übersichtsarbeit lediglich eine Studie identifiziert werden konnte, die gemeinsame neuronale Effekte des Alters, der Frequenz und der Wortlänge untersucht hat. Dabei sind gerade im Bereich der Neurowissenschaften Replikationsstudien unerlässlich, um zufällig statistisch signifikanten Ergebnissen vorzubeugen (Button et al., 2013).

Die von Whiting et al. (2003) gefundenen Aktivierungsmuster deuten darauf hin, dass ältere und jüngere Erwachsene Wortlänge und Frequenz neuronal unterschiedlich verarbeiten. Diese Ergebnisse decken sich im Wesentlichen mit den behavioralen Daten bezüglich des Längeneffektes, nicht jedoch mit denen zum Frequenzeffekt. Während auf Verhaltensebene mehrheitlich keine Interaktion von Alter und Frequenz beobachtet wird, finden Whiting et al. (2003) neuronal einen Unterschied in der Verarbeitung der Wortfrequenz zwischen den beiden Altersgruppen. Die Autoren deuten den gemeinsamen Effekt von Alter und Frequenz dahingehend, dass ältere Leser deutlich stärker auf die Hirnstrukturen der lexikalischen Verarbeitung setzen als jüngere Leser. Die Verortung des Längeneffekts im okzipitalen Kortex lässt dagegen vermuten, dass periphere, visuelle Prozesse der Wortverarbeitung eine maßgebliche Rolle spielen (Wydell et al., 2003), was die Annahmen von Aberson und Bouwhuis (1997) bezüglich der Bedeutung der Sehschärfe zu stützen scheint. Um eindeutigere Aussagen bezüglich Alterseffekten bei der neuronalen Verarbeitung sublexikaler Prozesse treffen zu können, sollten in weiteren Studien gezielt auch die Hirnareale untersucht werden, die mit sublexikalischer Verarbeitung assoziiert werden.

2.5. Fazit

Verändern sich Leseprozesse im Alter? Die Beantwortung dieser Frage hängt offensichtlich von der Betrachtung der betroffenen Teilverarbeitungsvorgänge ab. Der für Worterkennung und Lesen zentrale Vorgang des lexikalischen Zugriffs scheint nur partiell von Effekten des Alterns betroffen zu sein. Das Fehlen eines Interaktionseffekts von Frequenz und Alter in der lexikalischen Entscheidungsaufgabe spricht für eine über die Lebensdauer relativ stabile Ausprägung der visuellen Worterkennung. Andererseits deuten die Ergebnisse bezüglich der orthographischen Nachbarschaft darauf hin, dass sich lexikalische Inhibitions- und Aktivierungsprozesse durchaus im Alter verändern; diese Beobachtung beruht jedoch auf lediglich zwei Studien. Treten Unterschiede in der Leseleistung älterer Menschen im Vergleich zu jüngeren auf, scheinen diese eher in den sublexikalischen Prozessen begründet zu sein, wie es die Studien zum Wortlängeneffekt implizieren. Einen weiteren Hinweis für letztere Annahme liefern Bush et al. (2007), die für ältere Erwachsene einen größeren Zuwachs an Reaktionszeiten für Kunstwörter (sublexikalische Lesestrategie) im Vergleich zu

Wörtern (lexikalische Lesestrategie) finden als für jüngere Erwachsene. Insgesamt bedarf es hierzu jedoch weiterer Forschung, da die Ergebnislage nicht ganz eindeutig ist.

Auch wenn die Leseleistung älterer Menschen durch das Anpassen der Schriftgröße und dem Tragen von Sehkorrekturen unter Umständen erhalten werden kann, darf nicht vergessen werden, dass ältere Menschen bei der Wortverarbeitung neben sensorischen möglicherweise auch zentrale neuro-kognitive Defizite ausgleichen müssen, die durch den normalen Alterungsprozess entstehen (z.B. Arbeitsgedächtnis, zentrale Exekutive). Bei der Untersuchung altersbedingter Veränderungen in der visuellen Worterkennung sollten daher zusätzlich zu der Erfassung von Jahren der formalen Bildung und des Wortschatzes, Indikatoren für den Abbau sensorischer, kognitiver und neuronaler Ressourcen eingesetzt werden.

Abschließend soll an dieser Stelle noch auf das Fehlen von Ergebnissen zum altersbedingten Lesen flacher, regelhafter Orthographien (z.B. Deutsch) sowie auf die geringe Anzahl von neurophysiologischen Studien, die sich mit (sub)-lexikalischer Verarbeitung im Alter beschäftigen, hingewiesen werden. Dass altersbedingte neurovaskuläre und morphologische Veränderungen den Vergleich junger und älterer Erwachsener erschweren (Samanez-Larkin & D'Esposito, 2008), sollte Forscher nicht davon abhalten, Fragestellungen bezüglich neuronaler und behavioraler Altersunterschiede in der Wortverarbeitung zu untersuchen.

3. Drifting through Basic Subprocesses of Reading: A Hierarchical Diffusion Model Analysis of Age Effects on Visual Word Recognition

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3.1. Introduction

Reading, one of the most complex activities of the human brain, is a life-long learning process (Schrott & Jacobs, 2011; Wolf, 2007), which is performed effortlessly and routinely by most individuals even in old age. Especially for older adults, reading is not only one of the most popular leisure activities, but it is also essential for successfully mastering and participating in everyday life thus contributing significantly to maintaining functional independence (Meyer & Pollard, 2006). Yet, it is still an open issue to what extent age-related changes in perceptual-attentional or higher cognitive processes influence this important daily life activity (Froehlich & Jacobs, 2016). Moreover, considering the multitude of subprocesses underlying visual word recognition and reading, it is of interest to investigate how age affects these subprocesses. For example, if it is the case that vocabulary knowledge increases with age (Verhaeghen, 2003), one might expect beneficial effects of age on lexical processing but such an effect has not been consistently found in the literature (e.g., Allen et al., 1991; Balota & Ferraro, 1996). The aim of the present study was to systematically investigate the impact of aging on four basic subprocesses of reading (sublexical, lexical, phonological, and semantic) in a model-guided way using hierarchical diffusion modeling.

3.1.1. Hierarchical diffusion modeling

A potential reason for the somewhat inconclusive findings of age-related effects on word recognition and reading are the statistical methods used for analyzing age-related differences. Usually, results have been established comparing mean response times (RTs) of younger and older adults in basic decision tasks. The problem of this approach is that older people respond generally slower than younger adults (e.g., Salthouse, 1996), which might mask more subtle processing differences. One approach to circumvent this problem has been the use of Brinley plots, in which mean RTs of older adults are plotted against mean RTs of younger adults. The resulting graph can then be described in mathematical terms with the slope representing the amount of generalized slowing in older adults (Brinley, 1965). However, Brinley plots are of limited use for the assessment of the range of cognitive processes involved in a given decision task, as they neglect informative components of the experimental data, such as correct and incorrect RT distributions or accuracy rates (Ratcliff et al., 2004b).

Addressing this general issue in a more differentiated, model-guided approach, Ratcliff (1978) introduced diffusion models for analyzing two-alternative forced choice tasks. One of the advantages of this approach is that it takes into account a wider set of data, i.e., correct and incorrect RTs, their distributions as well as accuracy data. This facilitates model development by increasing constraints (Grainger & Jacobs, 1996). More important for the present purpose, it allows to disentangle several processing components that underlie performance in a decision task (Ratcliff & McKoon, 2008; Ratcliff & Rouder, 1998; Ratcliff et al., 2004a,c). A diffusion model conceptualizes the decision process as a continuous sampling of information that accumulates information over time until one of two decision thresholds is reached followed by the actual response. The original model postulates four parameters describing the decision process: a non-decision time (t) representing the time needed for stimulus encoding, configuration of task-related working memory, preparation and execution of motor response, the decision threshold (*a*) indicating the amount of information needed for making a decision, the drift rate (*v*), i.e., the speed of evidence accumulation over time reflecting processing efficiency, and the starting point (*z*) that maps potential a priori decision biases (Ratcliff, 1978; Voss et al., 2013). In appropriate task contexts, these parameters can directly be interpreted. When motor response preparation requires little effort (e.g., a simple button press), large estimates for *t* are interpreted as increasing difficulties in stimulus encoding. Large estimates for *a* indicate a conservative and slow decision style, while small estimates imply fast but less accurate decisions, thus explaining the commonly observed speed-accuracy tradeoff. Large estimates for *v* typically are a sign of faster information processing (Oganian et al., 2016; Ratcliff & Smith, 2010; Voss et al., 2013).

The diffusion model has been successfully applied to data from a variety of basic decision tasks that are directly or indirectly related to reading, such as letter discrimination (Thapar et al., 2003), lexical decision (Oganian et al., 2016; Ratcliff et al., 2004a), semantic decision (Spaniol et al., 2006; Vandekerckhove et al., 2010), and verbal working memory (Ratcliff, 1978). However, estimating diffusion model parameters requires a large number of data points per participant. With a limited number of trials ($N < 200$; Ratcliff & Tuerlinckx, 2002), parameter estimation might be inaccurate (but see Lerche et al., 2016). Finally, in diffusion modeling statistical inference is restricted to the specific sample and it does not allow for the investigation of interindividual differences (Vandekerckhove et al., 2011; Voss et al., 2013). To overcome these restrictions, Vandekerckhove et al. (2011) proposed a novel analytical approach combining the advantages of diffusion models and hierarchical models (Gelman & Hill, 2007). Hierarchical diffusion models explicitly allow to estimate diffusion model parameters for individual participants even if the number of data points per subject is relatively small. This makes hierarchical diffusion modeling an ideal method in fields such as psycholinguistics and reading where it is not always possible to generate a large number of stimuli per experimental condition that require careful matching and multiple controls (e.g., Jacobs et al., 2015).

3.1.2. Reading as a multicomponent activity

The complexity of reading may seem astonishing considering the ease with which most individuals perform it in everyday life. Successful reading depends on the interplay of multiple (sub-)conscious cognitive processes. The most basic and central of these processes, visual word recognition (Jacobs & Ziegler, 2015), is typically divided into sublexical (letter recognition, integration of letters into larger sublexical units), orthographic/lexical (whole word recognition), phonological (mapping these letters/units onto sounds) and lexico-semantic processes (assigning meaning to a string of letters; *cf.* Ziegler et al., 2008). Computational models of reading have successfully tried to capture this complexity by implementing these subprocesses in an interactive activation or parallel distributed processing approach (Coltheart et al., 2001; Grainger & Jacobs, 1996; Harm & Seidenberg, 1999; Hofmann & Jacobs, 2014; Perry et al., 2007; Plaut et al., 1996; Zorzi et al., 1998). Yet, computational models of the full literary experience provided by reading – including affective and aesthetic aspects – still await further development (Jacobs, 2015a,b,c).

At the neural level, numerous brain regions have been identified to be functional in reading allowing to isolate networks that are systematically associated with these four subprocesses (e.g., Price, 2012). While visual and orthographic processes are mainly associated with left posterior inferior occipital as well as left ventral occipitotemporal activations, phonological and semantic processes additionally recruit higher-order language areas, such as left temporal and left inferior frontal regions (e.g., Braun et al., 2015; Cavalli et al., 2016; Dehaene et al., 2002; Kronbichler et al., 2007; Poldrack et al., 1999; Schurz et al., 2014; Welcome & Joanisse, 2012).

3.1.3. Age-related effects on subprocesses of reading

It is a still open question how these basic subprocesses and their neural underpinnings are affected by age. A consistent finding concerns age-related deficits at the sublexical level (e.g., word length effects in lexical decision; Froehlich & Jacobs, 2016). Further evidence stems from studies employing letter detection or letter matching tasks in younger and older adults that systematically report RT disadvantages for the older age group (Allen et al., 1991; Guttentag & Madden, 1987; Madden et al., 2007). However, these findings are exclusively based on comparisons of mean RTs or the application of Brinley plots, respectively. Thus, they do not allow us to draw inferences as to whether the observed disadvantages are due to deficits in letter identification/discrimination in old age or whether they are caused by mere (perceptual) decoding difficulties in older adults as has previously been suggested (e.g., Aberson & Bouwhuis, 1997; Allen et al., 1991, 1993). A solution to this problem was offered by Thapar et al. (2003), who used diffusion modeling to examine the effects of aging on letter discrimination. They observed larger estimates for the decision threshold (*a*) for older compared to younger adults, implying a more conservative decision criterion for the older age group. More importantly, estimates for the non-decision time (*t*) were also larger for older participants than for younger ones, whereas the rate of evidence accumulation (*v*) was found to be smaller. Both of these results indicate a slowing in basic encoding processes and a slower uptake of information specific to letter discrimination in older compared to younger adults.

At the orthographic processing level, the lexical decision task is one of the most popular tasks for investigating age-related effects on word recognition and reading. Consistently, in all of the 16 studies recently reviewed by Froehlich and Jacobs (2016), mean RTs of older readers were longer than those of younger ones. However, these findings might have resulted from a mere general age-related slowing in older adults. More importantly, the frequency effect, a standard indicator for the efficiency of lexical access (e.g., Balota et al., 2004; Jacobs & Grainger, 1994) was found to be identical across age groups in twelve of the reviewed studies. This is evidence for preservation of orthographic processing across the life span, as also suggested by results from Cohen-Shikora and Balota (2016) as well as Ratcliff et al. (2004c). The latter applied diffusion modeling to data from a lexical decision task and observed no differences in the rate of evidence accumulation (v) between older and younger adults. Yet, similar to letter discrimination, larger estimates were found for the decision threshold (a) and the non-decision time (t) in older adults compared to younger ones.

At the phonological level, age-related language effects have predominantly been investigated using speech production tasks or tasks employing auditorily presented sounds, words and sentences (*cf.* Burke & Shafto, 2008; Thornton & Light, 2006). When it comes to age-related effects on phonological processing in visual word recognition, however, there is an apparent lack of research, although it is known that phonological representations are automatically activated during silent reading even in highly skilled readers (e.g., Braun et al., 2009, 2015; Briesemeister et al., 2009; Ziegler & Jacobs, 1995) The phonological decision task, which forces participants to engage in phonological rather than in orthographic processing during silent reading, is therefore exceptionally well suited for our purposes and has not yet been administered to an older cohort (Bergmann & Wimmer, 2008; Kronbichler et al., 2007). There is, however, evidence of age-related slowing in pseudoword reading (e.g. Bush et al., 2007; Madden, 1989; Stadtlander, 1995), which requires successful phonological recoding (e.g., Coltheart et al., 2001; Jacobs et al., 1998; Perry et al., 2007; Taylor et al., 2012).

Finally, to investigate age effects at the lexico-semantic level, several studies have employed semantic decision tasks, in which a target stimulus is classified according to a prespecified category (e.g., Forster & Shen, 1996). Age-related RT effects on semantic processing have been found to be either absent (Daselaar et al., 2003) or larger in older adults (Spaniol et al., 2006). Yet again, analyzing only mean RTs or the accuracy of responses does not allow one to decide whether peripheral encoding processes or semantic processes decline with age. A first step towards solving this issue was made by Spaniol et al. (2006), who applied diffusion model analyses to semantic categorization data of older and younger adults. They found non-decision time (t) to be longer in older adults for living versus non-living discrimination. Decision thresholds (a) and drift-rates (v), however, were comparable for both younger and older participants suggesting a preservation of the speed of lexico-semantic information uptake in age.

In summary, the aforementioned results from diffusion modeling of data from sublexical, orthographic, and lexico-semantic decision tasks point towards non-decision times (t) being generally longer in older adults compared to younger ones. The decision threshold (a) seems to be more conservative in older than in younger adults in sublexical and orthographic, but not in semantic processing. Age-related effects on the speed of information uptake (v) appear to be confined to sublexical processing, whereas orthographic and semantic processing seems to be unaffected by age.

3.1.4. The present study

The aim of the present study was to systematically investigate the impact of age on four basic subprocesses of reading. Use of hierarchical diffusion modeling allowed us to differentiate between age-related influences on decision thresholds, stimulus encoding processes, preparation and execution of motor responses as well as the degree of information uptake during specific reading-related tasks. To illustrate the gain of interpretable information in hierarchical diffusion modeling compared to standard RT analyses, we additionally performed mixed-effects modeling of RTs and accuracy rates. Subprocesses of reading performance were assessed with the help of a letter identification task (visual sublexical processing), a lexical decision task (orthographic processing), a phonological decision task (phonological processing), and a semantic decision task (lexico-semantic processing). We administered these two-forced choice alternative decision tasks to three groups of participants: young adults, high-performing older adults and low-performing older adults. The older reader cohort was split into two groups based on their performance in a sentence comprehension task. This was done because the heterogeneity in cognitive performance increases with age (de Frias et al., 2007; Lindenberger et al., 2008). Considering older adults as a homogenously performing group may leave valuable information undetected. Analyzing these two groups separately might possibly explain the inconsistent findings reported above.

Based on previous evidence, we hypothesize older adults to have prolonged non-decision times (*t*) compared to younger adults in all four decision tasks (Ratcliff et al., 2001, 2003, 2004c,d; Spaniol et al., 2006; Thapar et al., 2003). As non-decision times depend on speed of sensorimotor preparation, perceptual encoding of stimuli, as well as task-related working memory processes, it is expected that older adults show a disadvantage (e.g., Madden et al., 1993; Salthouse, 1996; Vallesi et al., 2009). Likewise, we expect both groups of older adults to show a higher decision threshold (*a*) than younger adults due to a generally more conservative decision strategy (Ratcliff et al., 2001, 2003, 2004c,d; Thapar et al., 2003 but see Spaniol et al., 2006, experiment 1).

The major interest of the present study concerns age-related effects on the speed of information uptake during sublexical, orthographic, phonological, and semantic processing. At the sublexical level, we expected lower drift rates (v) in the older group than in younger readers (*cf.* Thapar et al., 2003). In contrast, the speed of information uptake was thought to be unaffected by age in orthographic and lexico-semantic processing (*cf.* Ratcliff et al., 2004c; Spaniol et al., 2006). Concerning phonological processing, we can only speculate about the outcome as (to our knowledge) this is the first study to explicitly investigate phonological processing during visual word recognition in aging. Based on findings from pseudoword reading in lexical decision, we assume an age-disadvantage for the older group (Bush et al., 2007; Madden, 1989; Stadtlander, 1995), especially when considering the amount of focused spatial attention phonological processing requires (*cf.* Facoetti et al., 2006). With the additional grouping of the older cohort, we expect to gain a more differentiated and informative picture of the effects of aging on the four central subprocesses of reading with respect to all three hierarchical diffusion modeling parameters.

3.2. Methods

3.2.1. Participants

The present study recruited a subsample of 1,807 subjects (930 female, 877 male) from the Berlin Aging Study II cohort (BASE-II; Bertram et al., 2014). Selection was based upon completion of all reading tasks with individual error rates below 40%. The 384 younger adults (195 female, 189 male) were on average 30.7 years old (range 23 – 40 years). The sample of the 1,423 older adults (735 female, 688 male) was further split into two groups based on their performance in a sentence comprehension task. Using the SOS-algorithm (Armstrong et al., 2012), we identified 384 older adults (191 female, 193 male) whose reading scores were on average identical to that of younger participants ($M = 60.7$) and 1,039 older participants (544 female, 495 male) who differed significantly in their performance from the other two groups ($M = 52.0$, $p < .001$). High-performing older adults were on average 69.7 years old (range 61 – 88), low-performing older adults 70.2 years (range 60 – 86). The age difference between the older groups was not significant ($p = .11$, Tukey corrected). Due to technical problems during data acquisition information on education could not be evaluated for 14.7% of the participants (young adults = 19.5%, high-performing older adults = 10.7%, low-performing older adults = 15.3%). The remaining participants differed in years of education with low-performing older participants having less years of education (*M* = 14.1) than high-performing older participants (*M* = 14.6; $p < .05$) and younger participants (*M* = 15.0; $p < .001$). The two latter groups did not differ from each other ($p = .09$). All participants were German native speakers, right-handed and had normal or to normal corrected vision. None of the participants had a history of reading difficulties or language impairment, neurological disease, psychiatric disorders or a history of head injuries. Prior to the study, written informed consent was obtained and subjects received financial compensation for their participation. The study was approved by the Ethics Committee of the Max Planck Institute for Human Development, Berlin (MPIB).

3.2.2. Procedure

Participants were tested in small groups of up to six individuals in a quiet test room on the Charité Campus, Berlin. One test session lasted for about 3.5 hours and included additional tasks of the BASE-II test battery. Before each task, participants performed training trials. The following tasks were used to assess the four central subprocesses of reading: letter identification, lexical, phonological and semantic processing. The order of the tasks was as follows: Sentence comprehension task, phonological decision task, semantic decision task, lexical decision task, letter identification task. Within each task, item order was pseudorandomized and items were presented one by one at the center of a computer screen for three seconds or up to participant's response. Participants were instructed to give yes- or no-responses via button press as quickly and accurately as possible.

3.2.3. Stimuli and design

To ensure comparability of results and control for confounding linguistic variables, item length, number of orthographic neighbors, bigram frequency and (base word) frequency were carefully matched across the lexical, the phonological as well as the semantic decision task (all *F*'s < 1.83, all *p*'s > .2). Within these tasks, the mean number of letters per item varied from 4.43 to 4.53, the mean number of orthographic neighbors from 19.4 to 24.4. Normalized lemma frequency of the (base) word frequency ranged from 1.22 to 1.41, the bigram frequencies from 4.35 to 4.42. Bigram frequencies in the letter identification task were lower than those in the other tasks, $F(3, 316) = 33.4$, $p < .001$, as vowel-consonant combinations were excluded by design. Each item in the letter identification task consisted of five consonants (see Appendix B.1., Table B.1. for detailed item characteristics). Matching was based on the dlex database (dlexDB; Heister et al., 2011) norms for German words. Within each task 40 items served as targets and 40 as non-targets.

3.2.3.1. Letter identification task. To assess position-specific letter processing without lexical activation (Ziegler et al., 2008), participants had to indicate whether the letter ‚r' occurred within a consonant string (target; e.g., dbnrl) or not (non-target; e.g., djptd). Targets and non-targets were carefully matched for bigram-frequency and had on average the same number of lowercase letters, letters with ascenders and letters with descenders.

3.2.3.2. Lexical decision task. Orthographic processing was assessed by presenting either German nouns (targets; e.g. Park) or German pseudohomophones (non-targets; e.g., Waal [whale]). Pseudohomophones are a particular type of pseudowords, but different to pseudowords, which are pronounceable words with no meaning, pseudohomophones sound like real words (e.g., brane is phonologically identical to the real word brain). Participants had to decide whether the presented stimulus was a correctly spelled German word or not. Pseudohomophones were created by changing one letter of an existing German noun to keep them orthographically similar to real words. The initial letters of all items were capitalized to ensure the typical appearance of German nouns.

3.2.3.3. Phonological decision task. To investigate phonological processing participants had to judge whether pseudohomophones (target; e.g., Waal) or pseudowords (non-target; e.g., Lase) were presented. Specifically, they were asked to give a yes-response when the item on the screen *sounded* like a word and to give a no-response otherwise. Identical to pseudohomophone construction, pseudowords were created by changing one letter from an existing German noun and were presented with capitalized initial letters.

3.2.3.4. Semantic decision task. This task was designed to measure participants' abilities in lexico-semantic processing. Subjects had to indicate whether the presented item described living objects (target; e.g., Koala) or non-living objects (non-target; e.g., Plan). In line with the previous tasks, only German nouns served as targets and non-targets.

3.2.3.5. Sentence comprehension task. Overall reading ability was assessed using a computerized version of a standard German sentence reading test (Bergmann & Wimmer, 2008). Participants had to judge via button press whether each of a total of 77 successively presented sentences was meaningful or not. Sentences gradually increased in sentence length as well as word and morpho-syntactic complexity but were generally easy to comprehend (e.g., Ein Nashorn ist ein Blechblasinstrument [A rhinoceros is a brass instrument]). Overall reading performance was calculated by summing up the correctly answered items within three minutes. The scores of this task were solely used to differentiate between high-performing older adults and low-performing older adults.

3.2.4. Data analysis

3.2.4.1. Outlier exclusion. Prior to analyses, RTs smaller than 300ms were excluded to prevent fast guesses from biasing results (Voss et al., 2013). For RT and hierarchical diffusion modeling analyses we then removed RTs deviating more than 2.5

standard deviations from the individual’s mean within each task x stimulus type experimental cell. These procedures led to a removal of 3.37% of the data.

3.2.4.2. Analyses of mean response times and accuracy. Mean RTs and accuracy were analyzed to illustrate the added value of information the diffusion modeling approach provides. We used mixed-effects modeling (Baayen et al., 2008) as implemented in the „lme4“-package (Bates et al., 2014) with crossed random factors for subjects and items. Analyses were run in R version 3.3.0 (R Core Team, 2015). We analyzed RTs by linear mixed-effects regression, including main effects and interactions for task and age as fixed factors. Fixed effects were tested for significance using Type III Wald chi-square tests („car“-package; Fox & Weisberg, 2011). Accuracy was analyzed using logistic mixed-effects regression. As recommended by Barr et al. (2013; Barr, 2013), the random factor structure included intercepts for subjects and items, and random slopes for age within items, as well as random slopes for task within subjects.

3.2.4.3. Hierarchical diffusion modeling. RTs and accuracies were fitted to hierarchical diffusion models using the python toolbox HDDM, which provides hierarchical Bayesian parameter estimation of the drift-diffusion model (Wiecki et al., 2013). The hierarchical approach allows for simultaneous estimation of diffusion model parameters across participants and the possibility to restrain these parameters according to theoretical assumptions: While some parameters may vary from individual to individual, others are constrained to be equal across participants (Vandekerckhove et al., 2011; Voss et al., 2013). For our purposes, we created a model for each of the subprocesses of reading (i.e., letter identification, orthographic processing, phonological processing, lexico-semantic processing). Within these four models, the non-decision time (t), the decision threshold (a) with the upper threshold being the correct response and the lower threshold being the incorrect response, as well as the drift rate (v) were estimated for each individual separately. These parameters were allowed to vary across participants to account for the general increase in non-decision time (*t*) of older compared to younger participants (Ratcliff, 2008), for individual and age-related preferences in setting the decision threshold (*a*), and, most importantly, for age-effects on the speed of information uptake (*v*) within the subprocesses of reading. We constrained the bias parameter (*z*) of each individual to .5 as we did not assume an *a priori* preference of participants towards one of the response options as the number of targets and non-targets were equal. Additionally, following the approach of Oganian et al. (2016), we set parameters of trial-to-trial variances of non-decision time, drift rate and bias parameter to 0. Fixing these parameters can improve parameter estimation of *t, a* and *v* (Lerche & Voss, 2016). In summary, we estimated the posterior distributions of a total of 36 parameters across the four decision tasks: twelve non-decision time parameters (*t*), twelve threshold parameters (*a*), and twelve drift rate parameters (*v;* for *t, a* and *v* one for each age group within each of the four subprocesses of reading).

Parameters were estimated using a Bayesian approach as implemented in the HDDM toolbox. The Bayesian approach is particularly well suited for hierarchical model estimation (Vandekerckhove et al., 2011). It assigns prior probability distributions to each of the parameters to be estimated and applying the Bayes' theorem allows the estimation of the posterior probability distribution of the parameters given the observed data. Approximation of posterior distribution is done using an iterative procedure, the Markov chain Monte-Carlo sampling (MCMC; for an introduction to MCMC and Bayesian statistics, see Kruschke, 2015). When running several MCMC chains it is important to ensure that all chains of the model properly converge. We therefore assessed model convergence by visually inspecting the traces of the posterior distribution and in a second step by calculating the Gelman-Rubin statistic (R-hat; Gelman & Rubin, 1992). Comparing the within-chain and between-chain variance of different runs of the same model, this statistic will be close to one if the chains converged successfully. Values exceeding 1.02 indicate problems with convergence (Wiecki et al., 2013) and consequently deficient model estimation.

For each of the four models representing the basic subprocesses of reading, all model parameters were estimated using three MCMC chains with starting values being set to the maximum posterior (as implemented in the HDDM toolbox). The chains contained 15.000 samples drawn from the posterior distribution from which the first 5.000 samples were discarded as burn-in to ensure stabilization of the chains. After controlling for proper convergence, we assessed the quality of model-to-data fit by simulating 500 data sets (RTs and accuracy) from each participant's model and compared the means of these data sets with the empirical data.

3.2.4.4. Hypothesis testing. To examine age-related differences in letter identification, orthographic, phonological and lexico-semantic processing on non-decision time (t), decision threshold (a), and drift rate (v), we used Bayesian hypothesis testing as implemented in the HDDM toolbox. For each of the models, we calculated the proportion of overlap of the posterior distributions of the three age groups with respect to the parameters t, a and v.

3.3. Results

3.3.1. Regression analyses of response times and accuracy

3.3.1.1. Response times. Mean RTs are shown in Table 3.1. The 4 x 3 (task: letter identification vs. lexical decision vs. phonological decision vs. semantic decision x age: young vs. high-performing old vs low-performing old) linear mixed-effect model yielded a main effect of task, $\chi^2(3) = 867.0$, $p < .001$ and age, $\chi^2(2) = 499.3$, $p < .001$, as well as the significant interaction of both factors, $\chi^2(6) = 41.0$, $p < .001$. Planned comparisons, directly encoded in the model, showed that shortest RTs were obtained in the letter identification task, $b = -210.1$, $SE = 14.3$, $t = -14.7$. RTs in the semantic decision task were shorter, $b = -200.7$, $SE = 13.5$, $t = -14.9$ than in the lexical and phonological decision task and again RTs in the lexical decision task were shorter than in the phonological decision task, $b = -252.9$, $SE = 11.8$, $t = -21.4$. Generally, younger participants responded faster than older adults, $b = -105.1$, $SE = 5.38$, $t = -19.5$, and high-performing older adults responded faster than low-performing older adults, $b = -26.3$, $SE = 3.79$, $t = -6.94$. The identical age-related RT pattern was observed within all four tasks (see Table 3.2 for a detailed summary). Given the size of the data set and all absolute t-values being well above 2, we consider these differences to be significant (*cf.* Baayen et al., 2008).

3.3.1.2. Accuracy. Mean percentage accuracy rates are shown in Table 3.1. The 4 x 3 (task: letter identification vs. lexical decision vs. phonological decision vs. semantic decision x age: young vs. high-performing old vs low-performing old) logistic mixed-effects analyses showed a main effect of task $\chi^2(3) = 148.6$, $p < .001$ and age $\chi^2(2) = 19.4$, $p < .001$ as well as the significant interaction of task and age, $\chi^2(6) = 29.7$, $p < .001$. Highest accuracy rates were obtained in the letter identification task, $b = .43$, $SE = .12$, $z = 3.62$. Participants made fewer errors in the lexical decision task, $b = .71$, $SE = .11$, $z = 6.36$ than in the semantic and phonological decision task and fewer errors in the semantic decision task, $b = .93$, $SE = .10$, $z = 9.68$ than in the phonological decision task. Across all four tasks high-performing older adults showed higher accuracy rates than younger and low-performing older adults, $b = .13$, $SE = .03$, $z = 4.05$. The same age-related effects were found within the letter identification, the lexical and semantic decision task while within the phonological decision task higher accuracy rates were observed for younger participants than for high-performing older participants and higher accuracy rates for high-performing older participants than for low-performing older participants (see Table 3.3 for a detailed summary).

Table 3.1

Mean RTs (msec), accuracy (%) and standard deviations (SD) for all single item reading tasks as a function of age

	Younger Adults	High-Performing Older Adults	Low-Performing Older Adults
RTs (*SD*)			
Letter identification task	599 (132)	752 (176)	785 (194)
Lexical decision task	734 (233)	845 (251)	919 (305)
Phonological decision task	1,217 (449)	1,353 (479)	1,407 (490)
Semantic decision task	698 (174)	812 (198)	856 (224)
Accuracy (*SD*)			
Letter identification task	97.5 (15.7)	97.9 (14.5)	97.7 (14.9)
Lexical decision task	96.0 (19.6)	97.8 (14.7)	97.0 (17.0)
Phonological decision task	90.2 (29.8)	88.8 (31.5)	87.9 (32.7)
Semantic decision task	96.3 (18.9)	97.6 (15.4)	96.8 (17.6)

Table 3.2

Summary of linear mixed-effect regressions for RTs within the four single item reading tasks

Predictor	*b*	*SE*	*t-value*
Letter identification task			
Intercept	713.4	6.78	105.3
Age[1]	-113.7	4.95	-23.0
Age[2]	-16.6	3.28	-5.07
Lexical decision task			
Intercept	840.9	13.4	62.9
Age[1]	-97.8	7.41	-13.2
Age[2]	-38.7	4.99	-7.77
Phonological decision task			
Intercept	1,346.7	28.7	46.9
Age[1]	-117.1	11.1	-10.6
Age[2]	-27.3	7.07	-3.86
Semantic decision task			
Intercept	792.7	9.28	85.4
Age[1]	-91.6	5.49	-16.7
Age[2]	-22.8	3.39	-6.71

Note. b = beta-estimate; *SE* = standard error; [1]young adults compared to high- and low-performing older adults; [2]high-performing older adults compared to low-performing older adults. Within each task, the main effect of age was highly significant, $\chi^2_{\text{letter identification}}(2) = 598.0, p < .001$, $\chi^2_{\text{lexical decision}}(2) = 256.6, p < .001$, $\chi^2_{\text{phonological decision}}(2) = 147.1, p < .001$, $\chi^2_{\text{semantic decision}}(2) = 346.5, p < .001$.

Table 3.3

Summary of logistic mixed-effect regressions for accuracy within the four single item reading tasks

Predictor	*b*	*SE*	*z-value*	*p-value*
Letter identification task				
Intercept	4.43	.12	37.5	< .001
Age[1]	.10	.04	2.44	< .05
Age[2]	.05	.04	1.47	.14
Lexical decision task				
Intercept	4.57	.14	31.8	< .001
Age[1]	.23	.06	3.77	< .001
Age[2]	.05	.06	.75	.45
Phonological decision task				
Intercept	2.66	.11	23.7	< .001
Age[3]	.18	.06	2.80	< .01
Age[4]	.08	.03	2.70	< .01
Semantic decision task				
Intercept	4.38	.13	33.2	< .001
Age[1]	.29	.06	5.17	< .001
Age[2]	.09	.05	1.67	.10

Note. *b* = beta-estimate; *SE* = standard error; [1]high-performing older adults compared to young and low-performing older adults; [2]low-performing older adults compared to young adults; [3]young adults compared to high- and low-performing older adults; [4]high-performing older adults compared to low-performing older adults. The main effect of age was significant within each of the tasks, $\chi^2_{letter\ identification}(2) = 6.35, p < .05$, $\chi^2_{lexical\ decision}(2) = 17.9, p < .001$, $\chi^2_{phonological\ decision}(2) = 16.8, p < .001$, $\chi^2_{semantic\ decision}(2) = 27.8, p < .001$.

In summary, analyses of mean RTs and accuracy rates suggest an age-related slowing within all subprocesses of reading. Higher accuracy rates were observed for younger participants compared to older participants only within the phonological decision task. For letter identification, lexical decision, as well as semantic decision, high-performing older participants obtained higher accuracy rates than the other two groups. Together with the finding that older adults responded more slowly, this finding suggests a speed-accuracy tradeoff for high-performing older adults compared to younger participants in these three tasks.

3.3.2. Hierarchical diffusion modeling

3.3.2.1. Assessment of convergence and model fit. Model convergence was assessed by visually inspecting the traces of the posterior distributions and by calculating the R-hat statistics for each of the models separately.

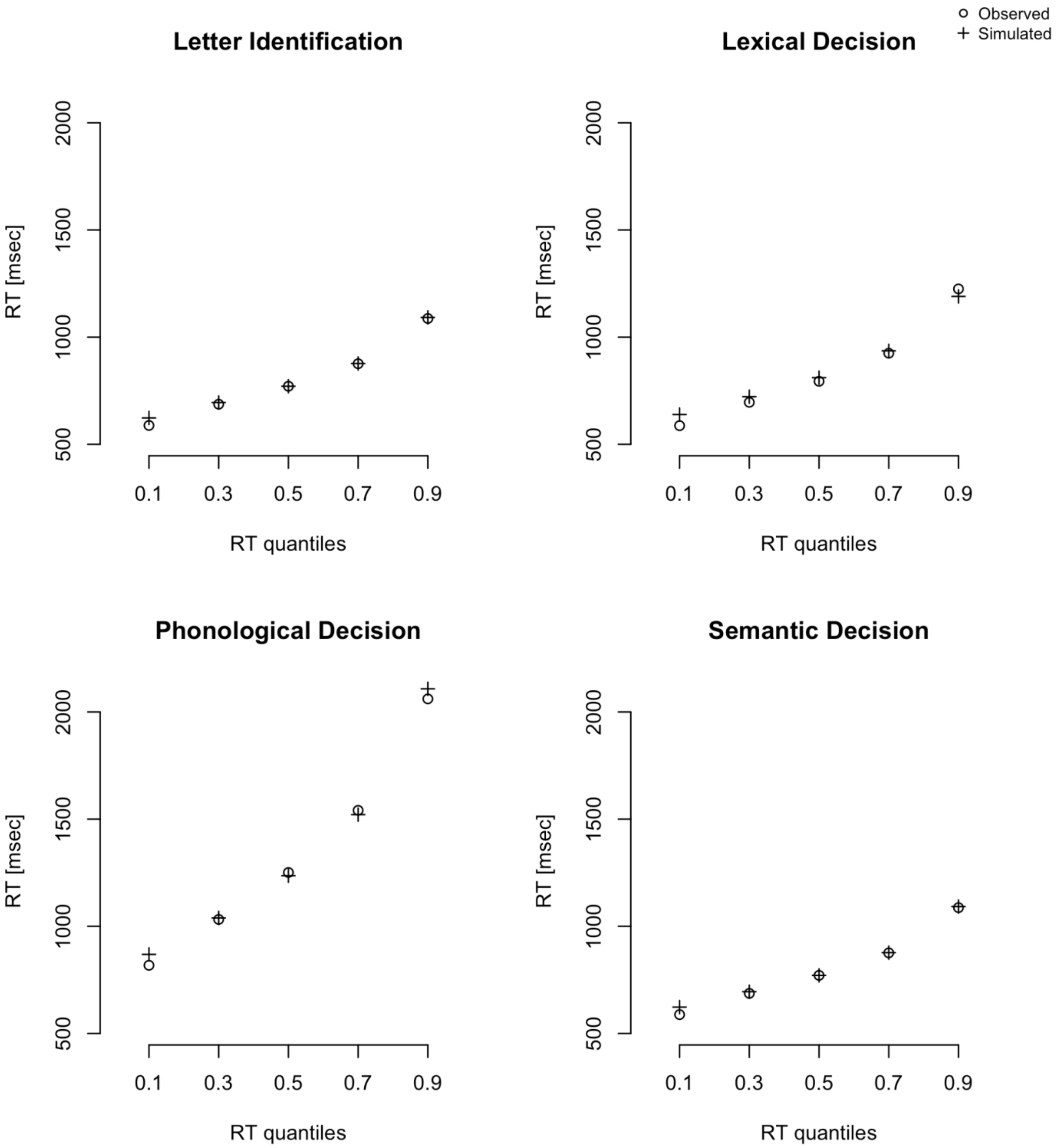

Figure 3.1. Plot of RT quantiles (0.1, 0.3, 0.5, 0.7, 0.9) for correct responses based on observed and simulated data; observed data is within a 95% credibility interval of simulated data.

We neither observed any drifts or large jumps within the plots nor any parameter values above 1.02 within the R-hat statistic, indicating successful convergence for all models of reading subcomponents. We then compared the simulated with the observed data, again for all models separately. The model fitted our data very well: The correlation between empirical data and model RT quantiles was $r = .98$ in the letter identification task, $r = .94$ in the lexical decision task, $r = .99$ in the phonological decision task, and $r = .96$ in the semantic decision task (Figure 3.1).

3.3.2.2. Model parameter analysis of posterior estimates. Analyses of the posterior estimates showed age-related differences in non-decision time (t), decision threshold (a), and drift rate (v) for all four reading tasks (Table 3.4 and Figure 3.2).

Table 3.4

Mean posterior estimates for non-decision time (t), decision threshold (a) and drift rate (v) as well as 95% credibility intervals [lower boundary; upper boundary] as a function of age for all single item reading tasks

	Younger Adults	High-Performing Older Adults	Low-Performing Older Adults
Letter identification task			
Non-decision time (t)	.376 [.371; .381]	.453 [.447; .460]	.459 [.455; .464]
Decision threshold (a)	1.62 [1.58; 1.66]	1.92 [1.86; 1.97]	1.99 [1.95; 2.02]
Drift rate (v)	3.58 [3.49; 3.66]	3.18 [3.10; 3.26]	3.04 [2.99; 3.09]
Lexical decision task			
Non-decision time (t)	.426 [.421; .432]	.484 [.477; .491]	.506 [.502; .511]
Decision threshold (a)	1.59 [1.56; 1.63]	2.00 [1.95; 2.06]	1.97 [1.95; 2.00]
Drift rate (v)	2.52 [2.46; 2.59]	2.80 [2.72; 2.88]	2.42 [2.37; 2.47]
Phonological decision task			
Non-decision time (t)	.537 [.529; .546]	.620 [.609; .631]	.641 [.634; .648]
Decision threshold (a)	2.08 [2.04; 2.12]	2.14 [2.10; 2.18]	2.17 [2.14; 2.20]
Drift rate (v)	1.29 [1.25; 1.33]	1.17 [1.13; 1.21]	1.10 [1.08; 1.13]
Semantic decision task			
Non-decision time (t)	.430 [.424; .435]	.487 [.480; .494]	.505 [.501; .509]
Decision threshold (a)	1.59 [1.55; 1.62]	1.90 [1.86; 1.94]	1.88 [1.86; 1.91]
Drift rate (v)	2.84 [2.77; 2.91]	2.88 [2.81; 2.95]	2.61 [2.57; 2.65]

As expected, older participants obtained larger estimates for both non-decision time (t) and decision threshold (a) than did younger participants with a probability ranging from .98 to 1 for both parameters for all four tasks as assessed via Bayesian hypothesis testing. Estimates of the non-decision time (t) in all four tasks were larger for low performing older adults compared to high-performing older adults with probabilities ranging from .94 to 1. Likewise, for the decision threshold (a), estimates were larger for low-performing older adults than for high-performing older adults in the letter identification and the phonological decision task with a probability of .98 and .88, respectively, whereas the opposite pattern was found for the lexical and semantic decision task with a probability of .88 and .71.

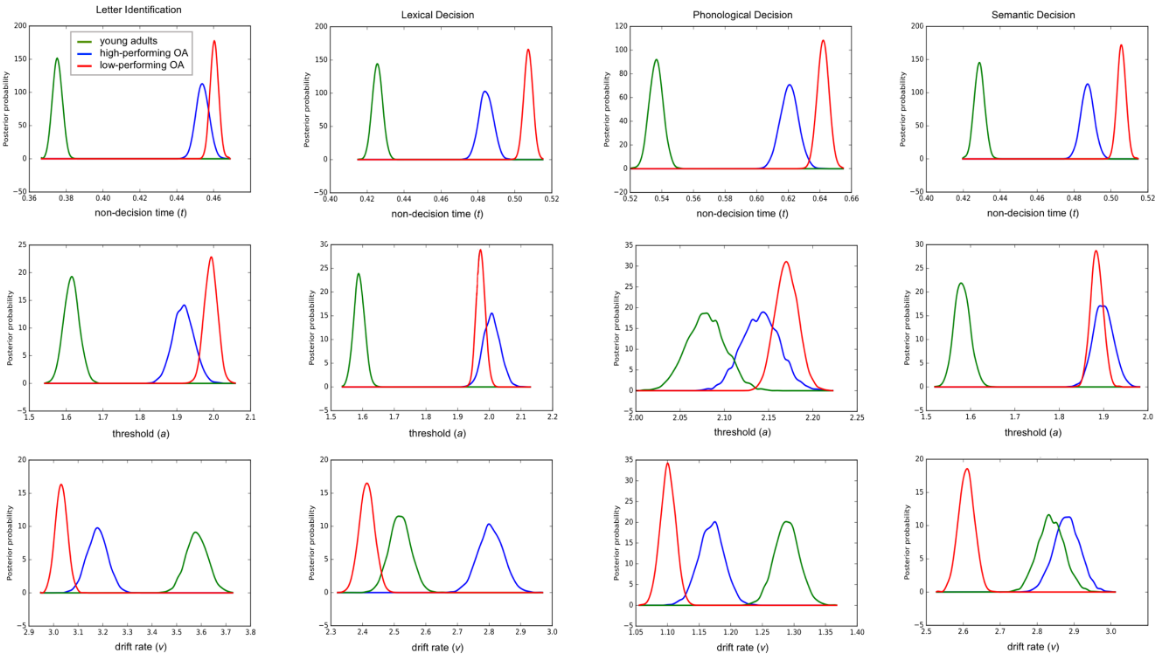

Figure 3.2. Posterior density plots of group means of the parameters non-decision time t (first line), decision threshold a (second line) and drift rate v (third line); OA = older adults.

Also, as expected, with a probability of 1, drift rates (v) were higher for younger than for older adults in the letter identification and phonological decision task. Yet, high-performing older adults obtained higher drift rates than low-performing older adults in both of these tasks, the probability being 1 in both cases. Against our expectations, we found an age-related advantage in drift rates (*v*) for high-performing older adults over young adults within the lexical and semantic decision task (probability of 1 and .80, respectively). Low-performing older adults, however, showed an age-related disadvantage compared to younger adults with probabilities of 1 in both tasks.

3.4. Discussion

The present study aimed at systematically investigating age-related effects on four basic subprocesses of reading. To account for the somewhat inconsistent age-related findings in sublexical, orthographic, phonological and lexico-semantic processing reported in the past, we differentiated between high- and low-performing older adults and used a hierarchical diffusion modeling approach. Results based on this approach showed that in general older readers obtained larger estimates for the non-decision times (*t*) and needed more information to make a decision (*a*). Most importantly, though, a different picture emerged with respect to the speed of information uptake within the subprocesses (*v*).

Non-decision times (*t*) were longest for low-performing older adults and longer for high-performing older adults than for younger adults. While high-performing older adults showed higher estimates for the decision threshold (*a*) in orthographic and lexico-semantic processing than did low performing older adults, the opposite pattern emerged for sublexical and phonological processing. Of special interest was the speed of information uptake (*v*). Here, an age-advantage was found for sublexical and phonological processing for young adults compared to high-performing older adults and an advantage was found for high-performing older adults over low-performing older adults. Most importantly, drift rates (*v*) of high-performing older adults in lexical and semantic decision tasks were superior to those of young adults while drift rates of young adults exceeded those of low-performing older adults.

3.4.1. Age-related effects on response times and accuracy

For mean RTs, we replicated the classical finding of an age-related slowing in older compared to younger adults in all four decision tasks. Additional analyses showed that young participants obtained shorter RTs than high-performing older adults and high-performing older adults obtained shorter RTs than did low-performing older adults. Based on these findings, one would have to conclude that all four central subprocesses of reading decline with increasing age to different degrees.

Accuracy rates across all four subprocesses of reading were higher for high-performing older adults than young and low-performing older adults. However, in phonological processing, younger adults obtained higher accuracy rates compared to high-performing older adults and high-performing older adults obtained higher accuracy rates than did low-performing older adults. Taking also mean RTs for this task into account, apparently, phonological processing was most demanding for older adults. Yet in sublexical, lexical and semantic processing, high-performing older adults showed higher accuracy rates than did young and low-performing older adults. In traditional mean RT/accuracy analyses, these results would be hard to interpret since high-performing older adults showed the classical speed-accuracy tradeoff compared to younger adults often reported for older adults in general (e.g., Forstmann et al., 2011; Heitz, 2014).

3.4.2. Hierarchical diffusion modeling

Hierarchical diffusion modeling is superior to traditional mean RT/accuracy analyses as it allows to disentangle a range of cognitive processes involved in decision making such as the time needed to prepare a response (t), the amount of information needed to make a decision (a), and the speed with which information is accumulated to reach a decision (v).

As expected, posterior estimates for non-decision times (*t*) were smaller for young adults than for older adults with an advantage in non-decision time for high-performing older adults compared to low-performing older adults. Yet, it is challenging to draw direct conclusions from these results. The parameter *t* is thought to estimate the time needed to encode the stimulus, to prepare the appropriate motor response, and to configure task-related working memory. However, all of these processes should yield a natural advantage for younger over older adults. Thus, this "compound" parameter still seems too fuzzy to determine the individual contribution of age on each of these subprocesses to allow inferences of age-related slowing on non-decision time in the present study. Further studies specifically targeting the subprocesses contributing to parameter *t* at the behavioral or neural level are strongly needed to clarify this open issue.

With consistently found larger estimates for decision threshold (*a*) in all four two-alternative forced choice tasks, older adults in the present study applied a more conservative criterion than younger adults. These results are in line with previous evidence from diffusion modeling studies on aging in various domains (e.g., Ratcliff et al., 2004c; Thapar et al., 2003). Obviously, older adults tend to collect more information before making a decision preferring accuracy over speed than younger adults (e.g., Forstmann et al., 2011). However, while low-performing older adults obtained larger estimates for the decision threshold (*a*) at the sublexical and phonological level than high-performing older adults, the opposite pattern was found at the orthographic and lexico-semantic processing level. Within the diffusion modeling framework, the above mentioned speed-accuracy tradeoff in high-performing older adults at the latter two processing levels can nicely be explained when considering both the decision threshold (*a*) and the drift rates (*v*): Low-performing older adults need to lower their decision threshold (*a*) due to the observed slowing in the speed of information uptake (*v*) to be able to still reach a decision within the designated time window. In lowering their decision threshold (*a*), low-performing older adults are prone to make more erroneous responses (*cf.* Heitz, 2014), though, a result we observed in comparison to high-performing older adults. Similarly, young adults with the lowest decision threshold (*a*) have lower accuracies than high-performing older adults; yet with a higher speed of information uptake (*v*) than low performing older adults they can afford to set such a liberal decision threshold (*a*). The large drift rate (*v*) observed for high-performing older adults allows this group to settle upon a very conservative decision threshold (*a*) and still make decisions on time with very high precision.

The major focus of the present study was to investigate age-related effects on four basic subprocesses of reading: sublexical, orthographic, phonological and lexico-semantic processes. The efficiency of these subprocesses was analyzed via hierarchical diffusion modeling by the speed of information uptake, i.e., drift rate (*v*). At the sublexical level, we found smaller drift rates (*v*) for low-performing older adults compared to high-performing older adults and, in turn, smaller drift rates (*v*) for high-performing older readers compared to younger readers. This replicates evidence from both, classic mean RT analyses and diffusion modeling studies (e.g., Allen et al., 1991, 1993; Froehlich & Jacobs, 2016; Thapar et al., 2003). It is still a matter of debate whether disadvantages for older adults in sublexical processing are mainly the result of difficulties in stimulus encoding or caused by an age-related decline in lexical subprocessing per se (e.g., Aberson & Bouwhuis, 1997; Allen et al., 1991). By applying hierarchical diffusion modeling, our results point towards both of these interpretations when considering the larger posterior estimates for non-decision time (*t*) together with the smaller drift rate (*v*) observed for older adults compared to young ones. Larger estimates for *t* have been interpreted as increased difficulties in stimulus encoding, when motor response preparation requires little effort (*cf.* Oganian et al., 2016), as was the case in the present study. Smaller estimates for the drift rate (*v*) suggest that older adults are also prone to a decline in sublexical processing itself. Yet, the age-related decrease in sublexical processing varied substantially within older subjects of this study. Successful sublexical processing is predominantly based on efficient grapheme to phoneme translation and formation of meaningful letter combinations (e.g., prefixes, syllables) and is thought to be the most basic stage of visual word recognition and reading (e.g., Coltheart et al., 2001; Grainger & Jacobs, 1996; Grainger & Ziegler, 2008; Hofmann et al., 2011; Perry et al., 2007). Importantly, low-performing older adults who were classified based on their results in a sentence comprehension task showed a stronger age-related decline already at the most fundamental level of visual word recognition compared to high-performing older adults.

At the orthographic processing level, larger estimates for drift rates (*v*) were observed for high-performing older adults compared to young adults and, in turn, drift rates (*v*) of young adults were higher than those of low-performing older adults. Our findings differ from those of previous studies (*cf.* Cohen-Shikora & Balota, 2016; Froehlich & Jacobs, 2016; Ratcliff et al., 2004c), which reported no age-related effects on orthographic processing. This discrepancy very likely is the result of assigning older participants to two performance groups, as suggested by an additional hierarchical diffusion model analysis of our data: When comparing young adults with all older adults assigned to a single large group we replicated the results of Ratcliff et al. (2004c; see Appendix B.2.). So what can account for the differences in speed of information uptake in the present study? Usually it is assumed that life-long exposure to text gives older adults a natural advantage in vocabulary knowledge (Allen et al., 1995; Verhaeghen, 2003). This should in turn lead to a larger and better organized orthographic lexicon and likely to higher drift rates in older compared to younger adults. Yet, low-performing older adults might show a reduced drift rate compared to high-performing older and young adults because of a less extensive and efficient orthographic lexicon, if their vocabulary knowledge is not as abundant. Low-performing readers tend to rely more on phonological recoding strategies and engage brain regions typically related to orthographic processing to a lesser extent (Jobard et al., 2011). Interactive activation models of reading, such as the MROM (Grainger & Jacobs, 1996) assume the orthographic lexicon to consist of a network of connected word nodes. Words are positively identified in lexical decision as soon as the activation of a single word node or the summed global activation of all word nodes reaches a certain decision criterion. In low-performing older adults of the present study, either initial lexical activation or the global spreading of activation might be affected as characterized by the lower drift rate (*v*) compared to the other two groups of participants. Findings provided by Robert and Mathey (2007) who investigated age-related effects on lexical inhibition point towards both possibilities: inefficient inhibition and activation processes in older adults. Further research using the MROM or alternative computational models to simulate individual word recognition performance (e.g., Jacobs et al., 2003; Ziegler et al., 1998) is necessary to decide this issue.

Results observed at the phonological processing level mirrored findings identified at the sublexical processing level: Highest drift rates (*v*) were found for young adults; drift rates (*v*) for high-performing older adults were higher than those of low-performing older adults. Because phonological processing requires successful encoding of grapheme-phoneme correspondences, it is conceivable that deficits identified at the sublexical processing level further prevail at the phonological processing level. However, phonological processing is not restricted to decoding simple spelling to sound correspondences of single letters, but also applies to successful whole word recognition (e.g., Coltheart et al., 2001; Perry et al., 2007; Taylor et al., 2012). It is assumed that grapheme-phoneme conversion operates either in a serial manner (e.g., Perry et al., 2007) or depends on the relative level of activation of the corresponding units (Jacobs et al., 1998). In the latter case, both low- and high-performing older adults may show similar deficits in activation mechanisms as proposed at the orthographic processing level for low-performing older adults to varying degrees. In the former case, older adults may experience deficits in temporal sampling. Evidence from speech perception studies suggests that even with a still intact auditory system, older participants persistently are more affected by (auditory) noise and temporal changes in auditory signals (Burke & Shafto, 2008; Thornton & Light, 2006).

At the lexico-semantic processing level, we identified similar results for posterior estimates in the speed of information uptake (*v*) as for orthographic processing. High-performing older adults obtained larger drift rates (*v*) than young adults whose drift rates (*v*) in turn exceeded those of low-performing older adults. These results deviate from the age-related null effects in semantic decision previously reported in the only other diffusion modeling study conducted so far (Spaniol et al., 2006). Again, we believe that this discrepancy is the consequence of dividing the older cohort into two groups which was done to account for the greater variability in performance reported for older adults in our very large sample. To check this, we collapsed the two older groups into a single group and we ran an additional hierarchical diffusion model analysis (see Appendix B.2.). Here, we observed smaller drift rates (*v*) for older than for younger readers, a finding that still differs from the data of Spaniol et al. (2006). Yet, we tested a considerably larger sample than these authors, and older adults of the present study showed significant differences in reading performance as measured by the German sentence reading test. These performance differences within the older age group at the sentence comprehension level are visible at every processing level of reading, including the lexico-semantic one. Lexico-semantic processing in word recognition is well captured by the AROM (Hofmann et al., 2011; Hofmann & Jacobs, 2014) which extends the framework of the MROM by an associative layer simulating long-term associations between words based on their co-occurrence statistics. Due to the strong connection between the orthographic and lexico-semantic layers in the AROM, lower drift rates (*v*) for low performing older adults who already exhibited deficits at the orthographic processing level, might thus just be due to those orthographic deficits. Alternatively or additionally, in low performing older adults, semantic processing itself might be affected. Yet, to what extent the level of activation or the efficiency of activation spreading or inhibition between associated words is affected by age remains an open issue that calls for further research using simulation modeling of individual performances (see above).

3.5. Conclusion

To summarize, our findings based on a very large sample of readers point towards a highly differentiated picture of age-related effects on word recognition and reading. While at the orthographic and lexico-semantic processing levels high-performing older adults outperform younger adults, older adults generally show age-related deficits both at the sublexical and phonological levels. Low-performing older adults are generally slowest in information uptake in all four reading subprocesses. The present results suggest that these age-related disadvantages are rooted in less efficient activation, inhibition and/or temporal sampling processes in older adults. However, concluding this issue requires further studies combining simulation modeling with neurocognitive methods like EEG or fMRI, i.e., both more sophisticated computational models and more constraining data (e.g., Braun et al., 2006; Hofmann & Jacobs, 2014). Although cross-sectional studies are somewhat limited to distinguish between cohort and true aging effects, we still believe that the present findings contribute substantially to research on aging, because this is the first study to systematically investigate age-related effects on all four basic subprocesses of reading within one very large sample. Since these subprocesses do not operate in an isolated manner but are highly intertwined, a major challenge for future research is to investigate the proposed mechanisms underlying changes in subprocesses over the life-span together with age-related effects on the reading network as a whole. Apart from neurocognitive methods and models, such future research should strive to include more natural reading tasks and texts (Willems & Jacobs, 2016) that may give an advantage to older readers compared to the basic speeded decision tasks used in most of the literature mentioned here.

4. Same, Same but Different: Processing Words in the Aging Brain

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4.1. Introduction

In terms of evolution, the human brain was not designed for reading (e.g., Dehaene & Cohen, 2007; Schrott & Jacobs, 2011). Yet, we practice this unique 'neurobiocultural' achievement routinely and effortlessly every day up to very old age. In fact, reading is not only one of the most popular leisure activities of the elderly but enables seniors to remain functionally independent (Meyer & Pollard, 2006). Identifying and consequently promoting those factors that contribute to successful reading performance in (later) life may bear the possibility to generate positive transfer effects to other cognitive domains that are adversely affected by aging (e.g., Demoulin & Kolinsky, 2016). However, in spite of extensive investigations on brain activity patterns associated with fundamental subprocesses underlying skilled reading (e.g., sublexical, orthographic, phonological and lexico-semantic processing) in the younger brain (e.g., Cavalli et al., 2016; Jobard et al., 2003; Liebig et al., 2017; Martin et al., 2015; Price, 2012), very little is known about the effects of healthy aging on the neural circuits associated with these reading-related processes (e.g., Daselaar et al., 2003; Gold et al., 2009). The apparent lack of neuroimaging research is even more astonishing when considering findings from behavioral studies. While reading performance of older adults seems to be preserved in orthographic and lexico-semantic processing, age-related differences have been observed for sublexical and phonological processing (e.g., Thapar et al., 2003; Ratcliff et al., 2004c; Spaniol et al., 2006; Froehlich et al., 2016). The aim of the present study was therefore to systematically investigate age-related effects on neural correlates associated with central subprocesses of reading in healthy younger and older adults.

4.1.1. Aging and reading

Even though global reading processes remain relatively stable over the life span (e.g., De Beni et al., 2007), zooming in on the four central subprocesses of reading that constitute successful visual word recognition (e.g., Ziegler et al., 2008) suggests differently. For instance, at the sublexical level, older adults show longer response times (RT) in letter detection and letter matching tasks as well as pronounced word length effects in lexical decision (Allen et al., 1991; Froehlich & Jacobs, 2016; Guttentag & Madden, 1987). Moreover, information uptake specific to letter discrimination and identification is slower in older adults (Froehlich et al., 2016; Thapar et al., 2003). Similarly, age-related differences seem to prevail at the phonological level. Older adults not only read pseudowords more slowly than younger adults (e.g. Bush et al., 2007; Madden, 1989; Stadtlander, 1995), but they also show reduced speed of information uptake in a phonological decision task (Froehlich et al., 2016). In contrast, the orthographic and lexico-semantic processing stages of reading seem to be relatively unaffected by aging. Frequency effects, which have been taken as an index for the efficiency of lexical access (e.g., Balota et al., 2004; Jacobs & Grainger, 1994), are comparable for younger and older adults (e.g., Cohen-Shikora & Balota, 2016; Froehlich & Jacobs, 2016). Furthermore, younger and older adults show a similar rate of orthographic information uptake in lexical decision tasks (Froehlich et al., 2016; Ratcliff et al., 2004c). Likewise, a number of studies observed no age-related differences in lexico-semantic processing when younger and older participants were asked to perform semantic decisions (e.g., Daselaar et al., 2003; Spaniol et al., 2006) or even identified an advantage for high-performing older adults over younger and low-performing older adults (Froehlich et al., 2016).

Visual word recognition as the most fundamental process of reading not only depends on the successful interplay of sublexical, orthographic, phonological and lexico-semantic processing, but relies additionally on perceptual-attentional processes and well-functioning memory operations (e.g., Hofmann & Jacobs, 2014; Jacobs, 2001; Jacobs & Ziegler, 2015; Just & Carpenter, 1992; Perry et al., 2007, 2010, 2013). Yet, these higher order cognitive processes are all marked by an age-related reduction in neurochemical, neuroanatomical and functional resources (e.g., Lindenberger et al., 2008). It has therefore been hypothesized that it might not be predominantly core language processing that is most likely susceptible to age-related changes but cognitive processes (e.g., Baciu et al., 2016; Cho et al., 2012; Wingfield & Grossman, 2006), including inhibition of irrelevant information, handling simultaneously multiple information, accurately manipulating information within working memory, and monitoring episodic memory operations (Cabeza & Dennis, 2013), which affect reading performance.

4.1.2. The reading brain

The reading brain needs to successfully integrate sublexical, orthographic, phonological, and lexico-semantic information of written words. The neuroanatomical circuits associated with processing these four types of information in single word reading have been systematically linked to functionally separable brain regions (e.g., Price, 2012; Welcome & Joanisse, 2012). While sublexical and orthographic processes are mainly associated with activation in left inferior and middle occipital gyri (IOG and MOG, respectively) and a left ventral occipito-temporal circuit (vOT), phonological and lexico-semantic processes appear to additionally recruit left inferior parietal, lateral temporal and bilateral frontal systems (e.g., Braun et al., 2015; Cavalli et al., 2016; Glezer et al., 2016; Jobard et al., 2003; McNorgan et al., 2015; Price, 2012; Schurz et al., 2014; Welcome & Joanisse, 2012).

More specifically, within the left vOT circuit, processing written stimuli reliably activates the fusiform gyrus (FG) and the inferior temporal gyrus (ITG), including the so-called visual word form area (VWFA; Dehaene et al., 2002) whose specific function in word recognition is still subject to current debate (e.g., Price & Devlin, 2003, 2011; Cohen & Dehaene, 2004; Kronbichler et al., 2007; Schurz et al., 2014). Left inferior parietal regions linked to phonological and lexico-semantic processing comprise the supramarginal and angular gyrus (SMG, ANG), left lateral temporal regions include the superior temporal and the middle temporal gyri (STG, MTG). Bilateral regions consistently implicated in the frontal circuit are the inferior frontal gyrus (IFG) including opercular and triangular parts as well as the precentral and the middle frontal gyrus (PRG, MFG; e.g., Binder et al., 2009; Jobard et al., 2003; Joubert et al., 2004; Martin et al., 2015; McNorgan et al., 2015; Newman & Joanisse, 2011; Richlan et al., 2009). More recently, Martin et al. (2015) found that the right cerebellum as well as the bilateral supplementary motor area (SMA) were consistently activated in the reading system of young adult readers.

Yet, very little is known about the neural correlates associated with the four subprocesses of reading in older adults. At the orthographic level, older adults compared to younger have been observed to underactivate the MOG and lingual gyrus bilaterally while an age-related overactivation was reported for left ventral temporal regions as well as the IFG (Gold et al., 2009). Based on these results, it had been speculated whether older adults may tend to depend more on higher linguistic processes than on orthographic processes during lexical decision. At the lexico-semantic level, findings from semantic decision tasks indicated age-related differences either in the left MTG (Daselaar et al., 2003) or left and right prefrontal cortex (PFC; Daselaar et al., 2003; Dennis et al., 2007; Lustig et al., 2003). However, as activity in left visual cortex, MTG, PFC, as well as in MFG extending into the anterior cingulate was largely overlapping for younger and older adults, Daselaar et al. (2003)

proposed semantic retrieval to be still intact in older adults. Dennis et al. (2007) attribute the differences in prefrontal activity to age-related attentional deficits.

To our knowledge, there are no functional magnetic resonance imaging (fMRI) studies investigating age-related differences in sublexical and phonological processing, even though older compared to younger adults have been found to be consistently slower in the speed of information uptake precisely within these two processes (*cf.* Froehlich et al., 2016). Yet, identifying neural correlates associated with the subprocesses of reading that show age-related differences as well as those, that are maintained in younger and older adults may further foster our understanding of preserved and declining neurocognitive performance in healthy aging readers and possibly in other cognitive domains. Moreover, it remains an open question, whether age affects sublexical, orthographic, phonological and lexico-semantic processing in a unitary, holistic way or whether different mechanisms may apply to the different subprocesses of reading.

4.1.3. The present study

The aim of the present study was to assess whether age-related differences in sublexical, orthographic, phonological and lexico-semantic processing observed at the behavioral level are in fact associated with age-related differences in brain activation patterns primarily contributing to single word reading in younger and older adults.

Reading performance of younger and older adults was assessed using letter identification (sublexical processing), lexical decision (orthographic processing), phonological decision (phonological processing) and semantic decision tasks (lexico-semantic processing). Importantly, we deliberately chose tasks that require single word recognition to assess reading-related processes given its central significance for fluent reading (e.g., Grainger & Jacobs, 1996; Jacobs & Ziegler, 2015). Additionally, participants were asked to silently read the linguistic stimuli to prevent the most commonly encountered age-related phonological retrieval deficit, i.e. the tip-of-the-tongue (TOT) state, in which a person is temporally unable to produce a word even though it is well known (e.g., Shafto et al., 2007; Burke & Shafto, 2008).

As reading performance in general is rather well maintained over the lifespan, we expected older and younger adults to recruit a similar set of brain regions during sublexical, orthographic, phonological and lexico-semantic processing (*cf.* section *4.1.2. The reading brain*). If the subprocesses of reading were indeed stable over the lifespan, then no age-related differences should be observed in terms of accuracy rates as well as within the core regions of the neural reading network. Rather, age-related differences should occur in brain regions consistently associated with cognitive functions supporting reading, such as, for instance working or episodic memory and executive functions. If the subprocesses of reading are affected by age, then we would expect age-related differences within core reading regions. However, as cognitive aging is marked by a decline in executive functions and memory operations, we would still assume to find age-related differences in regions associated with these processes.

4.2. Experimental Procedures

4.2.1. Participants

Fifty-eight older (*M* = 70.4 years, *SD* = 3.40, range = 63 – 79, 27 female) and 25 younger (*M* = 25.0 years, *SD* = 3.67, range = 21 – 35, 18 female) right-handed adults participated in this study. Older participants were recruited from the Max Planck Institute of Human Development Berlin, younger participants from the Freie Universität Berlin. Due to technical problems and/or excessive in-scanner movements (> 5mm/°) two younger and four older participants had to be excluded from further analyses. Furthermore, to ensure, that we recorded functional imaging data associated with the specific subprocesses and to keep the design balanced, we only included participants with a response rate of at least 75% per block. This led to the exclusion of three younger and eleven older participants. Additionally, five further older adults had to be excluded as they responded incorrectly to more than 40% of the trials in at least one of the blocks. The remaining 38 older (*M* = 70.2 years, *SD* = 3.15, range 65 – 76, 16 female) and 20 younger adults (*M* = 25.0 years, *SD* = 3.46, range 22 – 35, 13 female) were all German native speakers, did not differ in terms of years of formal education ($M_{\text{old}} = 14.7$; $M_{\text{young}} = 15.2$; $t(56) = .55$, $p = .58$), and reported all normal or corrected to normal vision. Older adults were additionally screened for cognitive deficits using the Mini-Mental State Exam (*M* = 28.2, *SD* = 1.42, range 25 – 30; Folstein et al., 1983). None of the participants had a history of reading difficulties or language impairment, neurological disease, psychiatric disorders or a history of head injuries. All participants gave written informed consent and received financial compensation for their participation. The study was approved by the ethics committee of the Department of Education and Psychology at the Freie Universität Berlin.

4.2.2. Tasks and procedure

Participants were tested individually at the Center for Cognitive Neuroscience Berlin (CCNB) within one test session lasting for approximately one hour. The task design implemented four tasks related to the specific subprocesses of reading: letter identification (sublexical processing), lexical decision (orthographic processing), phonological decision (phonological processing), semantic decision (lexico-semantic processing). A basic pattern recognition task served as explicit baseline task.

More specifically, a letter identification task was employed (*cf.* Ziegler et al., 2008), in which participants were asked to indicate whether a string of consonants contained an ‘r’ (target; e.g., dsmrl) or not (non-target; e.g., mpfst) to assess sublexical processing. Both, targets and non-targets were matched with respect to the number of letters with ascenders and descenders.

In the lexical decision task with which orthographic processing was assessed German nouns (target; e.g., Park) and pseudohomophones (non-target; e.g., Sant) were presented. Pseudohomophones were created by changing one letter of a German noun. Younger and older adults had to decide whether the presented stimulus was a correctly spelled word or not. To keep the typical appearance of German nouns the initial letters of the items were capitalized.

Phonological processing was investigated with a phonological decision task. Pseudohomophones (target; e.g., Sant) or pseudowords (non-target, e.g., Buhn) were presented. Pseudowords were generated analogous to pseudohomophones, i.e., we replaced one letter of an existing German noun to keep the items as orthographically similar to real words as possible and presented the stimuli with capitalized initial letters. Participants were asked to decide whether the item sounded like a word or not.

For assessing lexico-semantic processing we asked for an animacy judgment in a semantic decision task. Younger and older adults were shown items relating to a living (target; e.g., Koala) or a non-living (non-target; e.g., Plan) object and had to indicate with a yes-response if the stimulus referred to a living object and with a no-response when not. German nouns served as targets and non-targets.

The baseline task consisted of five tilted slashes that were equally oriented (target; e.g., /////) or not (non-target; e.g., //\//). Participants were asked to give a yes-response in case a target was presented and a no-response in case of a non-target. This task was used to assess non-linguistic visual pattern recognition as well as to capture basic decision processes related to yes/no-responses.

Functional data was acquired using a blocked design. Ten targets and 10 non-targets of the same task condition were presented during each block. At the beginning of each block a cue-screen informed the participants about the upcoming task. This was followed by the jittered presentation of a fixation cross with a mean duration of 6 s (range 3 to 9 s). The subsequently shown experimental trials consisted of a fixation cross (1 s) and the stimulus (2 s). At the end of each block, a fixation cross was presented for 15 s resulting in an average block length of 85 s. Five blocks, i.e. one for each task condition, constituted a run which lasted approximately 7 min. Participants performed 4 runs, resulting in a total of 400 trials. The order of trials, blocks as well as runs were pseudo-randomized across participants. Stimuli were presented singly in black on a grey background at the center of a screen on dual display goggles (VisuaStim, MR Research, USA) using Python 2.7 (Python Software Foundation, https://www.python.org/). Each participant was instructed to lie still, and to give their yes/no-responses as quickly and as accurately as possible via button press with their right index and middle finger, respectively. Prior to scanning, younger and older adults received training outside the scanner.

4.2.3. Stimuli

The stimulus set consisted of 80 items (40 targets/40 non-targets) per task. To ensure comparability of results and to control for confounding linguistic variables these items were carefully matched within and across tasks with respect to item length ($M_{\text{target}} = 4.49/M_{\text{non-target}} = 4.47$ letters per item), orthographic neighbourhood density ($M_{\text{target}} = 22.7/M_{\text{non-target}} = 21.1$), normalized lemma frequency of the (base) word ($M_{\text{target}} = 1.32/M_{\text{non-target}} = 1.32$), and bigram frequency ($M_{\text{target}} = 4.40/M_{\text{non-target}} = 4.39$; all F's < 1.83, all p's > .2) across the lexical, phonological and semantic decision task. As vowel-consonant combinations were excluded by design bigram frequencies of the letter identification task were lower ($M_{\text{target}} = 3.89/M_{\text{non-target}} = 3.81$) than in the other three tasks ($F(3, 316) = 33.4$, $p < .001$). Matching was based on the dlex database (dlexDB; Heister et al., 2011) norms for German words.

4.2.4. MRI data acquisition

Functional and structural imaging was performed with a 3.0 T Siemens Magnetom TimTrio MRI scanner (Siemens, Erlangen, Germany) using a 12-channel head coil. During the four runs, a total of 932 volumes were recorded applying a T2*-weighted, gradient echo planar imaging (EPI) pulse sequence (TE = 30ms, TR = 2000ms, FA = 70°, number of slices = 37, in-plane resolution = 3 x 3 x 3mm^3, 64 x 64 data acquisition matrix, FoV = 192 x 192mm^2). After recording the functional images, a high-resolution 3D T1-weighted anatomical scan was additionally acquired for each participant (176 sagittal sections, 1 x 1 x 1mm^3, 256 x 256 data acquisition matrix). To reduce head movements foam padding was placed around the participants' heads. During functional scanning images were visually checked for severe motion.

4.2.5. Data analysis

Mean response times and accuracy were analyzed using R version 3.3.0 (R Core Team, 2015). We chose a mixed-effects modelling approach (Baayen et al., 2008) as implemented in the lme4-package (Bates et al., 2014) with crossed random factors for subjects and items. Prior to analyzing RTs by means of linear mixed-effects regressions, including main effects and interactions for task and age as fixed factors, outliers deviating more than 3.5 SDs from the individual's mean within each task x stimulus type experimental cell were removed. Accuracy data were analyzed using logistic mixed-effects regressions, type III Wald chi-square tests to test for significant fixed effects (car-package; Fox & Weisberg, 2011). We implemented intercepts for subjects and items, and random slopes for age within items and random slopes for task within subjects into the random factor structure (Barr, 2013; Barr et al., 2013).

SPM12 software (revision 6685; Statistical Parametric Mapping, Wellcome Department of Imaging Neuroscience, University College London, UK, 2014) running in a Matlab 2016a (Mathworks Inc., Natick, MA, USA) environment was used for preprocessing and statistically analyzing MRI data. Preprocessing of functional images included slice time correction, realignment to the mean image, co-registration to the individual T1-weighted anatomical scans and spatial normalization of structural and functional images to MNI space. Spatial normalization was achieved by first segmenting the co-registered anatomical images into grey matter, white matter, CSF, bone, non-brain soft tissue and air/background (Ashburner & Friston, 2005). We then created a study-specific template by means of the DARTEL algorithm (Ashburner, 2007) and subsequently estimated the transformation from this template to MNI space. Data were spatially smoothed with an 8mm FWHM Gaussian kernel.

Statistical analysis of fMRI data was performed in two steps. At the first level, we constructed a GLM by modelling block onsets of each task, i.e. of the baseline task, phonological decision, semantic decision, orthographic decision and letter identification, with a canonical hemodynamic response function and included the six realignment parameters as regressors of no interest in the model space. Functional imaging data were high-pass filtered with a cut-off of 128 seconds and an AR(1) model corrected for autocorrelation (Friston et al., 2002). For each of the four reading tasks (i.e., letter identification, lexical, phonological and semantic decision) and the baseline task subject-specific contrast images were calculated. The resulting individual contrast images were subsequently entered into a second level group by task flexible factorial design analysis with subject serving as a random effect. We were interested in (a) activation associated with the different subprocesses of reading in younger adults (YA; four different contrasts, i.e., one for each reading task: reading task_{YA} > baseline task_{YA}), (b) activation associated with the different subprocesses of reading in older adults (OA; four different contrasts, i.e., one for each reading task: reading task_{OA} > baseline task_{OA}), (c) reading-related activation common to both groups (four different conjunction analyses, i.e., one for each reading task, with a fixed-effect for brain activation common to both age groups: [reading task_{YA} > baseline task_{YA}] & [reading task_{OA} > baseline task_{OA}] with statistical parametric maps of the minimum T-statistic based on rejection of the conjunction null) and (d) age-related differences with respect to these neural activation patterns (eight different contrasts, i.e., two for each reading task: [reading task_{OA} > baseline task_{OA}] > [reading task_{YA} > baseline task_{YA}] and vice versa). For the latter purpose, we conducted a group by task analysis of variance (ANOVA) using an F-contrast followed by calculating post-hoc t-contrasts between groups for each task. With the exception of the ANOVA, results are reported at a cluster-wise FWE-corrected threshold of $p < .05$ to correct for multiple comparisons (voxel-level uncorrected at $p < .001$). A more conservative threshold was considered for the F-contrast (voxel-wise FWE-corrected threshold of $p < .001$) to ensure the validity of performing the post-hoc tests. Significant activations are reported in MNI coordinates and were anatomically labelled using the AAL (Tzourio-Mazoyer et al., 2002) and AAL2 (Rolls et al., 2015) toolboxes as implemented in SPM12 using both the local maxima approach as well as the extended local maxima approach with a 6mm sphere to determine whether local maxima extended into other anatomical brain regions. For further examination of cluster extent, the MARSBAR toolbox was used (Brett et al., 2002).

4.3. Results

4.3.1. RT and accuracy data

The 5 x 2 (task: baseline task vs. letter identification vs. lexical decision vs. phonological decision vs. semantic decision x age: younger vs. older adults) linear mixed-effect model yielded a main effect of task, $\chi^2(4) = 724.8$, $p < .001$, as well as age, $\chi^2(1) = 30.8$, $p < .001$, and a significant interaction of both factors, $\chi^2(4) = 22.4$, $p < .001$. As expected, younger adults responded faster than older adults across all five tasks, $b = -55.1$, $SE = 9.93$, $t = -5.55$ as well as within all five tasks (all χ^2's > 5.73, all p's < .05). The 5 x 2 logistic mixed-effects analysis of accuracy data revealed significant effects of task, $\chi^2(4) = 106.3$, $p < .001$, and task by age, $\chi^2(4) = 10.8$, $p < .01$, yet, more importantly, no overall performance differences between the age groups, $\chi^2(1) = 1.47$, $p = .23$. Consequently, older adults responded as accurately as younger adults in the baseline task, sublexical, orthographic, and phonological processing and even outperformed younger adults in lexico-semantic processing, $\chi^2(1) = 3.95$, $p < .05$ (for detailed analyses and results see Appendix Table C.1 and C.2; for mean response times and accuracy rates see Table 4.1). Judging by the comparable accuracy performance of younger and older adults we assumed both groups of participants to be equally capable to comply to task demands.

4.3.2. Neuroimaging data

As the main focus of our study was to investigate commonalities and differences of neural correlates corresponding to sublexical, orthographic, phonological and lexico-semantic processing in younger and older adults, we will focus on these two aspects only. Detailed results regarding activation patterns associated with the four subprocesses of reading within the two age groups are presented in the Appendix (Table C.3 and C.4 for younger and older adults, respectively).

Table 4.1

Mean response times and accuracy rates (%) for all five in-scanner tasks and standard deviations (SD) as a function of age

	Younger Adults	Older Adults
RT (*SD*)		
Baseline task[a]	619 (147)	714 (154)
Letter identification[b]	753 (188)	921 (217)
Lexical decision[c]	896 (257)	977 (264)
Phonological decision[d]	1,110 (288)	1,249 (301)
Semantic decision[e]	870 (245)	929 (219)
Accuracy Rates (*SD*)		
Baseline task	97.9 (14.2)	99.0 (9.89)
Letter identification	97.0 (17.1)	95.8 (20.1)
Lexical decision	94.4 (23.1)	95.4 (21.0)
Phonological decision	88.9 (31.4)	88.6 (31.8)
Semantic decision[1]	94.3 (23.2)	96.6 (18.3)

Note. SD = standard deviation. There were significant effects of age: $^{a}\chi^2_{baseline\ task}(1) = 23.7, p < .001$; $^{b}\chi^2_{letter\ identification}(1) = 41.2, p < .001$; $^{c}\chi^2_{lexical\ decision}(1) = 8.81, p < .01$; $^{d}\chi^2_{phonological\ decision}(1) = 22.8, p < .001$; $^{e}\chi^2_{semantic\ decision}(1) = 5.73, p < .05$; $^{f}\chi^2_{semantic\ decision}(1) = 3.95, p < .05$

4.3.2.1. Conjunction analyses in younger and older adults per reading task. To assess brain regions commonly activated by both age groups during sublexical ([letter identification$_{YA}$ > baseline task$_{YA}$] & [letter identification$_{OA}$ > baseline task$_{OA}$]), orthographic ([lexical decision$_{YA}$ > baseline task$_{YA}$] & [lexical decision$_{OA}$ > baseline task$_{OA}$]), phonological ([phonological decision$_{YA}$ > baseline task$_{YA}$] & [phonological decision$_{OA}$ > baseline task$_{OA}$]) and lexico-semantic processing ([semantic decision$_{YA}$ > baseline task$_{YA}$] & [semantic decision$_{OA}$ > baseline task$_{OA}$]), four separate conjunction analyses were performed (Figure 4.1; for respective peak voxels and cluster extent see Table 4.2). With the exception of the left superior parietal gyrus (SPG) in letter identification active regions were identical to those observed for younger adults in all four reading-related tasks.

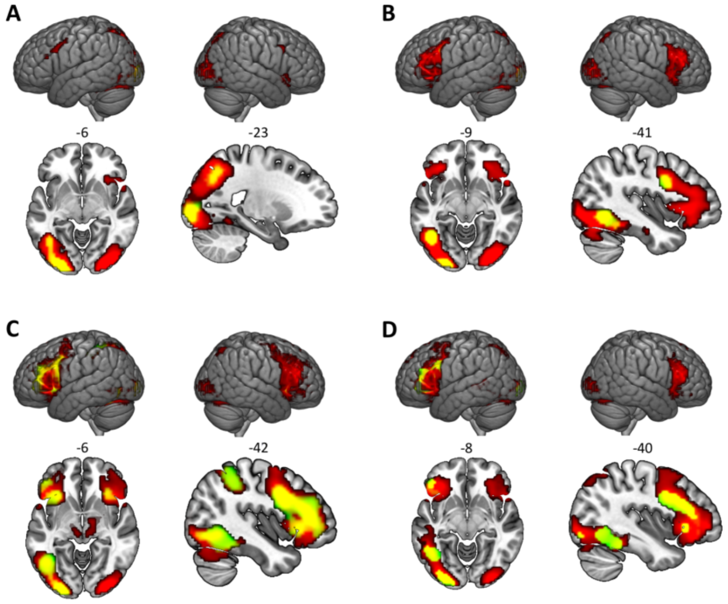

Figure 4.1. Active regions of younger (green) and older (red) adults (overlap in yellow) during letter identification (panel A; $k_{\text{younger/older adults}} = 95/135$), lexical decision (B; $k = 95/104$), phonological decision (C; $k = 135/278$) and semantic decision (D; $k = 146/222$). Whole-brain analyses for the contrasts reading $\text{task}_{\text{younger/older adults}} > \text{baseline task}_{\text{younger/older adults}}$ (cluster-wise FWE-corrected at $p < .05$, voxel-level uncorrected at $p < .001$).

More precisely, both, younger and older adults showed expected activation of the ventral temporal and prefrontal left-hemispheric regions typically associated with these subprocesses in the younger brain. These regions included the IOG extending into the FG and ITG (sublexical processing), the ITG (orthographic processing), the IOG, MOG, ITG, SMA, PRG, IFG (triangular part and opercular part; phonological processing) as well as the IOG, FG, ITG, PRG, IFG (triangular and opercular part; lexico-semantic processing). Additionally, we observed left-hemispheric engagement of the inferior parietal gyrus (IPG) extending into the left ANG and SMG (x =-60 to -21; y = -75 to -30; z = 27 to 63) in phonological decision, yet no significant activation of left lateral temporal regions, such as the STG and MTG in neither phonological nor semantic decision. During letter identification and phonological decision, younger and older adults recruited the left superior parietal gyrus (SPG). Moreover, a significant increase in BOLD signal was observed for the bilateral insula, and the right midcingulate cortex during phonological decision.

Table 4.2

Brain regions showing significant BOLD signal increases within the conjunction analyses (younger and older adults) of the four reading-related tasks

Brain region	BA	Hemisphere	MNI coordinates			T	P_{FWE}	k
			x	y	z			
Letter identification								
Inferior occipital gyrus	17	LH	-24	-96	-6	7.90	.000	338
Inferior occipital gyrus	37	LH	-39	-63	-9	4.31		LM
Inferior occipital gyrus	19	LH	-39	-75	-9	4.04		LM
Lexical decision								
Inferior temporal gyrus	37	LH	-45	-57	-9	5.07	.038	88
Phonological decision								
Inferior frontal gyrus, opercular part	9	LH	-48	9	27	9.16	.000	1,229
Precentral	-	LH	-45	6	30	8.98		LM
Inferior frontal gyrus, triangular part	46	LH	-42	30	15	8.97		LM
Insula	47	LH	-33	24	0	8.93		LM
Inferior occipital gyrus	18	LH	-24	-99	-6	8.58	.000	412
Inferior temporal gyrus	37	LH	-45	-57	-9	8.43		LM
Supplementary motor area	8	LH	-6	18	48	6.51	.002	169
Midcingulate gyrus	9	RH	12	27	33	4.09		LM
Insula	47	RH	33	24	0	6.50	.003	158
Inferior parietal gyrus	40	LH	-45	-42	48	5.7	.000	450
Middle occipital gyrus	19	LH	-24	-69	36	5.58		LM
Superior parietal gyrus	7	LH	-27	-63	45	5.16		LM
Inferior parietal gyrus	40	LH	-54	-36	42	4.96		LM
Semantic decision								
Inferior occipital gyrus	18	LH	-24	-99	-6	6.83	.013	117
Inferior frontal gyrus, triangular part	46	LH	-42	27	18	5,64	.000	567
Inferior frontal gyrus, triangular part	-	LH	-45	30	15	5,59		LM
Precentral	9	LH	-48	12	30	5,38		LM
Inferior frontal gyrus, opercular part	9	LH	-36	12	27	5,26		LM

Table 4.2 (continued)

Brain region	BA	Hemi-sphere	MNI coordinates x	y	z	T	P_{FWE}	k
Semantic decision (continued)								
Inferior frontal gyrus, triangular part	47	LH	-48	39	-3	4,28		LM
Inferior frontal gyrus, triangular part	47	LH	-36	24	-3	4,09		LM
Inferior temporal gyrus	37	LH	-45	-54	-12	5.40	.004	153
Fusiform gyrus	-	LH	-36	-45	-21	4.86		LM

Note. Peaks were identified using MNI coordinates and anatomically labelled with the aal and aal2 toolboxes (Tzourio-Mazoyer et al., 2002; Rolls et al., 2015). Brodmann areas (BA) were identified using NeuroElf version 1.1 (http://neuroelf.net). At the whole-brain level, a significance statistical threshold of $p < .05$ cluster-wise FWE-corrected for multiple comparisons has been used (voxel-level uncorrected at $p < .001$) with minimum clusters of 105 (letter identification), 88 (lexical decision), 158 (phonological decision) and 117 (semantic decision). k = cluster size (number of voxels), LH = left hemisphere, RH = right hemisphere, LM = local maxima.

4.3.2.2. Age-related differences in the reading brain. The 2 x 4 ANOVA showed differences in BOLD signal between both age groups and tasks widely distributed across the brain (see Appendix, Table C.5). However, as the F-contrast does not provide any information about directed differences, we analyzed post-hoc t-contrasts between age groups for each task separately. Contrasting the activation associated with the particular subprocesses of reading of older adults against that of younger adults revealed that age-related differences in reading-related activation (*cf.* section 4.1.2. *The reading brain*) were predominantly found for orthographic and phonological processing. Differences in activation outside reading circuits were mainly confined to midline regions. The four opposite contrasts ([reading task$_{\text{YA}}$ > baseline task$_{\text{YA}}$] > [reading task$_{\text{OA}}$ > baseline task$_{\text{OA}}$]) did not yield any significant results (see Figure 4.2, Table 4.3).

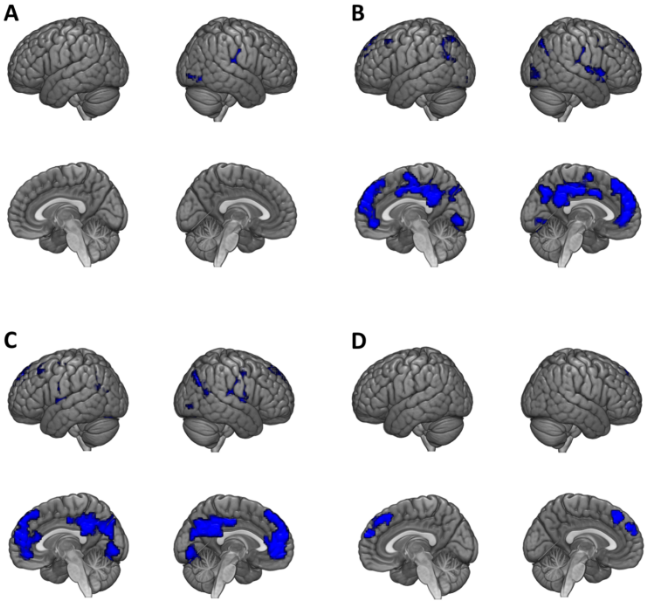

Figure 4.2. Activation maps of between-group comparisons during letter identification (panel A; k = 89), lexical decision (B; k = 114), phonological decision (C; k = 81) and semantic decision (D; k = 355). Whole-brain analyses for the contrasts [reading $\text{task}_{\text{older adults}}$ > baseline $\text{task}_{\text{older adults}}$] > [reading $\text{task}_{\text{younger adults}}$ > baseline $\text{task}_{\text{younger adults}}$] (cluster-wise FWE-corrected at $p < .05$, voxel-level uncorrected at $p < .001$).

Within (right-hemispheric homologous) reading-related regions we observed greater increase in BOLD signal for older adults in the right SMG and SMA (letter $\text{identification}_{\text{OA}}$ > baseline task_{OA}] > [letter $\text{identification}_{\text{YA}}$ > baseline task_{YA}]), the right IOG, FG, the left SMG, ANG extending into the MTG as well as SMA ([lexical $\text{decision}_{\text{OA}}$ > baseline task_{OA}] > [lexical $\text{decision}_{\text{YA}}$ > baseline task_{YA}]), the bilateral cerebellum, right MOG, left FG and ITG, the bilateral ANG, STG, MTG, PRG, right SMA and left MFG ([phonological $\text{decision}_{\text{OA}}$ > baseline task_{OA}] > [phonological $\text{decision}_{\text{YA}}$ > baseline task_{YA}]) as well as in the left SMA, bilateral MFG and right IFG ([semantic $\text{decision}_{\text{OA}}$ > baseline task_{OA}] > [semantic $\text{decision}_{\text{YA}}$ > baseline task_{YA}]). Outside these regions, older adults compared to younger adults engaged predominantly midline regions, such as the postcentral gyrus (bilaterally: phonological decision; right: letter identification), the bilateral midcingulate (letter identification, lexical decision, phonological decision) and anterior cingulate (phonological decision) cortex as well as its left posterior parts (lexical decision), the bilateral precuneus (lexical decision, phonological decision) as well as the SFG and its medial parts (lexical decision, phonological decision, semantic decision).

Table 4.3

Brain regions showing significant BOLD signal increases in older adults compared to younger adults during the four reading-related tasks (contrasts: [reading task$_{older\ adults}$ > baseline task$_{older\ adults}$] > [reading task$_{younger\ adults}$ > baseline task$_{younger\ adults}$])

Brain region	BA	Hemi-sphere	MNI coordinates			T	P_{FWE}	k
			x	y	z			
Letter identification								
Supramarginal gyrus	2	RH	57	-18	24	4.61	.030	94
Postcentral gyrus	6	RH	63	-12	33	3.86		LM
Midcingulate gyrus	24	RH	12	12	33	3.94	.047	82
Supplementary motor area	32	RH	9	12	45	3.93		LM
Midcingulate gyrus	32	RH	3	9	39	3.72		LM
Midcingulate gyrus	32	LH	-3	9	39	3.56		LM
Midcingulate gyrus	-	LH	-9	12	42	3.35		LM
Lexical decision								
Superior frontal gyrus	9	LH	-12	54	36	5.04	.000	830
Superior frontal gyrus, medial segment	10	LH	0	63	21	4.72		LM
Superior frontal gyrus, medial segment	10	LH	-3	60	24	4.61		LM
Superior frontal gyrus, medial segment	8	RH	9	51	39	4.5		LM
Superior frontal gyrus, medial segment	-	RH	6	51	45	4.48		LM
Superior frontal gyrus, medial segment	6	LH	-9	33	51	4.39		LM
Superior frontal gyrus	9	RH	18	51	33	4.09		LM
Superior frontal gyrus, medial segment	10	LH	-6	51	3	3.72		LM
Superior frontal gyrus	8	RH	21	30	39	3.67		LM
Superior frontal gyrus	9	LH	-24	36	33	3.65		LM
Superior frontal gyrus, medial orbital	10	RH	3	48	-6	3.53		LM
Superior frontal gyrus, medial orbital	-	RH	9	42	-9	3.5		LM
Superior frontal gyrus	8	RH	21	39	39	3.3		LM
Midcingulate gyrus	31	LH	-9	-48	36	4.65	.000	846
Midcingulate gyrus	24	RH	3	-15	42	4.44		LM

Table 4.3 (continued)

			MNI coordinates					
Brain region	BA	Hemisphere	x	y	z	T	P_{FWE}	k
Lexical decision (continued)								
Midcingulate gyrus		LH	-3	-18	42	4.42		LM
Midcingulate gyrus	31	LH	-3	-27	45	4.39		LM
Midcingulate gyrus	31	RH	9	-39	33	4.38		LM
Posterior cingulate gyrus	23	LH	0	-39	24	4.17		LM
Midcingulate gyrus	32	LH	-3	6	39	4.02		LM
Precuneus	31	RH	12	-54	36	3.92		LM
Precuneus	7	LH	-3	-69	42	3.86		LM
Supplementary motor area	6	LH	0	-6	63	3.58		LM
Midcingulate gyrus	-	LH	-15	-39	45	3.24		LM
Inferior parietal gyrus	40	LH	-51	-57	39	4.07	.001	208
Angular gyrus	39	LH	-42	-66	27	3.94		LM
Angular gyrus	7	LH	-42	-69	51	3.71		LM
Inferior parietal gyrus	-	LH	-30	-78	48	3.49		LM
Supramarginal gyrus	39	LH	-57	-57	27	3.47		LM
Lingual gyrus	18	RH	6	-81	-3	3.93	.025	99
Inferior occipital gyrus	18	RH	39	-87	-6	3.61		LM
Fusiform gyrus	19	RH	30	-78	-9	3.53		LM
Inferior occipital gyrus	-	RH	45	-84	-6	3.52		LM
Lingual gyrus	-	RH	18	-78	-12	3.34		LM
Phonological decision								
Superior frontal gyrus	8	LH	-15	51	36	6,22	.000	1,698
Superior frontal gyrus, medial segment	10	LH	-3	60	21	5,85		LM
Anterior cingulate gyrus	9	LH	-3	48	15	5,68		LM
Superior frontal gyrus	9	LH	-18	51	27	5,51		LM
Superior frontal gyrus, medial segment	8	RH	9	51	39	5,42		LM
Superior frontal gyrus, medial segment	-	RH	12	48	36	5,33		LM
Superior frontal gyrus	10	RH	15	60	21	5,07		LM
Superior frontal gyrus, medial segment	8	LH	-6	39	51	4,65		LM
Superior frontal gyrus, medial orbital	10	LH	-3	48	-6	4,38		LM
Superior frontal gyrus	8	RH	24	36	45	4,37		LM
Anterior cingulate gyrus	32	LH	-6	39	3	4,29		LM
Superior frontal gyrus, medial segment	8	RH	9	36	51	4,23		LM
Anterior cingulate gyrus	24	RH	6	30	15	4,01		LM
Superior frontal gyrus	8	LH	-15	33	39	3,98		LM
Anterior cingulate gyrus	-	LH	0	33	12	3,85		LM

Table 4.3 (continued)

Brain region	BA	Hemi-sphere	MNI coordinates			T	P_{FWE}	k
			x	y	z			
Phonological decision (continued)								
Supplementary motor area	6	RH	15	24	57	3,74		LM
Midcingulate gyrus	31	RH	9	-39	33	5,5	.000	1,080
Precuneus	31	LH	-9	-54	30	5,24		LM
Precuneus	31	LH	-3	-45	39	5,1		LM
Midcingulate gyrus	31	LH	0	-18	42	4,42		LM
Cuneus	31	LH	-6	-69	27	4,34		LM
Midcingulate gyrus	31	LH	-3	-27	42	4,32		LM
Precuneus	31	RH	9	-66	27	3,92		LM
Cuneus	19	RH	9	-81	42	3,68		LM
Paracentral lobule	7	RH	12	-39	51	3,45		LM
Cuneus	18	LH	0	-81	15	3,41		LM
Postcentral gyrus	4	RH	57	-12	30	5,02	.000	593
Postcentral gyrus	4	RH	57	-6	21	4,91		LM
Superior temporal gyrus	42	RH	63	-24	12	4,7		LM
Precentral	6	RH	39	-9	45	4,44		LM
Superior temporal gyrus	13	RH	51	-33	21	4,03		LM
Postcentral gyrus	3	RH	42	-21	36	3,85		LM
Angular gyrus	39	LH	-42	-63	24	4,83	.000	232
Angular gyrus	39	LH	-51	-60	36	3,66		LM
Angular gyrus	39	LH	-57	-60	24	3,57		LM
Lingual gyrus	18	RH	9	-81	-3	4,71	.000	355
Cerebellum	-	RH	15	-75	-15	4,55		LM
Fusiform gyrus	-	LH	-21	-81	-18	3,86		LM
Cerebellum	-	LH	-12	-72	-15	3,65		LM
Lingual gyrus	18	LH	-15	-78	-3	3,49		LM
Lingual gyrus	-	RH	24	-84	-6	3,16		LM
Angular gyrus	39	RH	42	-69	33	4,63	.001	201
Middle occipital gyrus	48	RH	48	-66	27	4,45		LM
Angular gyrus	39	RH	51	-60	24	4,27		LM
Middle temporal gyrus	39	RH	57	-54	12	3,9		LM
Precentral gyrus	6	LH	-51	-6	30	4,43	.000	262
Postcentral gyrus	4	LH	-39	-18	42	4,29		LM
Postcentral gyrus	-	LH	-42	-15	45	4,21		LM
Superior temporal gyrus	6	LH	-54	-6	6	4,13		LM
Middle frontal gyrus	9	LH	-39	15	42	4,26	.020	106
Middle frontal gyrus	8	LH	-33	27	48	3,84		LM
Middle frontal gyrus	6	LH	-33	21	57	3,71		LM
Middle frontal gyrus	-	LH	-24	21	30	3,23		LM
Middle frontal gyrus	9	LH	-30	21	39	3,22		LM
Middle temporal gyrus	20	LH	-54	-33	-12	3,97	.009	127
Middle temporal gyrus	22	LH	-60	-27	0	3,95		LM
Middle temporal gyrus	21	LH	-60	-3	-24	3,79		LM

Table 4.3 (continued)

Brain region	BA	Hemi-sphere	MNI coordinates x	y	z	T	P_{FWE}	k
Phonological decision (continued)								
Middle temporal gyrus	20	LH	-48	-3	-30	3,69		LM
Inferior temporal gyrus	20	LH	-42	-15	-24	3,56		LM
Middle temporal gyrus	20	LH	-63	-18	-18	3,46		LM
Middle temporal gyrus	-	LH	-57	-12	-24	3,46		LM
Middle temporal gyrus	-	LH	-60	-15	-21	3,44		LM
Middle temporal gyrus	21	LH	-60	-24	-12	3,33		LM
Superior temporal gyrus	22	LH	-66	-21	3	3,26		LM
Inferior temporal gyrus	-	LH	-48	-21	-18	3,25		LM
Semantic decision								
Superior frontal gyrus, medial segment	8	RH	9	48	39	4,48	.000	414
Superior frontal gyrus, medial segment	8	LH	-6	36	48	4,35		LM
Superior frontal gyrus, medial segment	8	RH	6	36	48	4,06		LM
Superior frontal gyrus, medial segment	9	LH	-6	51	33	4,03		LM
Superior frontal gyrus, medial segment	8	LH	-9	33	36	4,02		LM
Supplementary motor area	6	LH	-6	12	60	3,98		LM
Superior frontal gyrus, medial segment	9	RH	6	57	27	3,9		LM
Superior frontal gyrus, medial segment	-	LH	0	60	24	3,84		LM
Superior frontal gyrus	8	RH	18	39	39	3,74		LM
Middle frontal gyrus	10	LH	-24	48	27	3,38		LM
Superior frontal gyrus	8	LH	-21	48	39	3,36		LM
Middle frontal gyrus	6	RH	33	6	45	4,16	.038	88
Inferior frontal gyrus, opercular part	9	RH	30	6	36	3,88		LM
Middle frontal gyrus	8	RH	36	15	42	3,61		LM
Middle frontal gyrus	-	RH	39	18	45	3,58		LM

Note. Peaks were identified using MNI coordinates. Brodmann areas (BA) were identified using NeuroElf version 1.1 (http://neuroelf.net). At the whole-brain level, a significance statistical threshold of $p < .05$ cluster-wise FWE-corrected for multiple comparisons has been used (voxel-level uncorrected at $p < .001$) with minimum clusters of 82 (letter identification), 99 (lexical decision), 106 (phonological decision) and 88 (semantic decision). k = cluster size (number of voxels), RH = right hemisphere, LH = left hemisphere, LM = local maxima.

4.4. Discussion

The present study examined neural correlates of sublexical, orthographic, phonological and lexico-semantic processing in healthy younger and older adults to investigate similarities and age-related differences in brain activation patterns. Given the relatively stable reading performance of older adults in general, we expected both age groups to recruit similar brain regions related to the subprocesses of reading. However, as cognitive functions supporting the central subprocesses of reading decline with age, two mechanisms were proposed to account for possible age-related differences. On the one hand, previously reported age-related differences in the subprocesses of reading may originate primarily from age-related deficits in cognitive functions, in which case differences in neural activation patterns of younger and older adults should mostly be confined to brain regions associated with cognitive functions prone to age-related decline. On the other hand, the subprocesses themselves may be affected by age. We then would additionally expect age-related differences in neural correlates typically associated with these subprocesses of reading. Our behavioral and neuroimaging results indicated a preservation of reading-related component processes over the lifespan, yet they also demonstrated processing differences in younger and older adults, particularly for phonological and orthographic processing.

4.4.1. Conjointly activated brain regions in older and younger adults during reading

Both, younger and older adults exclusively recruited brain regions which are specific to the subprocesses of reading. During sublexical and orthographic processing we observed engagement of left inferior occipital and vOT regions and during phonological and lexico-semantic processing additionally activation in left inferior parietal and prefrontal gyri. Furthermore, younger and older adults activated bilaterally the insula, a region, previously implicated in phonological processing and thought to be involved in orthographic-phonological mapping (Borowsky et al., 2006). No active lateral temporal regions (i.e., STG, MTG) were observed during phonological processing in both age groups and during lexico-semantic processing in younger adults. As these regions are typically related to grapheme-phoneme-conversion which plays an important role during reading acquisition in children, this is may not be surprising (Bitan et al., 2007; Jobard et al., 2003; Martin et al., 2015; Schlaggar & McCandliss, 2007). Indeed, in their meta-analysis, Martin et al. (2015) found only limited convergence across studies for an involvement of left temporal regions in adult readers. Yet, the most important result of the conjunction analysis was, that, with the exception of the SPG in sublexical processing, active brain regions common to both age groups were in fact identical to the reading circuits of younger adults (*cf.* Table C.3). This gives very strong evidence for the preservation of the core processes of reading across the lifespan since older adults recruited the very same set of brain regions, albeit not exclusively, (*cf.* Table C.4) in all four reading tasks as did younger adults. Accordingly, accuracy rates were age-equivalent in sublexical, orthographic and phonological processing and higher for older adults in lexico-semantic processing.

4.4.2. Age-related differences inside brain regions associated with reading

Neural effects of aging were evident in all four central subprocesses of visual word recognition with older adults showing consistently more activation than younger adults. However, age-related neural differences were rather specific with respect to the particular subprocesses.

4.4.2.1. Age-related differences in sublexical processing. In letter identification (sublexical level), we observed age-related differences within the right SMG and right SMA, regions typically not recruited by younger adults during sublexical processing. The ventral parietal cortex, including the SMG, has been implicated in bottom-up attentional processes (Cabeza et al., 2008) and the SMA plays a crucial role in various control mechanisms during speech and language operations (Hertrich et al., 2016). With that in mind, the age-related increase in BOLD-signal in these regions may reflect an increased effort of older adults to resolve sublexical processing demands, possibly related to stimulus encoding related processes (*cf.* Allen et al., 1991; Froehlich & Jacobs, 2016; Froehlich et al., 2016; Guttentag & Madden, 1987). The extensive recruitment of the bilateral occipital lobe during sublexical and phonological processing observed in older adults during sublexical processing (*cf.* Table C.4) may further support this interpretation. Generally, not only during sublexical processing, activation patterns of older adults seem to be relatively unspecific with respect to the associated subprocesses. However, it is beyond the scope of this study to infer about underlying mechanisms in terms of cognitive aging, such as for instance, compensation (Berlingeri et al., 2013; Reuter-Lorenz & Cappel, 2008) or dedifferentiation (Carp et al., 2011; Li et al., 2001) as our block design does not allow for correlating behavioral performance to trial-wise hemodynamic activity.

4.4.2.2. Age-related differences in orthographic processing. At the orthographic processing level, older compared to younger adults showed increased activation in right inferior occipital and vOT circuits. Additionally, age-related differences were also present in left inferior parietal regions (SMG, ANG). The latter are typically associated with grapheme-phoneme conversion (e.g., Jobard et al., 2003; Joubert et al., 2004). Yet, to successfully perform in our lexical decision task, this process is theoretically irrelevant, as both, the word (target) as well as the pseudohomophone (non-target) sound like real words. Apparently, older adults failed to neurally adjust to the specific demands of the task. While younger adults did not recruit regions typically associated with phonological processing, older adults did in addition to the expected ventral temporal ones (*cf.* section *4.4.1. Conjointly activated brain regions in older and younger adults during reading*). Two different mechanisms may account for this finding. First, readers with lower scores in the Reading Span Test (RST; Daneman & Carpenter, 1983) have been found to be more likely to recruit phonology-based reading circuits than readers with higher scores during silent single word reading (Jobard et al., 2011). Since the RST is closely related to working memory capacity and working memory capacity in older adults is prone to age-related decline (e.g., Hedden & Gabrieli, 2004; Lindenberger et al., 2008), older adults may have preferably engaged brain regions associated with grapheme-phoneme conversion, which would usually help them to identify an (in)correctly spelled word. Second, the apparent lack of neural adaptation observed for older adults may also be caused by an age-related decline in inhibition of automatic grapheme-phoneme conversion or general inhibitory control processes.

Our results regarding orthographic processing did not replicate the findings from Gold et al. (2009), the only other fMRI study, we could identify, to investigate age-related effects using lexical decision. We did not observe the reported posterior-anterior shift with aging, that is, an overrecruitment of frontal regions accompanied by an underrecruitment of posterior regions with declining performance in older adults (Dennis & Cabeza, 2008). However, this may not be as surprising, because in contrast to Gold et al. (2009) who used words and pseudowords, the present lexical decision task comprised words and pseudohomophones obviating the use of phonological or semantic codes to successfully complete the task. In fact, young adults of the present study did not engage regions associated with phonological and lexico-semantic processing at all (*cf.* Table C.3). Based on their results, Gold et al. (2009) hypothesized that during lexical decision older adults may rely to a greater extent on higher-level linguistic processes than on orthographic processes. Findings of the present study support this claim only partly. While the absence of age-related differences within left vOT circuits backs the proposal by Gold et al. (2009), the absence of age-related differences in prefrontal and frontal regions and especially the presence of age-related differences within right inferior occipital regions and the right FG rather speak against it. In particular, the right hemispheric recruitment of the FG may explain age-equivalence performance in older adults.

4.4.2.3. Age-related differences in phonological processing. In phonological decision, age-related differences comprised nearly all brain regions typically associated with this subprocess of reading except for left inferior occipital and inferior frontal regions. Older adults compared to younger adults showed pronounced activation in regions recruited by both age groups (left ITG, ANG, PRG) as well as activation in regions not implicated in phonological processing in younger adults (bilateral cerebellum, right MOG, left FG, right ANG, bilateral STG and MTG, right PRG, left MFG and right SFG). Of special notice is the number of brain regions that demonstrated increased activation in both left and right hemispheres (e.g., cerebellum, ANG, STG, MTG, PRG). This impressive age-related increase in BOLD signal may reflect additional processing demands for older adults imposed by the phonological decision task. Of the four reading tasks, it was clearly the hardest as indicated by the significantly lower accuracy rates for both younger and older adults compared to the other tasks. This would be in line with the idea that increased activation in older adults is not only linked to cognitive decline but also to increasing task demands (Cabeza & Dennis, 2013).

More importantly however, we observed a similar lack of neural adaptation to task demands as we did for orthographic processing in older adults. Deciding whether the target stimuli (pseudohomophones) or non-target stimuli (pseudowords) sound like a word requires grapheme-phoneme conversion, thus increased engagement of ANG and SMG. Even though older adults recruited these regions, compared to younger adults they also showed pronounced activation in left ventral temporal regions (FG, ITG) usually associated with orthographic processing. Yet, neither pseudohomophones nor pseudowords correspond to entries in the orthographic lexicon (e.g., Grainger & Jacobs, 1996). Recruiting these structures would not support successful task completion. Again, we speculate about an age-related deficit in older adults to inhibit the activation of a non-optimal processing route. As older adults have lifelong experience with printed words, both, phonological as well as orthographic processing might be automatically activated in older adults without having necessarily consequences at the behavioral level. Functional network analyses may help to further understand the interplay of these two processes and the effect age has upon them.

4.4.2.4. Age-related differences in lexico-semantic processing. At the lexico-semantic processing stage, age-related differences were confined to the left SMA, bilateral MFG and right IFG (opercular part). It seems that lexico-semantic processing is fairly similar across age groups, especially during early processing steps involving the inferior occipital and ventral temporal regions. With older adults outperforming younger adults in terms of accuracy, life-long exposure to words may not only help older adults to build up an extensive vocabulary (Allen et al., 1995; Verhaeghen, 2003), but possibly preserves lexico-semantic processing mechanisms, both at the behavioral as well as neural level (*cf.* Cho et al. 2012; Daselaar et al., 2003; Dennis et al., 2007; Froehlich et al., 2016; Spaniol et al., 2006; Wierenga et al., 2008). The greater engagement of bilateral MFG, which has been linked to semantic retrieval processes (e.g., McNorgan et al., 2015; Welcome & Joanisse, 2012) may have also contributed to the superior performance of older adults observed in the present study. In contrast to sublexical, orthographic and phonological processing, only at the lexico-semantic processing stage, we observed age-related differences in the (right) IFG. The role of the IFG for language-related processes has among others been attributed to phonological output (Taylor et al., 2013), grapheme-phoneme-conversion (Jobard et al., 2003), orthographic selectivity (Glezer et al., 2016) as well as semantic processing (e.g., Binder et al., 2009; Poldrack et al., 1999) and has been shown to be functionally connected to vOT (Schurz et al., 2014). Since no age-related differences in IFG were detected for orthographic and phonological processing and since the engagement of especially the right IFG in semantic tasks has been ascribed to the involvement of executive functions (Vigneau et al., 2009), the overrecruitment of this region by older adults in the present study may closely be related to the involvement of those cognitive functions supporting successful word recognition. This notion receives further support when considering, that only during lexico-semantic processing age-related differences were observed in all main components of the PFC (i.e., IFG, MFG, SFG), a brain region that has systematically been linked to working and episodic memory, attention, executive functions and inhibition (e.g., Cabeza et al., 2004; Dennis et al., 2007; Grady, 2012; Laird et al., 2011; Lindenberger et al., 2013; Reuter-Lorenz et al., 2000; Sugiura, 2016).

4.4.3. Age-related differences outside brain regions associated with reading

While age-related differences within brain regions associated with reading seem to be relatively specific to the different subprocesses, age-related differences outside these core reading regions seem to be rather general. Older compared to younger adults showed greater activation primarily within parts of the bilateral cingulate cortex (sublexical, orthographic, phonological processing), the bilateral precuneus (orthographic, phonological processing) and in the bilateral SFG (orthographic, phonological and lexico-semantic processing).

The latter region has been identified to be functionally and anatomically connected to a number of frontal, sensorimotor and midline regions (e.g., Li et al., 2013) being a key component of the working memory network (Boisgueheneuc et al., 2006) and a bilateral dorsal attention network (Corbetta et al., 2008; Fox et al., 2006). The age-related increase in BOLD signal within the bilateral SFG may point towards an increased effort to access working memory and attentional processes in older compared to younger adults during orthographic, phonological and lexico-semantic processing. However, one might argue, that enhanced attentional and working memory processes of older adults may simply mirror efforts to select and execute the appropriate response. However, if this were entirely the case, then we should have observed an overactivation of the SFG during sublexical processing as well given the identical response criteria (yes/no, button press). Moreover, working as well as episodic memory has been found to correlate with reading single words (Frick et al., 2011). In line with the latter finding, we observed increased activation in the bilateral precuneus during orthographic and phonological processing for older compared to younger adults. Previous research has linked activation in the precuneus to successful episodic memory retrieval processes (e.g., Cavanna & Trimble, 2006; Lundstrom et al., 2005).

However, most striking are the age-related differences outside reading-related circuits when we consider them in concert. The posterior cingulate, the precuneus as well as the SFG have been identified to be functionally linked and to be part of the so called default mode network (DMN; Buckner et al., 2008; Mevel et al., 2011; Raichle et al., 2001). The DMN is thought to reflect the baseline activity of the brain (Raichle et al., 2001). Besides the DMN, several other functionally connected networks being active at rest have been identified, such as the dorsal attention network (van den Heuvel & Hulshoff Pol, 2010). Activity in regions comprising these networks decline with age (e.g., Maillet & Schacter, 2016) and have been interpreted to possibly reflect a decreasing ability of older adults to switch from a default mode to an active task-related mode (Mevel et al., 2011). Most interestingly, those regions for which we found an age-related overactivation during single word recognition (e.g., MFG, SFG, posterior and anterior cingulate cortex, precuneus) seem to be affected by this age-related decline at rest (Mevel et al., 2011). Interpreting these results is far from easy. One suggestion had been, that the age-related decrease in activity at rest is compensated by an increased activation during active task performance (*cf.* Damoiseaux et al., 2007). However, the interpretation of cognitive processes underlying the age-related decreased activation at rest is still matter to debate (e.g., Maillet & Schacter, 2016; Mevel et al., 2011). Given the present results, it would be interesting to further investigate the significance of resting state activation on word recognition and reading in younger and older adults.

4.4.4. Conclusion and Limitations

In conclusion, the present study found older and younger adults to engage a similar set of neural circuits associated with the central subprocesses of reading leading us to conclude that basic reading-related mechanisms are preserved across the life-span. Despite age-equivalent performance in terms of accuracy, age-related differences were found within brain regions typically associated with reading within all four reading-related tasks speaking against the idea that the neural subcomponents of reading are not affected by age. Moreover, age-related differences were also found outside typical reading circuits, especially in midline regions, which have been identified to play a crucial role in resting state networks and are also associated with memory functions, attentional processes and executive functioning. During phonological and orthographic processing age-related differences were most evident in brain activation patterns, possibly because of an impediment of neural adaptation to task demands in older adults.

There are a few limitations to the present work. First, we did not obtain any measures directly assessing cognitive functions declining with age but used reverse inference (*cf.* Poldrack, 2011, but Hutzler, 2014). Second, aging leads to changes in the cerebral vasculature and it is not yet known how these alterations affect the BOLD signal (D'Esposito et al., 2009). Third, comparing younger and older adults cross-sectionally may bear the risk of confusing cohort effects with true aging effects (e.g., Lindenberger, 2014). Finally, to our knowledge, this is the first study to investigate age-related differences in functional brain activation for all four central subprocesses of reading within one older sample. A major challenge to future research is to investigate the specific neural mechanisms underlying these observed neural effects of aging accounting also for changes in brain anatomy, neurochemistry and structural connectivity. Moreover, reading is a highly complex skill relying not only on the successful interplay of its central subprocesses but also on the input from other higher cognitive functions. As some of these functions show neural overlap to those in reading, further research is needed to disentangle the specific contributions to (age-related differences in) neural activation.

5. Age-related Differences in the Subprocesses of Reading and Sentence Comprehension: The Impact of Working and Episodic Memory

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5.1. Introduction

Reading is a highly automatized skill acquired early in life, which, once learned, is mastered effortlessly and routinely even in old age by most individuals (e.g., Cohen-Shikora & Balota, 2016; de Beni et al., 2007; Froehlich & Jacobs, 2016). Its complexity may seem surprising: To successfully read and comprehend written text, a reader has to integrate the outcome of multiple (sub-)conscious processes (e.g., visual, orthographic, phonological, lexico-semantic, or morpho-syntactic) that virtually all depend on well-functioning memory operations (Jacobs, 2001; Jacobs & Ziegler, 2015; Perry et al., 2007, 2010, 2013). For instance, most state-of-the art computational models of reading have an orthographic and phonological memory system, also referred to as a "lexicon", and they tend to have various input and output buffers at the letter and phoneme level, in which information is accumulated and integrated (Coltheart et al., 2001; Hofmann & Jacobs, 2014; Perry et al., 2007, 2010, 2013; Zorzi et al., 1998). The most basic process underlying successful reading is visual word recognition (Grainger & Jacobs, 1996; Jacobs, 2001; Jacobs & Ziegler, 2015), which is typically divided into sublexical, orthographic, phonological and lexico-semantic subprocesses (e.g., Froehlich et al., 2016; Ziegler et al., 2008).

Yet, while older adults have life-long experience in handling and comprehending written words, sentences and texts resulting in, for instance, a superior vocabulary (Verhaeghen, 2003), memory performance as well as other cognitive functions, such as processing speed (PS) and attentional control processes, have been found to decline with age (e.g., Craik, 1994; Kramer & Kray, 2006; Lindenberger et al., 2008; Salthouse, 2003, 2009). The age-related reduction of memory performance is not restricted to a particular type of memory and has been shown to correlate across its functions. Yet, the magnitude and onset of the decrement are subject to debate. While cross-sectional studies observed a decline in both working memory (WM) and episodic memory (EM) starting as early as in the 20s, results from longitudinal studies, which control for possible cohort effects, indicate a relatively stable memory performance up until approximately 60 years of age. Only then does the decline seem roughly similar for both cross-sectional and longitudinal data (e.g., Hedden & Gabrieli, 2004; Rönnlund et al., 2005; Siegel, 1994). Given the evidence for a relatively stable reading performance even in old age on the one hand, and the decline in cognitive functions supporting visual word recognition and reading on the other hand, surprisingly few studies have investigated this ambiguous relationship, especially with respect to how these age-related cognitive alterations may affect the basic subprocesses of word recognition in the aging individual.

The importance of WM (capacity) for reading has been well established (e.g., Baddeley et al., 1985; Daneman & Carpenter, 1980; Daneman & Merikle, 1996) with one of its key functions being the maintenance and updating of surface, text-based and situation models (Borella et al., 2011; Zwaan, 2015). In literary reading, WM plays a central role in the subtle interplay between the “nucleus” of the stream of thought and its “fringe” that determines meaning making in inherently ambiguous textual structures (Jacobs, 2015). Studies on age-related differences in text comprehension suggest a decline in accessing surface or text-based levels of representation but no notable difference has been observed between younger and older adults in situation model processing (Radvansky & Dijkstra, 2007).

Adopting a multivariate approach to disentangle the impact of typically declining cognitive functions in older adults and their impact on language comprehension have brought mixed results. Age-related effects on text processing were either found to be mediated by WM with age-related effects on WM being mediated by inhibitory control processes and PS (Borella et al., 2011; Van der Linden et al., 1999), or have been reported to be only mediated by age-related differences in PS and inhibitory control but not by WM (Kwong See & Ryan, 1995). Whether WM predicts reading comprehension seems to be at least partly depending on the modality of the WM task (e.g., visuo-spatial vs. verbal), its complexity and demands on other (underlying) cognitive processes (e.g., attentional control; Caretti et al., 2009) as well as on the task with which text comprehension is measured. DeDe et al. (2004), using structural equation modeling, found verbal WM to account for age-related differences in sentence and text comprehension, yet not for online syntactic processing.

However, focusing on WM functions as the single contributor of memory processes supporting single word recognition and reading may seem to be too simplified. Neurobiological evidence from functional connectivity analyses indicates that readers with high WM capacities may benefit from their ability to form elaborate event representations, which are partly based on the engagement of EM systems. These systems are thought to activate and integrate information of previously experienced events or schematic abstractions (Newman et al., 2013). The finding that performance in reading irregularly spelled words significantly correlates with verbal EM and WM measures adds to the assumption that not only WM but also EM predicts reading performance (Frick et al., 2011).

At the level of single word recognition, there is evidence indicating that individual exposure to words, that is, personal experiences with written and spoken language, thus most likely EM processes, influences the speed of lexical access. For instance, word frequency effects were found to be greater for subjective than for objective frequency measures, or when objective frequency measures were specifically adapted to the mental lexicons of the age cohort in question (Balota et al., 2004; Dorot & Mathey, 2010). Further evidence for a potential influence of EM on reading performance stems from neurocognitive studies. For instance, activity in the fusiform gyrus, a region playing a crucial role in word recognition and therefore reading (e.g., Dehaene et al., 2002; Price, 2012) is associated with better EM performance (Mei et al., 2010). Likewise, in semantic decision, better recognition performance leads to higher engagement of the hippocampal complex, a brain structure reliably implicated in EM (e.g., DeQuervain & Papassotiropoulos, 2006; Otten et al., 2001; Wagner et al., 1998). Moreover, brain regions associated with EM seem particularly activated in poetry reading (Jacobs, 2015; Zeman et al., 2013), their engagement depending greatly on the formation and preference for mental simulation during reading due to individual personal experiences of the readers (Jacobs & Willems, 2017).

Given the empirically and theoretically close relationship between WM, EM and reading, it is yet an open issue how these memory functions affect sublexical, orthographic, phonological and lexico-semantic processing, specifically, but not exclusively, in older adults. Therefore, the present study aims at clarifying the influence of WM and EM on the four central subprocesses of reading and on sentence comprehension in younger and older adults using a structural equation modeling approach. For this purpose, a subsample of younger and older adults from the cohort of the Berlin Aging Study II (BASE-II; Bertram et al., 2013) participated in four different single word reading tasks each tapping either sublexical, orthographic, phonological or lexico-semantic processing. We explicitly used word recognition of isolated words as it is foundational to fluent reading (Grainger & Jacobs, 1996; Jacobs, 2001; Jacobs & Ziegler, 2015). Additionally, sentence comprehension of older and younger adults was measured to mirror reading in everyday life. Performance in WM and EM was assessed by tasks addressing different memory modalities related to processing of verbal, numerical, or figural-spatial information (*cf.* Düzel et al., 2016). Furthermore, PS was considered as an additional variable due to its close relation with memory measures (*cf.* Borella et al., 2011; Hertzog et al., 2003) and because all four single word reading measures were based on response times (RT). For the latter, older adults typically show an age-related disadvantage due to cognitive slowing (e.g., Salthouse, 1996) or because of decision making processes (e.g., Ratcliff, 2008). Different to previous studies, we used at least three indicators per latent variable and incorporated EM into the model; its influence on single word recognition and reading being investigated for the first time within this frame work (at least to our knowledge).

We expected older adults to respond more slowly than younger adults in all tasks requiring speeded responses. Moreover, younger adults were expected to outperform older adults within each of the memory as well as the PS tasks (e.g., Hedden & Gabrieli, 2004; Hoyer et al., 2004; Salthouse, 2003). Within the structural equation model, we assumed WM and EM to reliably predict sentence comprehension (*cf.* Borella et al., 2011; DeDe et al., 2004; Jacobs & Willems, 2017; Van der Linden et al., 1999) and possibly performance in the four subprocesses of reading (*cf.* Daselaar et al., 2003; Frick et al., 2011). However, reading single words may not require as many memory resources as reading text (e.g., no need to store and update syntactic information and parse and integrate preceding text with subsequent text). Age-related decline in WM performance has been reliably related to age-related slowing and decrement in inhibitory control, while age-induced changes in EM have been found to correlate with age-related changes in WM and speed (e.g., Borella et al., 2011; Düzel et al., 2016; Head et al., 2008; Hertzog et al., 2003). Thus, PS, WM and EM were thought to correlate with each other as were the four subprocesses of reading. The latter were in turn presumed to reliably predict sentence comprehension. As overall reading performance remains relatively stable over the life span (*cf.* de Beni et al., 2007; Froehlich & Jacobs, 2016), we expected little or no age-related differences in the contribution of sublexical, orthographic, phonological and lexico-semantic processing to sentence comprehension. However, with declining memory functions in older adults, we were interested whether anticipated age-related differences in associations between memory and sentence comprehension (Borella et al., 2011; Van der Linden et al., 1999; DeDe et al., 2004) would similarly apply to associations between memory and the four subprocesses of reading.

5.2. Method

5.2.1. Participants

The present study recruited a subsample of 1,532 subjects (805 female, 727 male) from the BASE-II cohort (Bertram et al., 2013). Selection criteria were based upon complete participation in all tasks regarding memory and reading, completion of questionnaires including basic descriptive data. Individual error rates above 40% in all tasks were set as an additional exclusion criterion. The sample was split into two age groups: The 309 young adults (161 females, 148 males) were on average 31.2 years old (range 23 – 39 years), the 1,223 older adults (644 females, 579 males) were on average 70.5 years old (range 60 – 84 years). Younger and older adults differed with respect to formal education, $t(539.5) = -4.98$, $p < .001$ with younger adults having more years of education (15.0 years) than older adults (14.2 years). Participants were German native speakers, right-handed and had normal or corrected to normal vision. None of the participants had a history of reading difficulties or language impairment, neurological disease, psychiatric disorders, a history of head injuries or took medication that might affect memory function. Prior to the study, written informed consent was obtained and subjects received financial compensation for their participation. The study was approved by the Ethics Committee of the Max Planck Institute for Human Development, Berlin (MPIB).

5.2.2. Tasks and Procedure

Participants were tested in small groups of up to six individuals in a quiet test room on the Charité Campus, Berlin. The two test sessions were scheduled one week apart at exactly the same time of the day to avoid circadian confounding effects on performance. Each test session lasted for about 3.5 hours and included other tasks of the BASE-II test battery. All tasks were presented on a computer screen; answers were obtained via button-presses. Before each task participants performed training trials.

5.2.2.1. Reading Measures. The following tasks were used to access the four central subprocesses of reading: letter identification, lexical, phonological and semantic decision. The order of the tasks was as follows: phonological decision task, semantic decision task, lexical decision task, letter identification task. Within each task, item order was pseudorandomized and items were presented one by one at the center of a computer screen for three seconds or up to participant's response. Participants were instructed to give yes- or no-responses via button press. To ensure comparability of results, item length, number of orthographic neighbors, bigram frequency and (base word) frequency were carefully matched across the lexical, the phonological as well as the semantic decision task (all *F*'s < 1.83, all *p*'s > .2; see Table B.1.1.). Bigram frequencies in the letter identification task were lower than those in the other tasks ($F(3, 316) = 33.4$, $p < .001$) as vowel-consonant combinations were excluded by design. Matching was based on the dlex database (dlexDB; Heister et al., 2011) norms for German words. Within each task 40 items served as targets and 40 as non-targets.

Latency and accuracy served as dependent variables. Prior to the single word reading tasks, a sentence comprehension task was administered to measure overall reading performance.

Letter identification task. To assess position-specific letter processing without lexical activation (Ziegler et al., 2008), participants had to indicate whether the letter ‚r' occurred within a consonant string (target; e.g., dbnrl) or not (non-target; e.g., djptd). Targets and non-targets were carefully matched for bigram-frequency and had on average the same number of corpus-sized letters, letters with ascenders and letters with descenders.

Lexical decision task. Orthographic processing was assessed by presenting either German nouns (targets; e.g. Park) or German pseudohomophones (non-targets; e.g., Waal [waale]). Pseudohomophones are pseudowords that sound like real words (e.g., brane is phonologically identical to the real word brain). Participants had to decide as quickly and accurately as possible whether the presented word was a correctly spelled German word or not. Pseudohomophones were created by changing one letter of an existing German noun to keep them orthographically similar to real words. The initial letters of all items were capitalized to ensure the typical appearance of German nouns.

Phonological decision task. To investigate phonological processing participants had to judge whether pseudohomophones (target) or pseudowords (non-target; e.g., Lase) were presented (Bergmann & Wimmer, 2008). Specifically, they were asked to give a yes-response when the item on the screen sounded like a word and to give a no-response if otherwise. Just as it was done for pseudohomophones pseudowords were created by changing one letter from an existing German noun and were presented with capitalized initial letters.

Semantic decision task. This task was designed to measure the participants' efficiency in making semantic judgments. Subjects had to indicate whether the presented item described living objects (target; e.g., Lama) or non-living objects (non-target; e.g., Plan). As before, only German nouns served as targets and non-targets.

Sentence comprehension task. To assess reading ability not only on single word but also on sentence level, a computerized version of a standard German sentence reading test (Wimmer et al., 2010) was administered. Participants were asked to judge via button press whether each sentence of 77 successively presented sentences was meaningful or not. Over the course of the task, sentences contained longer and also more words and became morpho-syntactically more complex. Overall reading performance was calculated by summing up correct responses within 3 minutes.

5.2.2.2. Working memory measures.

Spatial updating. In each block of this task, two or three 3x3 grids were presented with each grid containing a blue dot in one of the nine possible positions. These locations had to be memorized and updated according to shifting operations, which were indicated by arrows appearing beneath the corresponding field. After six shifting operations, the grids reappeared and participants had to click on the end positions. Averaged percentages of correct placements were used to assess spatial updating performance.

Letter updating. Participants were presented with a letter sequence of seven to 13 letters and were asked to report the last three letters they had seen once the sequence stopped via button press. Performance was measured by the number of correct responses.

Number-n-back. In this task, a three-digit number was sequentially shown, followed by a further three-digit number, also shown sequentially. This cycle was repeated 30 times. Within each cycle participants were asked to indicate via button press whether the number shown three steps earlier had been identical or not. The score of correct answers was used for further analyses.

5.2.2.3. Episodic memory measures.

Scene encoding. Within this incidental encoding task, participants performed an indoor/outdoor judgement on 44 indoor and 44 outdoor scenes. 22 of indoor and 22 of outdoor scenes were then replaced by new images in the retrieval test and subjects had to indicate whether they recognized the scenes. Recognition memory performance for scenes was assessed after a delay of approximately 2.5 h (short-delay memory). Recognition performance was assessed by the number of hits minus false alarms.

Verbal learning. This task was designed to assess auditory verbal learning. Fifteen words had to be learned within five learning trials and recalled (early recall). After presenting an interference list participants were asked to freely recall those words and again 30 minutes later (late recall). Finally, participants performed a recognition test on the initial word list. The sum of items recalled across trials provided the measure of overall learning performance.

Face-profession. To assess the associative binding on the basis of recognition of incidental encoded face-profession pairs participants had to indicate whether 45 presented faces matched the profession via button presses. Within the test phase following the study phase, with a three-minute delay nine face-profession combination were replaced by new pairs and 18 pairs were newly arranged. Participants had then to decide if they had seen the face-profession combination before. Recognition memory for the rearranged face-profession pairs was assessed by the correct responses minus the false alarms.

Object location. Within two short test trials participants were presented sequentially with 12 colored photographs of real-world objects displayed at different locations in a 6x6 grid on a computer screen. After presentation, objects appeared at the side of the screen and had to be moved to the correct locations. The sum of correct placements across the two test trials was used as a measure of memory performance.

5.2.2.4. Processing speed measures.

Basic pattern recognition. We assessed each individual’s PS by having participants judge whether a series of tilted slashes were oriented equally (target; e.g., /////) or not (non-target, e.g., //\///). Item presentation and, most importantly, the decision process (yes/no response) was identical to that of the reading tasks.

Multi-source interference task. In this task, a set of three numbers (1, 2, 3 or 0) is presented in the center of a screen with one number being different to the other two. Participants were asked to indicate the identity of the diverging number (target) by using the index, middle or ring finger of their right hand. Numbers were shown for 1000ms with an interstimulus interval of 750ms in alternating blocks of 42 seconds. Within control trials, the position of the target number always matched its position on the button press (i.e., the target number 1 would appear in the first, leftmost position) while within interference trials it never did (*cf.* Bush & Shin, 2006). We presented a total of 8 alternating blocks, each consisting of 24 trials. Performance was assessed using the RT of correctly answered control trials.

Digit symbol substitution test. In the digit symbol substitution test a code box with nine digits and corresponding symbols was presented as well as rows of double boxes, which consisted of empty lower boxes and an upper boxes showing digits. Participants were asked to fill the lower boxes with the symbols corresponding to the digits in the upper boxes (*cf.* Wechsler, 1997). Test scores for further analyses were obtained by summing the correct responses within 90 seconds. As this test was administered during the first as well as the second test session two scores per participant entered the analyses.

5.2.3. Data Analysis

5.2.3.1. Reading measures. Accuracy rates and RTs of the four single word reading tasks were analyzed using mixed-effects modeling (LME, Baayen et al., 2008) as implemented in the „lme4“-package (Bates et al., 2014) with crossed random factors for subjects and items. Analyses were run in R version 3.3.0 (R Core Team, 2015). We used linear mixed-effects regression to analyze RTs, including main effects and interactions for task and age as fixed factors. Fixed effects were tested for significance using Type III Wald chi-square tests („car“-package; Fox & Weisberg, 2011). Accuracies were analyzed using logistic mixed-effects regression. As recommended by Barr and colleagues (Barr, 2013; Barr et al., 2013), the random factor structure included intercepts for subjects and items, and random slopes for age within items as well as random slopes for task within subjects. Prior to RT analyses, maximum error rates were re-examined to ensure an accuracy of at least 60% per task and subject. Next, all erroneous trials were removed. Additionally, RTs deviating more than 3.5 standard deviations from the individual's mean within each task were excluded. Group differences in sentence comprehension were evaluated using an independent t-test.

5.2.3.2. Memory and processing speed measures. Tasks were analyzed separately by means of independent t-tests as implemented in R version 3.2.2 (R Core Team, 2015). Only correct responses were considered for further analyses. Scores deviating more than 2.5 SDs from the population mean of each task were removed.

5.2.3.3. Structural equation modeling. Before conducting confirmatory factor analyses (CFA) to evaluate the measurement model, reading measures were transformed to latent variables through parceling. Parceling bears the advantage of stabilizing parameter estimates and increasing the parsimonious representation of the latent variables (e.g., Little et al., 2013; Matsunaga, 2008). As recommended by Matsunaga (2008), we created three parcels per reading task by averaging the RT/score (sentence comprehension task) of every third item, starting with item 1 for the first parcel, with item 2 for the second, and item 3 for the third. After parceling, outliers deviating more than 2.5 SDs from the parcel mean within each age group were removed. All indicators entering the analyses were converted to z-scores.

We then tested the CFA model including all constructs for each age group separately (see Brown, 2006; Byrne, 2008) to assess the measurement qualities. The indicators consisted of RTs of correct responses (letter identification, lexical decision, phonological decision, semantic decision, basic pattern recognition, multi-source interference), of the sum of correct responses (sentence comprehension, letter updating, number-n-back, verbal learning, object location, digit symbol substitution), averaged percentages of correct placements (spatial updating) and hits minus false alarms (scene encoding, face profession) with lower RTs and higher scores indicating better performance. Marker indicators for all reading tasks were parcels 1, for memory measures and PS letter updating, verbal learning and basic pattern recognition were used, respectively. Residual errors were assumed to be uncorrelated while all latent factors were assumed to be correlated. With the 351 elements of the empirical covariance matrix and the 80 freely estimated model parameters the model was over-identified with 271 *df*. As not all subjects completed all tasks, data was partially missing from 39 younger and 96 older adults. Since Mardia's coefficient, as implemented in the "MVN"-package (Korkmaz et al., 2014; R version 3.2.2, R Core Team, 2015), indicated a significant deviation of the data from normality, g2p = 610.3, $z_{\text{kurtosis}} = 17.8$, $p_{\text{kurtosis}} < .001$, the robust maximum likelihood estimator (MLR), which provides standard errors and chi-square test statistics robust to violations of normality, was chosen for further analyses. After identifying the multigroup baseline model, i.e., establishing configural equivalence, we evaluated cross-group metric equivalence, i.e., whether factor loadings are similar across groups (Byrne, 2008). With these constrains in place, we then used structural equation modeling to investigate how PS, WM and EM relate to reading performance as a function of age group.

Finally, to compare path coefficients between groups, we applied likelihood ratio tests with parallel null hypotheses of each path coefficient being equal across groups. We applied Satorra and Bentler's (2001) correction to correct for potential non-normality in the outcomes.

All models were tested in R version 3.2.2 (R Core Team, 2015) using the "lavaan"-package (Rosseel, 2012). Missing data was handled using a full information maximum likelihood approach. To assess model fit, we used multiple indicators. We report chi-square tests even if known to be highly overpowered and practically often of little value (Bollen, 1989). Therefore, we base our model evaluations primarily on the root mean square error of approximation (RMSEA), which adjusts for sample size and model parsimony and describes to what extent a model fits reasonably well in the population, as well as on the comparative fit index (CFI), which compares the model fit of the specified model in relation to a more restricted independence model. As an absolute index of model fit, we also report the standardized root mean square (SRMR). We consider the model fit acceptable, when the following criteria are met: RMSEA ≤ .08; CFI ≥ .95 and SRMR ≤ .08 (Brown, 2006; Hu & Bentler, 1999; McDonald & Ho, 2002).

5.3. Results

5.3.1. Reading, Memory and Processing Speed Performance

Participants' performance and age-related differences are shown in Table 5.1. As expected, older compared to younger adults displayed longer RTs within each of the four different word reading tasks, the control task and the multisource interference task as well as scored significantly lower in sentence comprehension, all memory tasks and the digit symbol substitution task. Accuracy performance within lexical and semantic decision was comparable across age groups. Older adults responded more accurately within the letter identification task while the opposite pattern was observed within the phonological decision task (see Appendix D for detailed analyses).

Table 5.1

Results on group differences between younger and older adults on the indicators used in the structural equation model

			Group comparison		
	YA *M* (*SD*)	OA *M* (*SD*)	χ^2	*t*	Cohen's *d*
Reading Measures					
Accuracy					
Letter identification	97.3 (16.3)	97.8 (14.8)	11.5***		
Lexical decision	95.7 (20.2)	97.0 (17.0)	1.48		
Phonological decision	89.0 (31.3)	86.6 (34.1)	8.52**		
Semantic decision	96.3 (19.0)	96.9 (17.2)	3.81		
RTs[1]					
Letter identification	605 (145)	783 (203)	456.8***		
Lexical decision	748 (261)	907 (310)	166.1***		
Phonological decision	1,226 (464)	1,398 (497)	108.2***		
Semantic decision	706 (192)	851 (233)	240.4***		
Sentence comprehension[1]	60.9 (10.2)	54.7 (10.7)		-9.42***	.58
Working Memory					
Spatial updating	32.9 (6.41)[a]	21.1 (8.86)[b]		-26.2***	1.39
Letter updating	46.3 (9.0)[c]	39.2 (10.3)[b]		-11.7***	.69
Number-n-back	.89 (.13)[a]	.69 (.17)[b]		.22.0***	1.21
Episodic Memory					
Scene encoding	.38 (.15)	.28 (.14)[d]		-10.3***	.70
Verbal learning	60.5 (10.8)[e]	43.2 (13.3)[f]		-24.1***	1.35
Face-profession	.54 (.19)	.27 (.21)[f]		-21.9***	1.32
Object location	16.3 (5.30)[c]	13.3 (3.82)[g]		-9.18***	.72
Processing Speed					
Basic pattern recognition	501 (60.9)[h]	649 (90.7)[i]		33.8***	1.72
Multiple interference	462 (46.1)[j]	656 (95.4)[k]		50.7***	2.21
Digit symbol[2]	65.4 (11.3)[l]	43.2 (9.62)[m]		-31.0***	2.23
	63.4 (10.1)[n]	45.0 (8.30)[o]		-28.7***	2.11

Note. YA = younger adults; OA = older adults; SD = standard deviation; RTs = response times. To analyze accuracy data and response times of the four word reading tasks logistic and linear mixed-effect regression were used, respectively. Independent t-tests were applied for the other group analyses.

[1]measures were parceled into three indicators per task before entering analyses. [2]two measures per subject from two sessions one week apart. prior to entering confirmatory factor analyses and structural equation modeling RTs, scores of sentence comprehension, memory and processing speed were converted to z-scores.

[a]*n* = 303. [b]*n* = 1,210. [c]*n* = 301. [d]*n* = 1,222. [e]*n* = 308. [f]*n* = 1,221. [g]*n* = 1,208. [h]*n* = 305. [i]*n* = 1,197. [j]*n* = 302. [k]*n* = 1196. [l]*n* = 293. [m]*n* = 1,130. [n]*n* = 294. [o]*n* = 1,153.

$^{**}p < .01$. $^{***}p < .001$.

5.3.2. Confirmatory Factor Analyses

The measurement model with the unconstrained factor loadings is depicted in Figure 5.1. It yielded a good fit to the data for both younger and older adults, $\chi^2_{\text{younger}}(271) = 493.3$, $p < .001$/ $\chi^2_{\text{older}}(271) = 1{,}227.4$, $p < .001$, $\text{RMSEA}_{\text{younger}} = .052$, 90% CI [.044, .059]/ $\text{RMSEA}_{\text{older}} = .054$, 90% CI [.051, .057], $\text{CFI}_{\text{younger/older}} = .966$, $\text{SRMR}_{\text{younger/older}} = .044$. Likewise, the baseline model to test for configural equivalence, yielded a good fit to the data, $\chi^2(542) = 1{,}734.1$, $p = < .001$, RMSEA = .054, 90% CI [.051, .056], CFI = .966, SRMR = .044. To test for measurement equivalence across age groups, we then compared the configural model to the more restrained metric model. The metric model provided likewise a good fit to the data, $\chi^2(560) = 1{,}844.6$, $p < .001$, RMSEA = .055, 90% CI [.052, .057], CFI = .963, SRMR = .052. Measurement equivalence was established by calculating the difference between the CFI-values of these two models (ΔCFIs = .003) and accepting equivalence if $\Delta\text{CFI} < .01$ (as suggested by Cheung & Rensvold, 2002).

5.3.3. Structural Equation Modeling

We set up a multi-group structural equation model combining the four latent variables of the subprocesses of reading and that of sentence comprehension with the memory and PS constructs to test for influences of PS, WM and EM on reading (Figure 5.2). Latent memory and PS variables were assumed to be correlated with each other as were the four latent variables of the subprocesses of reading. PS, WM and EM were regressed on each of the four latent reading variables, the latter, WM and EM additionally on sentence comprehension. The model yielded a good fit to the data, $\chi^2(562) = 1{,}846.9$, $p = < .001$, RMSEA = .055, 90% CI [.052, .057], CFI = .963, SRMR = .052.

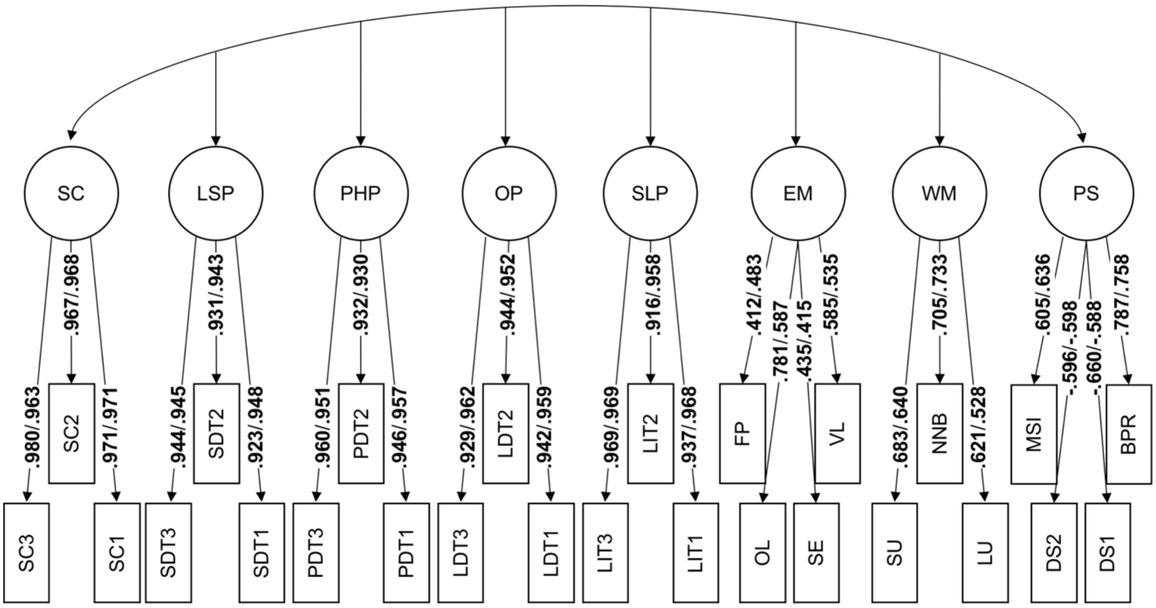

Figure 5.1. Configural measurement model showing standardized factor loadings for younger and older adults (younger/older). Circles denote latent variables (SC = sentence comprehension; LSP = lexico-semantic processing; PHP = phonological processing; OP = orthographic processing; SLP = sublexical processing; EM = episodic memory; WM = working memory; PS = processing speed), rectangles denote indicator variables (SDT = semantic decision; PDT = phonological decision; LDT = lexical decision; LIT = letter identification; FP = face-profession; OL = object location; SE = scene encoding; VL = verbal learning; SU = spatial updating; NNB = number-n-back; LU = letter updating; MSI = multi-source interference; DS = digit symbol substitution; BPR = basic pattern recognition). All factor loadings are significant at the .001 level.

As shown in Figure 5.2, WM was found to be positively associated with all four subprocesses of reading in older adults (standardized path coefficients in letter identification: .421; lexical decision: .289; phonological decision: .283; semantic decision: .299), whereas for younger adults this positive association was only observed for sentence comprehension (.586). EM was significantly correlated with sentence comprehension in both age groups. A closer inspection of path coefficients revealed a negative relationship in younger adults (-.410) and a positive relationship for the older group (.117). As expected, PS correlated positively with all four subprocesses of reading in both age groups (sublexical$_{\text{younger/older}}$: .970/.987; orthographic$_{\text{younger/older}}$ .645/.803; phonological$_{\text{younger/older}}$ .591/.749; lexico-semantic$_{\text{younger/older}}$ .828/.972). All four subprocesses of reading were significantly associated with sentence comprehension in older adults with letter identification and phonological processing being positively correlated and orthographic and lexico-semantic processing being negatively correlated (.089; .080; -.481; and -.159, respectively). With the exception of phonological processing, the same result pattern was observed for the younger group (.150; -.333; -.298).

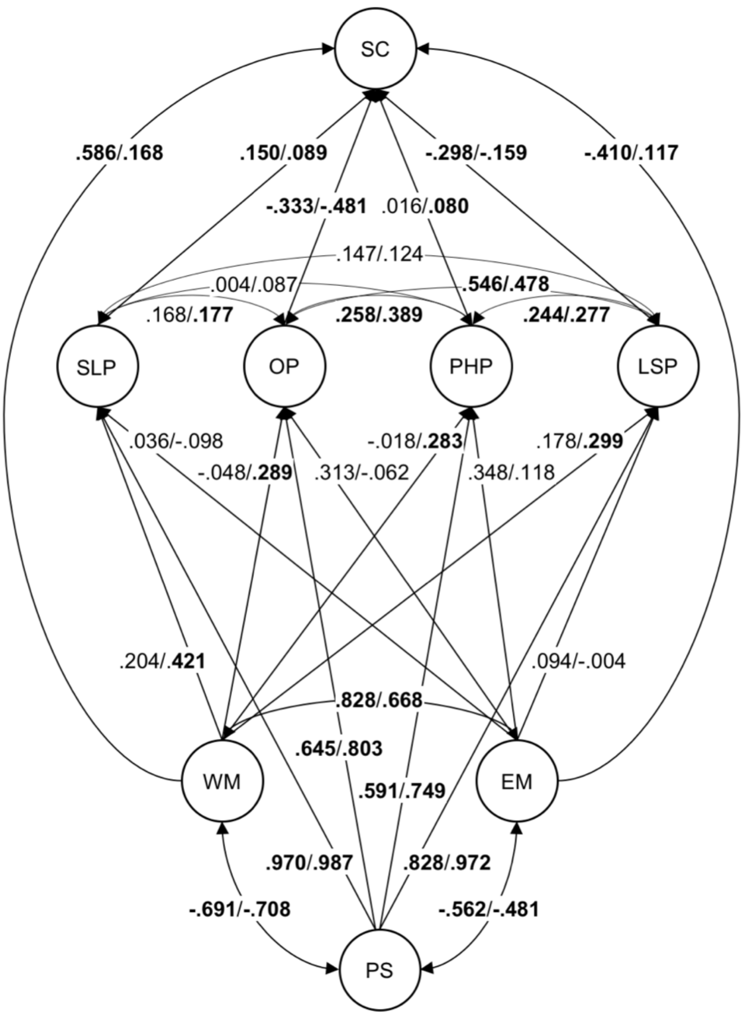

Figure 5.2. Simplified structural equation model showing standardized path coefficients for younger and older adults (younger/older) with bold numbers representing significant relationships (all *p*'s < .05). Circles denote latent variables (SC = sentence comprehension; SLP = sublexical processing; OP = orthographic processing; PHP = phonological processing; LSP = lexico-semantic processing; EM = episodic memory; WM = working memory; PS = processing speed).

PS, WM and EM correlated significantly with each other in both age groups: While WM and EM were positively associated (younger: .828; older: .668), the opposite relationship was found for both memory measures and PS ($\text{WM}_{\text{younger/older}}$: -.691/-.708; $\text{EM}_{\text{younger/older}}$: -.562/-.481). The four subprocesses of reading correlated positively with each other: In younger adults this held true for all possible associations excluding sublexical processing (orthographic with phonological and lexico-semantic processing: .258; .546; phonological with lexico-semantic processing: .244), while in older adults, sublexical processing correlated with orthographic processing (.177) yet not with phonological and lexico-semantic processing. All other correlations between the subprocesses were, however, significant (orthographic with phonological and lexico-semantic processing: .389; .478; phonological with lexico-semantic processing: .277).

Comparing path coefficients of the regressions showed differences between age groups for the association of WM and sentence comprehension, $\Delta\chi^2(1) = 8.07, p < .01$, of EM and sentence comprehension, $\Delta\chi^2(1) = 50.1, p < .001$, as well as orthographic processing, $\Delta\chi^2(1) = 4.84, p < .05$, and for the association of lexico-semantic processing and sentence comprehension, $\Delta\chi^2(1) = 4.33, p < .05$. All other comparisons of regressed path coefficients did not differ between groups, all *p*'s > .05.

5.4. Discussion

The aim of the present study was to investigate the influence of WM and EM on the four central subprocesses of reading as well as on sentence comprehension as a function of age. For this purpose, latent variables of PS, WM, EM, sublexical, orthographic, phonological and lexico-semantic processing as well as sentence comprehension were combined into a multi-group structural equation model. As expected, both EM and WM contributed to sentence comprehension in younger and older adults. Yet the contribution of the two memory functions to sentence comprehension differed as a function of age. At the subprocess level, age-related differences were limited to an influence of EM on orthographic processing. WM was found to positively affect sublexical, orthographic, phonological and lexico-semantic processing of the older age group. All four subprocesses of reading were found to significantly contribute to sentence comprehension in older adults and with the exception of phonological processing to sentence comprehension of younger adults, emphasizing the importance of these subprocesses for elaborate reading. Given the relative stability of reading performance across the life-span (e.g., Cohen-Shikora & Balota, 2016; de Beni et al., 2007; Froehlich & Jacobs, 2016) we assumed no or only little age-related differences with regard to the influence of the four central subprocesses of reading on sentence comprehension. In line with these expectations, only lexico-semantic processing was identified to contribute differently to sentence comprehension in younger and older adults. As hypothesized, PS, WM and EM correlated with each other within both age groups as did orthographic, phonological and lexico-semantic processing.

5.4.1. The Influence of Working Memory on Reading

In text comprehension, WM is needed to maintain and update surface, text-based and situational models (Borella et al., 2011; Zwaan, 2015). As previously mentioned, younger and older adults seem to rely on roughly the same processes when constructing situation models and both age groups create situations models already for very basic text units, such as sentences (Radvansky & Dijkstra, 2007). Accordingly, in the present study, WM was found to reliably influence sentence comprehension in older and younger adults. For both age groups, the relationship between these two factors was positive indicating that participants with higher WM scores also performed more successfully in sentence comprehension regardless of age.

However, the influence of WM was reliably stronger for younger than for older adults, which meant that younger participants relied to a higher degree on WM operations to solve this task than did older adults. An obvious explanation for this observation might be the age-related advantage of younger adults in available WM resources (e.g., Craik, 1994; Hedden & Gabrieli, 2004; Lindenberger et al., 2008).

Even though, younger and older adults probably use similar processes to create situation models to comply to task demands, the sentence comprehension task of the present study required participants to rapidly update their situation model in case of a no-response because of violations to semantic expectations. With a still intact WM at hand, younger adults may have been more capable to flexibly adapt their situation models than were older adults, which in turn lead to a superior task performance. In line with this reasoning, items of the sentence comprehension task increased in syntactic complexity over the course of the experiment. The age-related decline in WM functions may have left older adults to construct rather incomplete or erroneous situation models resulting in lower scores in sentence comprehension (*cf.* Radvansky & Dijkstra, 2007). However, even though our results are in line with findings, that identified WM to account for age-related differences in sentence and text comprehension (*cf.* Borella et al., 2011; DeDe et al., 2004; Van der Linden et al., 1999 but see Kwong See & Ryan, 1995), the influence of WM and its age-related decrement on the construction of effective situation models has not yet been resolved and should be addressed in future research.

At the level of single word recognition, at which the four central subprocesses of reading were assessed, we observed no age-related differences in the contribution of WM on any of the subprocesses. Additionally, WM did not predict performance in sublexical, orthographic, phonological or lexico-semantic processing in younger adults. As the present decision tasks did not require integrating preceding with subsequent text and build elaborate text representations, it seems plausible for the influence of WM to be far less pronounced than in sentence comprehension. However, results of older adults may question this assumption. For older adults, WM was found to be positively associated with all four subprocesses of reading indicating, that similar to sentence comprehension, a good WM performance supports successful sublexical, orthographic, phonological and lexico-semantic processing in older adults. Indeed, besides perceptual-attentional processes, WM operations are also required on the single word level, for instance for grapheme-phoneme conversion and assembly of letters into meaningful units (sublexical and phonological processing; e.g., Coltheart et al., 2001; Perry et al., 2007, 2010) as well as for matching processes with the mental lexicon (orthographic and lexico-semantic processing; e.g., Grainger & Jacobs, 1996; Hofmann et al., 2011; Perry et al., 2007). In fact, older adults show the strongest influence of WM on sublexical processing, the only task in which they outperformed younger adults in the present study (in terms of accuracy). Furthermore, an association of WM and orthographic processing has been reported elsewhere (Frick et al., 2011). Yet, the null effects in younger adults and the non-significant group differences in the contribution of WM on the subprocesses of reading, make it relatively hard to interpret our results.

5.4.2. The Influence of Episodic Memory on Reading

Findings of the present study confirmed our assumption, that not only WM but also EM plays an important role for sentence comprehension in both younger and older adults. When readers encounter written texts, they relate not only their knowledge but also their personal experiences to the events and situations described in the narrative (Bower & Morrow, 1996; Jacobs & Willems, 2017; Kintsch & van Dijk, 1978; Zwaan, 2015). However, the way EM impacts sentence comprehension seems to differ as a function of age. While we observed a negative association of these two factors for younger adults, the opposite relationship was found for older ones. Thus, for older readers, the contribution of EM processes on sentence comprehension appears to be similar to the one for WM: Older adults with high EM performances will also excel in sentence comprehension. Taking into account the close relationship of EM and WM (e.g., Head et al., 2008; Hertzog et al., 2003; Rajah & D'Esposito, 2005) and considering the positive correlation of both memory functions with sentence comprehension in older adults, for this particular age group WM and EM may work in concert for successfully comprehending sentences and texts. The reason for this "co-operation" might again originate in the age-related declines of these cognitive functions, basically serving as a compensational mechanism. Yet, lower scores in sentence comprehension for older compared to younger adults implicate rather attempted than successful compensation.

In light with the age-related decline in the contribution of lexico-semantic processing to sentence comprehension, one might further speculate whether older adults of the present study used preferably EM over lexico-semantic processing for successful sentence reading. For older adults EM seems to foster sentence comprehension whereas for younger adults it appeared to be impedimental. The negative association of EM with sentence comprehension in younger adults may possibly mirror age-related differences in response strategies. Older adults tend to put more emphasis on accuracy than on speed (e.g., Forstmann et al., 2011), younger adults rather focus on speed than on accuracy (e.g., Froehlich et al., 2016). Thus, younger adults with low EM yet successful sentence comprehension, may not be as effective to form elaborate situation models and event representations, but due to fast guesses and possibly because of the marked WM contribution, sentence comprehension is still superior to that of older adults. To prevent participants from using different response strategies, one could, for example use simple reading tasks, that do not require timed responses.

Age-related differences in the contribution of EM to the subprocesses of reading were confined to orthographic processing. However, as EM processes were not reliably associated with any of the four subprocesses of reading in neither younger nor older adults, we cannot meaningfully interpret this difference between age groups. It may reflect age-related differences in matching processes of words with representations stored in long-term memory (Grainger & Jacobs, 1996), yet if this were the case, we then would most likely expect a similar effect for lexico-semantic processing (Hofmann & Jacobs, 2015; Hofmann et al., 2011). The absence of any associations of EM with the subprocesses of reading may again be rooted in the use of single word recognition tasks which do not require formation of elaborate event representations, apparently neither for younger nor for older adults.

5.4.3. Shortcomings and Conclusion

While the present study applied a multivariate approach to examine the impact of WM and EM on the subprocesses of reading and sentence comprehension in younger and older adults, it is somewhat limited. First, we employed a cross-sectional design which excludes the possibility to differentiate between cohort effects and true aging effects (e.g., Lindenberger, 2014). Second, due to experimental constraints and principle of parsimony, we did not consider variables, that have previously been identified to directly or indirectly affect reading performance in younger and older adults, for instance vocabulary, visual acuity as well as perceptual-attentional and/or inhibitory control processes. Furthermore, at least to our knowledge, this is the first study to investigate the contribution of WM and EM on the four subprocesses of reading at the single word level as a function of age. Therefore, additional multi-methodological research (e.g., functional magnetic resonance imaging, eye-tracking) is needed to extent our still limited understanding of the interplay between declining cognitive functions and relatively stable ones, such as reading in general. Finally, we suggest, that future studies should assess the ability of older and younger adults to construct surface, text-based and situation models because of their importance for sentence and text reading.

In conclusion, our study showed that, regardless of age WM and EM contribute to sentence comprehension and reading. However, whereas for older adults both memory functions seem to promote successful sentence reading, for younger readers a different result pattern emerged with a supporting role of WM and an opposing one of EM. Regarding older adults, we interpret these findings to be related to possible compensational mechanisms due to age-related decline in memory functions or to be linked to selection processes of choosing an optimal processing route. Findings concerning the younger group were ascribed to age-related advantages in memory functions, especially in WM and age-related differences in response strategies. Yet, little is known about the contribution of WM and age on the construction of situation models, so we strongly propose this topic for future research to cast further light on our findings. EM appears to have no impact on the subprocesses of reading, that is, when they are operationalized through single word recognition tasks. The specific contribution of WM to the subprocesses of reading seems to be more ambiguous, at least older adults tend to recruit WM processes to successfully perform within all four subprocesses. Again, we advocate for further research. Studies investigating age-related differences in structural and functional brain correlates associated with memory functions and reading in younger and older adults may help to clarify whether indeed mechanisms such as compensation, selection or rather dedifferentiation (e.g., Li et al., 2001; Lindenberger, 2014) account for our results. Apart from neuroimaging methods, future research should also focus on natural reading environments for which older adults may be less disadvantaged than in laboratory settings and speeded decision tasks.

6. General Discussion

The aim of this dissertational work was to investigate cognitive and neural mechanisms underlying basic subprocesses of visual word recognition and reading in younger and older adults. For this purpose, I reviewed existing literature and conducted three empirical studies. I compared younger (21 – 40 years) to older adults (60 – 86 years) using either hierarchical diffusion modeling (study 2), fMRI (study 3) or structural equation modeling (study 4) to address the following four major research questions.

The initial research question of this work centered on summarizing previous findings on age-related differences with respect to central measures of single word recognition. Based on these results, the next research question dealt with the impact of age and interindividual differences in reading ability on the four basic subprocesses of single word recognition and reading. The findings led to the third research question which revolved around possible age-related differences in neural correlates associated with typical reading-related brain regions, as well as around age-related differences in brain activation patterns outside these regions. Finally, the fourth main research question focused on the influence of cognitive functions supporting successful word recognition and reading. More specifically, I investigated effects of WM and EM on the subprocesses of reading and sentence comprehension in younger and older adults.

6.1. Age-related Differences on Central Measures of Single Word Recognition

The results of the first study of this dissertational work pointed towards differential age-related effects with respect to word frequency, word length and orthographic neighborhood density/frequency. The vast majority of the reviewed studies reported frequency effects for both younger and older adults, yet an absence of a reliable interaction between frequency and age. Neither age-related differences in reading proficiency, in years of formal education, nor the use of objective or subjective frequency measures seemed to account for this result pattern (e.g., Allen et al., 1991, 2004; Bowles & Poon, 1981; Caza et al., 2005; Frederiksen, 1978; Tainturier et al., 1992) leading us to conclude that orthographic processing is preserved across the lifespan. Our assumptions are supported by studies, that either found no reliable association between word frequency and age (Cohen-Shikora & Balota, 2016) or reported age-equivalent speed of information uptake in lexical decision (Ratcliff et al., 2004c). Additionally, results from studies 2 and 3 of the present work (*cf.* chapters 2 and 3; sections *6.2. The Impact of Age and Interindividual Reading Ability on the Subprocesses of Reading* and *6.3 Neural Correlates of Single Word Recognition in Younger and Older Adults*) seem likewise to confirm a life-long stability in orthographic processing.

In contrast to word frequency effects, results concerning age-related differences in word length effects were more ambiguous. Based on the reviewed studies, effects of word length seemed to be more pronounced in older adults as reported in four of six studies. According to the CDP++ model (*cf.* section *1.2.1. Computational models of reading*), word length effects point towards a serial sublexical reading strategy, its size reflecting the engagement of sublexical processing strategies (e.g., Perry et al., 2007, 2010). Thus, increased word length effects in older compared to younger adults would imply sublexical processing to be affected by age. However, as both age groups show word length effects, especially for low frequency words, sublexical processing per se seems to be intact for both younger and older adults. Age-related differences in sublexical processing may therefore originate from processes other than the core process itself, for instance, age-related differences in WM or perceptional-attentional processes (*cf.* sections *6.3. Neural Correlates of Single Word Recognition in Younger and Older Adults* and *6.4. Contribution of Memory and Aging to Single Word Recognition and Reading*), as grapheme-phoneme conversion and subsequent assembly may especially draw on these resources. Age-related differences in brain activity associated with sublexical processing, especially in SMA and SMG may support this speculation (e.g., Cabeza et al., 2008; Hertrich et al., 2016; *cf.* chapter 4 and section *6.3. Neural Correlates of Single Word Recognition in Younger and Older Adults*). However, interpreting results regarding word length was generally challenging. One of the difficulties we faced was that the reported results were either based on simple mean RTs or had been adjusted using Brinley plots (e.g., Allen et al., 1993; Brinley, 1965). Before these adjustments, older adults in two studies showed age-equivalent effects of word length, which changed to increased word length effects after the application of Brinley plots. As this poses a universal problem when analyzing data from different age groups, more sophisticated methods should be applied (e.g., hierarchical diffusion modeling, *cf.* sections *1.2.2. Computational models of decision making*). Results from study 2 of this dissertational work implicate persisting age-related differences at the sublexical level (*cf.* chapter 3 and *6.2. The Impact of Age and Interindividual Reading Ability on the Subprocesses of Reading*).

According to the MROM, the orthographic lexicon is thought to consist of a network of connected word nodes. Neighborhood density is thought to have a facilitating effect on word recognition, as larger numbers of neighbors increase global lexical activity (σ) within that network, whereas neighborhood frequency is thought to have inhibitory effects because of the time it takes for the activation level of an individual word (μ) to reach the decision criterion (Grainger & Jacobs, 1996; *cf.* section *1.2.1. Computational models of reading*). The only two studies investigating age-related differences in the effects of orthographic neighborhood density and neighborhood frequency observed smaller facilitating effects of neighborhood density for older compared to younger adults (Balota et al., 2004) and no inhibitory effects of neighborhood frequency in older adults (Robert & Mathey, 2007). Accordingly, reduced facilitation of neighborhood density may indicate some form of “deficiency” in the overall activity (σ) within older adults’ orthographic lexicon. The absence of neighborhood frequency effects in older adults, on the other hand, would then most likely point towards age-related differences at initial activation levels of the word unit (μ). Even though, these conclusions may be a first proposal towards age-related differences in brain activation patterns associated with orthographic processing (*cf.* chapter 3 and section *6.2. The Impact of Age and Interindividual Reading Ability on the Subprocesses of Reading*), one has to point out that results regarding orthographic neighborhood effects are based on two studies only. Additionally, although age-related differences seem to exist at the neural level (*cf.* chapter 4 and section *6.3. Neural Correlates of Single Word Recognition in Younger and Older Adults*), the vast majority of studies implicate no age-related differences in orthographic processing at the behavioral level (e.g., Allen et al., 1991, 2004; Bowles & Poon, 1981; Caza et al., 2005; Cohen-Shikora & Balota, 2016; Stadtlander, 1995; Tainturier et al., 1989; Taler & Jarema, 2007; *cf.* chapters 3 and 4).

6.2. The Impact of Age and Interindividual Reading Ability on the Subprocesses of Reading

A further main finding of this dissertational work concerned the effects of age and individual reading ability on sublexical, orthographic, phonological and lexico-semantic processing (*cf.* chapter 3). Study 2 was, to our knowledge, the first study to investigate all four subprocesses of reading within one very large sample using a hierarchical diffusion modeling approach (*cf.* section *1.2.2. Computational models of decision making*). With older adults showing consistently larger parameter estimates for the decision threshold (a) than younger adults, our findings confirmed that older compared to younger adults tend to apply a more conservative decision criterion (e.g., Ratcliff et al., 2004c,d; Thapar et al., 2003), thus generally preferring accuracy over speed (Forstmann et al., 2011). This notion received further support when jointly examining accuracy rates, individual reading performance, as well as parameter estimates for the decision threshold (*a*) and the speed of information uptake (*v; cf.* chapter 3).

More important for the second research question, however, was the examination of age-related differences in the efficiency of the central subprocesses of reading, which is reflected by the speed of information uptake, i.e. by the drift rate (*v*). At the sublexical and phonological processing levels, younger adults outperformed older adults, yet high-performing older adults in turn outperformed low-performing older adults. Our results thus replicated previous results (e.g., Allen et al., 1991, 1993; Guttentag & Madden, 1987; Thapar et al., 2003) and confirmed conclusions drawn in study 1 (*cf.* chapter 2 and section *6.1. Age-related Differences on Central Measures of Single Word Recognition*) about age-related disadvantages in sublexical processing. By using hierarchical diffusion modeling, we found evidence that these disadvantages may originate not only from age-related differences in sublexical processing per se but also (as previously suggested) from age-related differences in more basal processes such as stimulus encoding (e.g., Aberson & Bouwhuis, 1997; Allen et al., 1991), indicated by the larger estimates for non-decision time (*t*) in older than in younger adults. Noticeably, low-performing older adults who were classified according to their performance in a sentence comprehension task exhibited the smallest parameter estimates (*v*) already at the most fundamental stage of visual word recognition, which deals with efficient grapheme-phoneme-conversion and/or the formation of meaningful letter combinations (e.g., Coltheart et al., 2001; Grainger & Jacobs, 1996; Grainger & Ziegler, 2008). Although these processes may prevail on the phonological processing level, thus accounting for the observed results, successful phonological processing additionally involves whole word recognition (e.g., Coltheart et al., 2001; Taylor et al., 2012), which in turn may depend on the activation level of connected units (*cf.* MROM-p; Jacobs et al., 1998). Therefore, it was speculated that activation mechanisms may be affected by age. Results from study 3 (*cf.* chapter 4 and section 6.3. *Neural Correlates of Single Word Recognition in Younger and Older Adults*) support the notion of age-related differences at sublexical and phonological processing stages with phonological processing being affected more strongly.

At the orthographic and lexico-semantic processing levels, high-performing older adults obtained larger drift rates (v) than younger adults. Low-performing older adults were slowest in information uptake. These results illustrate two major points. First, they clearly demonstrate the need to consider the greater heterogeneity in cognitive performance in older adults (e.g., Lindenberger, 2014) as we had done in this study by differentiating between high- and low-performing older participants. Treating older adults as a homogeneous group may mask subtle but important effects. For instance, previous studies using hierarchical diffusion modeling to investigate age-related differences in orthographic and lexico-semantic processing reported age-equivalent speed of information uptake for younger and older adults (Ratcliff et al., 2004c; Spaniol et al., 2006) whereas we observed an age-related increase for high-performing older adults as well as an age-related decrease for low-performing older adults. Collapsing the two older groups into one and consequently comparing them to younger adults replicated findings for orthographic processing. In lexico-semantic processing however, older adults showed now smaller drift rates than did younger adults (see Appendix B.2 for detailed analyses as well as Figures B.1.1 and B.1.2). Secondly, the results offer two interesting perspectives: One can either consider factors, that enable older adults to process orthographic and lexico-semantic information at a youth-like and even superior level or one can hypothesize on mechanisms causing performance of low-performing older adults to decline. In the former case, life-long experience with written words and text may give older adults a natural advantage over younger ones (*cf.* Verhaeghen, 2003; Cohen-Shikora & Balota, 2016), however, it does not explain the differences within the older group. Within the framework of the MROM/AROM, high-performing older adults may have formed not only stronger connections between word units, allowing for a more efficient global spreading of activation, but may also have a higher initial lexical activation. In contrast, low-performing older adults possibly rely on a less extensive orthographic/semantic lexicon in addition to inefficient processing strategies. For instance, low performing readers in general tend to engage more in phonological recoding strategies than in orthographic ones (Jobard et al., 2011; *cf.* chapter 4 and section *6.3. Neural Correlates of Single Word Recognition in Younger and Older Adults*). Furthermore, cognitive processes supporting successful reading may also have contributed to performance differences observed in the present study (*cf.* section *1.4. Memory Processes in Reading and Aging*). However, we did not obtain any direct measures to follow up on that hypothesis.

6.3. Neural Correlates of Single Word Recognition in Younger and Older Adults

Comparing the neural correlates of the subprocesses of reading in healthy younger and older adults yielded three major findings. Firstly, we identified a set of reading-related brain regions (*cf.* section *1.3.1. Neural correlates of reading*), that seem to be active during sublexical, orthographic, phonological and lexico-semantic processing regardless of age. Secondly, age-related differences were observed for brain regions typically associated with the component processes of reading, with relatively distinct result patterns for each of the subprocesses. Thirdly, older adults showed an increased BOLD signal within neural circuits predominantly linked to memory operations, attentional processes as well as executive functioning and that have been associated with the DMN (*cf.* chapter 4).

During sublexical, orthographic, phonological and lexico-semantic processing, brain regions, that were jointly recruited by both younger and older adults consisted exclusively of brain regions, that are typically engaged during these processing steps. More importantly, with the exception of the SPG during sublexical processing, commonly activated brain regions in both age groups were identical to those found for younger adults (*cf.* Appendix, Table C.3). In detail and according to expectations, younger and older adults recruited the left inferior occipital and vOT regions in sublexical and orthographic processing. During phonological and lexico-semantic processing, we additionally observed left inferior parietal and prefrontal activation for both age groups (e.g., Braun et al., 2015; Cavalli et al., 2016; Glezer et al., 2016; Jobard et al., 2003; McNorgan et al., 2015; Price, 2012; Schurz et al., 2014; Welcome & Joanisse, 2012; *cf.* Table 4.2 and Figure 4.1). The mutual recruitment of these neural circuits as well as the age-equivalent performance in terms of accuracy, led us to conclude, that core processes of reading are well preserved across the lifespan.

However, despite the perseveration of reading-related processing mechanisms, age-related differences were identified in brain regions specifically linked to the subprocesses of reading as well as to the cognitive functions that support them. Concerning age-related differences within reading circuits, older adults showed an increase in BOLD signal for the right SMA and SMG during sublexical processing. While the role of the SMA has been ascribed to various control mechanisms during speech and language operations (Hertrich et al., 2016), the SMG has been implicated to be of importance for bottom-up attentional processes (Cabeza et al., 2008). Consequently, the age-related differences in these brain regions may mirror an increased effort of older adults to resolve sublexical processing demands, possibly related to stimulus encoding difficulties (*cf.* Allen et al., 1991; Guttentag & Madden, 1987; chapter 2 and chapter 3).

During orthographic processing older compared to younger adults showed increased activation within right inferior occipital and vOT regions as well as in left inferior parietal regions (SMG, ANG). The latter are associated with grapheme-phoneme-conversion (e.g., Jobard et al., 2003; Joubert et al., 2004), yet in the lexical decision task of our study, letter by letter encoding did not allow to decide whether the presented word or pseudohomophone was spelled correctly. Based on these results, we hypothesized older adults to engage left inferior parietal regions due to either age-related declines in working memory (as readers with lower WM capacity tend to recruit phonology-based reading circuits; *cf.* Jobard et al., 2011) or because of an age-related disadvantage in inhibiting activation of grapheme-phoneme conversion. Our results only partly support the claim of Gold et al. (2009), that lexical processing in older adults relies to a greater extent on higher-level linguistic processes: The absence of an age-related effect within left vOT regions may back this assumption, however, the lack of any age-related differences within prefrontal and frontal regions contests this conclusion. Moreover, the right hemispheric recruitment of the FG may in fact account for the age-equivalent performance of older adults.

Pronounced age-related differences were also observed at the phonological processing level, especially in bilateral recruitment (cerebellum, ANG, STG, MTG, PRG) as well as in the left ITG, FG and right MFG. As the phonological decision task was clearly more challenging than the other three decision tasks (in terms of accuracy rates) this massive increase in brain activation in older adults may reflect augmented processing requirements due to an increase in task demands (*cf.* Cabeza & Dennis, 2013). More importantly, similar to orthographic processing, an age-related disadvantage in neural adaptation was evident in older adults. Although, they engaged ANG and SMG as would be expected in phonological decision, older compared to younger adults also demonstrated greater involvement of left ventral temporal regions (FG, ITG), which are usually associated with orthographic processing. However, neither pseudohomophones nor pseudowords correspond to entries in a mental lexicon (e.g., Grainger & Jacobs, 1996; Perry et al., 2007, 2010). These findings would correspond to a proposal made by Robert & Mathey (2007) who interpreted the absence orthographic neighborhood frequency effects in older adults as a decline in both lexical inhibition and activation (*cf.* chapter 2 and section *6.1 Age-related Differences on Central Measures of Single Word Recognition*).

At the lexico-semantic processing stage, age-related differences were limited to the left SMA, bilateral MFG and the right IFG (opercular part). Apparently, lexico-semantic processing is well preserved across the lifespan (*cf.* Cho et al., 2012; Daselaar et al., 2003; Dennis et al. 2007; Spaniol et al., 2006; Wierenga et al., 2008; chapter 2), especially during early processing steps (i.e., inferior occipital and ventral temporal regions). Superior performance of older compared to younger adults in terms of accuracy may have stemmed from the greater engagement of the bilateral MFG, which has been reliably linked to semantic retrieval processes (e.g., McNorgan et al., 2015; Welcome & Joanisse, 2012). Moreover, we speculated about a pronounced involvement of executive functions in older adults due to their increased BOLD signal in the right IFG. Activation within this right brain region during semantic decision has previously been associated with executive functioning (Vigneau et al., 2009). Age-related differences within all three main components of the PFC (i.e., IFG, MFG, SFG), which has systematically been linked to working and episodic memory, attention, executive functions and inhibition (e.g., Cabeza et al., 2004; Dennis et al., 2007; Grady, 2012; Laird et al., 2011; Lindenberger et al., 2013; Reuter-Lorenz et al., 2000; Sugiura, 2016) further promotes the notion, that older adults may have relied on these supporting cognitive functions during lexico-semantic processing.

Brain regions outside reading-related circuits, that demonstrated increased activation in older compared to younger adults were mainly confined to the bilateral cingulate cortex (sublexical, orthographic, phonological processing), the bilateral precuneus (orthographic, phonological processing) and the bilateral SFG (orthographic, phonological and lexico-semantic processing). As the latter has been identified to be a key region within the working memory network (Boisgueheneuc et al., 2006) and a bilateral dorsal attention network (Corbetta et al., 2008; Fox et al., 2006) the engagement of the SFG may reflect pronounced recruitment of these resources during orthographic, phonological and lexico-semantic processing. Similarly, age-related differences in the involvement of the precuneus, which has been linked to successful EM retrieval processes (e.g., Cavanna & Trimble, 2006; Lundstrom et al., 2005;) may point towards greater contribution of EM processes in older adults during orthographic and phonological processing. In fact, study 4 identified age-related differences in the influence of EM on orthographic processing (*cf.* section 6.4. *Contribution of Memory and Aging to Single Word Recognition and Reading*). However, most noticeable are the age-related differences outside reading-related circuits when we consider them in concert. The posterior cingulate, the precuneus as well as the SFG have been identified to be functionally linked and to be part of the DMN (Buckner et al., 2008; Mevel et al., 2011; Raichle et al., 2001). The DMN is said to be active during rest. Its activity declines with age, yet interpretations of this age-related decline are still subject to debate (e.g., Maillet & Schacter, 2016). One proposal relates the age-related decrease in activity at rest to compensation in terms of increased activation during active task performance (*cf.* Damoiseaux et al., 2007). An alternative one links it to an increasing inability of older adults to switch to active task demands (Mevel et al., 2011). Given the results and the complexity of this topic, it would be interesting to further investigate the significance of resting state activation on word recognition and reading in younger and older adults.

6.4. Contribution of Memory and Aging to Single Word Recognition and Reading

Findings concerning the fourth major research question of the present work indicated WM and EM to influence sentence comprehension in both younger and older adults with the degree and direction of the contribution differing as a function of age. At the level of the four central subprocess, results were more ambiguous. To our knowledge, this was the first study to investigate the impact of EM on sentence comprehension not only in older but also in younger adults.

In accordance with previous research, WM was found to influence sentence comprehension (*cf.* Borella et al., 2011; Zwaan, 2015) and to account for age-related differences in sentence comprehension (e.g., Borella et al., 2011; DeDe et al., 2004; Van der Linden et al., 1999 but see Kwong See & Ryan, 1995; section *1.4.1. Memory functions and aging*). The positive associations we observed indicated a beneficial role of WM for sentence comprehension in both age groups. The considerably stronger recruitment of WM processes in younger adults led us to conclude, that they relied more heavily on WM operations while performing the sentence comprehension task than older adults, possibly as a result of age-related advantages in available WM resources (e.g., Craik, 1994; Hedden & Gabrieli, 2004; Lindenberger et al., 2008). Generally, we assume younger and older adults to similarly create situation models during sentence reading because of the reliable association of WM and sentence comprehension observed for both age groups. However, our sentence comprehension task required participants to rapidly update their situation model in case of no-responses, which constituted violations of semantic expectations. With plenty of WM resources available, younger adults may have had an advantage over older adults in flexibly adapting their situation models, which resulted in their superior task performance. Moreover, sentences became syntactically more complex over the course of the experiment, demanding additional WM operations.

Results concerning the association of WM with the subprocesses of reading, which we assessed at the single word level, were more ambiguous. We neither observed age-related differences nor any effects of WM for younger adults. In contrast, WM contributed significantly to all four subprocesses of reading in the older age group. This result pattern makes it hard to draw any conclusions on behalf of the influence of WM on these component processes. The absence of any reliable contributions in younger adults may mirror a genuine effect as processing single words does not require to integrate preceding with subsequent text and build elaborate situation models. On the other hand, WM operations are also required at the single word level: For instance, for grapheme-phoneme conversion and assembly of letters into meaningful units (sublexical and phonological processing; e.g., Coltheart et al., 2001; Perry et al., 2007, 2010) as well as for matching processes with the mental lexicon (orthographic and lexico-semantic processing; e.g., Grainger & Jacobs, 1996; Hofmann et al., 2011; Perry et al., 2007). Relating these findings to results of study 3, a more coherent picture seems to emerge. While we found no active brain regions associated with memory processes in younger adults, older adults recruited circuits usually linked to WM and EM operations (*cf.* chapter 4 and section *6.3. Neural Correlates of Single Word Recognition in Younger and Older Adults*). Apparently, processing words requires older adults to engage in enhanced WM operations.

Similar to WM, EM contributed positively to sentence comprehension in older adults. Given the close relationship of both memory functions (e.g., Head et al., 2008; Hertzog et al., 2003; Rajah & D'Esposito, 2005) we hypothesized EM and WM to work in concert to possibly compensate for age-related decline within these functions. As readers relate their knowledge as well as their personal experiences to the events and situations described in the narrative (Bower & Morrow, 1990; Jacobs & Willems, 2017; Kintsch & van Dijk, 1978; Zwaan, 2015) we assumed EM to influence sentence comprehension regardless of age. Accordingly, EM was found to also contribute significantly to sentence comprehension in younger adults, however, with an opposing direction to that of older adults. This negative association may reflect age-related differences in response strategies with younger adults focusing rather on speed than on accuracy (Forstmann et al., 2011). Given the marked WM contribution to sentence comprehension in the younger age group, younger adults may not necessarily need to form elaborate situation models and event representations before executing speeded responses. Therefore, younger adults with low EM scores may still show better performance in sentence comprehension than do older adults.

All four subprocesses of reading were found to significantly contribute to sentence comprehension of older adults and with the exception of phonological processing to sentence comprehension of younger adults. Interestingly, for both age groups orthographic and lexico-semantic processing seem to support sentence comprehension while the opposite was found for sublexical and phonological processing. These results back the assumption that basic subprocesses in younger and older adults operate in a similar way (*cf.* chapter 4 and section *6.3. Neural Correlates of Single Word Recognition in Younger and Older Adults*). At the same time, they promote the notion, that skilled reading relies to a greater extent on orthographic and lexico-semantic processes (e.g., Jobard et al., 2011). Moreover, our findings emphasize the importance of all four different subprocesses for elaborate reading. The significant contribution of sublexical processing to sentence comprehension in older adults speaks against a strong interpretation of the unitization hypothesis (*cf.* Balota & Spieler, 2000), which assumes a decrease in the influence of sublexical factors with increasing age. Age-related differences in the contribution of the subprocesses to sentence comprehension was limited to lexico-semantic processing giving further evidence for a relative stability of reading performance across the life-span (e.g., Cohen-Shikora & Balota, 2016; de Beni et al., 2007; *cf.* chapter 2, 3, 4 and sections *6.1. Age-related Differences on Central Measures of Single Word Recognition*, *6.2. The Impact of Age and Interindividual Reading Ability on the Subprocesses of Reading* and *6.3. Neural Correlates of Single Word Recognition in Younger and Older Adults*). Lexico-semantic processing was found to contribute less to sentence comprehension in older adults, possibly because this age group utilized EM in contrast to younger adults.

6.5. Limitations and Future Directions

This dissertational project provided new insights into the processing stream of written words in healthy younger and older adults. Especially with respect to older participants, the nature of the present work was highly exploratory. Therefore, for the sake of generalization and reliability, it is highly recommended to replicate and extend our findings. Particularly in the field of neuroscience, reproducing effects avoids statistically spurious results (*cf.* Button et al., 2013). Studies 2 to 4 in this dissertation compared groups of younger and older adults, thus using a cross-sectional design. Given the efficiency of this design and the time frame of the dissertational project, this is a feasible approach. However, in contrast to longitudinal studies, cross-sectional designs bear the risk of confusing cohort with true aging effects and tend to overestimate the outcome (e.g., Hedden & Gabrieli, 2004; Lindenberger, 2014; MacDonald & Stawski, 2016; Rönnlund et al., 2005). Additionally, when assessing neural correlates of older and younger adults one has to consider that aging leads to changes in the cerebral vasculature and it is not yet known how these alterations affect the BOLD signal (D'Esposito et al., 2009). Moreover, aging brings changes in brain anatomy, neurochemistry and structural connectivity which impacts the cognitive performance of older adults (e.g., Cabeza & Dennis, 2013; Grady, 2012; Lindenberger et al., 2013). Future research regarding age-related differences in reading and its supporting cognitive functions should clearly address these issues to expand our understanding of these complex interrelations.

In study 2, we showed the necessity to consider the increasing behavioral heterogeneity observed in older adults (e.g., Baltes & Lindenberger, 1997; De Frias et al., 2007; Lindenberger, 2014; Nagel et al., 2011), however, further research is needed to investigate the contribution of the genetic make-up on this heterogeneity (*cf.* Lindenberger et al., 2008), not only in behavioral but also in neural terms. Imaging genetics may be a suitable approach to do so (e.g., De Quervain & Papassotiropoulos, 2006). Yet, investigating the efficiency of neural reading networks and their underlying biological factors should not be limited to older adults but needs to be extended to younger participants, as the influence of genes on the circuits of reading has not yet been studied.

Results from study 3 showed an increased activation in older compared to younger adults in circuits primarily linked to cognitive processes such as WM, EM and executive functioning. It is important to point out, that we did not directly assess these cognitive operations but rather used reverse inference (Hutzler, 2014; Poldrack, 2011) to draw conclusions about processes contributing to reading performance in older adults. Future studies should therefore, not only measure reading related performances inside and outside the MRT scanner but also obtain EM and WM measures to infer about the influences of these memory function in reading. Furthermore, it was beyond the scope of study 3 to relate the findings to underlying mechanisms of neurocognitive aging, such as for instance, maintenance (e.g., Lindenberger, 2014), compensation (Berlingeri et al., 2013; Reuter-Lorenz & Cappel, 2008), selection (e.g., Lindenberger et al., 2014) or dedifferentiation (Carp et al., 2011; Li et al., 2001): Firstly, our block design did not allow for correlating behavioral performance to trial-wise hemodynamic activity and secondly, the study focused on age-related differences in the subprocesses of reading. It is definitely a challenge for future studies to address this topic as these theories depend, amongst others, on the assessment of the behavioral performance of older compared to younger adults. However, as we described in study 2, there are several different ways to do so (e.g., accuracy, RTs, Brinley plots, speed of information uptake *v,* etc.).

Based on results of study 3, study 4 was designed to directly investigate the contribution of WM and EM on the subprocesses of reading and sentence comprehension in younger and older adults using a structural equation approach. Due to experimental constraints and the principle of parsimony (Raykov & Marcoulides, 1999), various factors that had been previously identified to possibly contribute to age-related differences in reading could not be considered (e.g., visual acuity, vocabulary, inhibitory control). Furthermore, study 4 replicated findings that identified WM to account for age-related differences in sentence and text comprehension (*cf.* Borella et al., 2011; DeDe et al., 2004; Van Der Linden et al., 1999 but see Kwong See & Ryan, 1995). However, the influence of a declining WM and particularly EM in older adults on the construction of effective situation models has not yet been resolved and should be addressed in future research.

A more general issue of this work concerns the language and the tasks we used in study 2 to 4 to assess sublexical, orthographic, phonological and lexico-semantic processing. Younger and older adults of the present study were German native speakers in contrast to the vast majority of studies testing English speaking participants. English and German differ in terms of the depths of their orthographies. While in English grapheme-phoneme mapping is rather inconsistent, in German the mapping of single letters to sound is relatively regular (Ziegler & Goswami, 2005, 2006). As a result, reading strategies between these orthographies differ with German readers engaging more in sublexical and phonological processing than English ones (Ziegler et al., 2001b). As age-related differences in the present work were particularly pronounced for phonological processing, it is of interest to further investigate whether this is a genuine age-related phenomenon or rather limited to transparent orthographies.

We explicitly used tasks employing single word recognition, as it is foundational to fluent reading (Grainger & Jacobs, 1996; Jacobs, 2001; Jacobs & Ziegler, 2015). Elaborate computational models of (word) reading have been developed to capture the complexity of the reading process. A future challenge for these models is to test whether they can also account for reading behavior in older adults. For instance, results from study 2 and 3 led us to speculate about an age-related disadvantage in initial activation levels or within the spreading of activation in (low-performing) older adults. Combining empirical research, such as resting state and/or connectivity analyses with simulation modeling (e.g., by means of the AROM; Hofmann et al., 2011; Hofmann & Jacobs, 2014) will foster further understanding of mechanisms involved. Moreover, by using speeded decision tasks, we might have involuntarily put older adults at a disadvantage. Creating a more natural reading environment may avoid this pitfall in the future. In line with this reasoning, we propose to eventually graduate from single word recognition towards sentence (*cf.* study 4) and text reading to develop or expand neurocognitive and computational models of word reading. Natural settings of text reading not only increase ecological validity, they also allow for studying depth of immersion and (neurocognitive) literary reception in older readers. Most importantly, as general reading ability of older adults seems to be fairly stable across the lifespan, we want to draw attention to future research on factors that enable older adults to maintain high proficiency levels in reading (e.g., Curzietti et al., 2017; Demoulin & Kolinsky, 2016; Gaál et al., 2017) despite the age-related decline of other cognitive functions supporting sublexical, orthographic, phonological and lexico-semantic processing.

6.6. Conclusion

This dissertational work provided new insights into cognitive and neural mechanisms underlying central subprocesses of single word recognition and reading in younger and older adults. For the first time, we systematically studied similarities as well as age-related differences in sublexical, orthographic, phonological and lexico-semantic processing, both at the behavioral as well as neural level. Furthermore, we investigated the impact of cognitive functions supporting these subprocesses. One major and highly promising finding constitutes the relative stability of reading processes across the lifespan. Especially, orthographic and lexico-semantic processing (which might be most similar to natural reading) seem to be well preserved regardless whether behavioral performance was assessed by means of speed of information uptake or in terms of accuracy. In addition, brain activation patterns showed younger and older adults to recruit a similar set of brain regions associated with the central subprocesses of reading. Accordingly, sublexical, orthographic and lexico-semantic processing were found to contribute to successful sentence comprehension in both younger and older adults. The second major finding revolved around age-related differences originating in the subprocesses of reading. Despite the profound similarities, older compared to younger adults were found to be more slowly in the speed of information uptake in sublexical and phonological processing. Particularly during phonological processing, older adults showed marked differences in neural activation compared to younger adults. However, these differences in neural activation patterns were not confined to phonological processing but we observed age-related differences within reading-related brain regions for all four subprocesses. Given the activation patterns of older adults during orthographic and phonological processing, it seems that they may have difficulties in neurally adapting to the optimal processing route, possibly because of disadvantages in mental operations related to inhibition or activation. Outside neural circuits typically associated with reading, older adults engaged particularly brain regions that have been linked to memory operations, executive functioning and attentional processes. These results support our third main finding. It concerns the influence of WM and EM on the subprocesses of reading and extends our findings to sentence comprehension, i.e., towards more natural reading. For the former we only found a supportive function of WM in older adults, for the latter we observed an influence of memory functions regardless of age. The beneficial effect of both memory functions on sentence comprehension for older adults may reflect compensational mechanisms due to age-related decline. At the same time, age-related differences in the degree of WM contribution and direction of EM influence may signal differences between younger and older adults in the construction and updating of situation models necessary for successful sentence comprehension.

To sum up, the present work constitutes a first step into the systematic research of age-related differences in basic subprocesses of single word recognition and reading and provides an enhanced understanding for the relative stability of the highly complex cognitive function of reading in the face of the age-related decline of another.

References

Aberson, D. H. A., & Bouwhuis, D. G. (1997). Silent reading as determined by age and visual acuity. *Journal of Research in Reading*, *20,* 184–204.

Abrams, L., & Farrell, M. T. (2011). Language processing in normal aging. In J. Guendouzi, F. Loncke, & M. J. Williams (Eds.), *The handbook of psycholinguistic and cognitive processes: Perspectives in communication disorders* (pp. 49–73). New York, NY: Psychology Press.

Allen, P. A., Madden, D. J., & Crozier, L. C. (1991). Adult age differences in letter-level and word-level processing. *Psychology and Aging, 6*, 261–271.

Allen, P. A., Madden, D. J., & Slane, S. (1995). Visual word encoding and the effect of adult age and word frequency. *Advances in Psychology*, *110*, 30–71.

Allen, P. A., Madden, D. J., Weber, T. A., & Groth, K. E. (1993). Influence of age and processing stage on visual word recognition. *Psychology and Aging, 8,* 274–282.

Allen, P. A., Murphy, M. D., Kaufman, M., Groth, K. E., & Begovic, A. (2004). Age differences in central (semantic) and peripheral processing: The importance of considering both response times and errors. *Journal of Gerontology: Psychological Sciences, 59 B,* 210–219.

Allen, P. A., Smith, A. F., Groth, K. E., Pickle, J. L., Grabbe, J. W., & Madden, D. J. (2002). Differential age effects for case and hue mixing in visual word recognition. *Psychology and Aging, 17*, 622–635.

Andrews, S. (1989). Frequency and neighborhood size effects on lexical access: Activation or search? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15,* 802–814.

Andrews, S. (1992). Frequency and neighborhood effects on lexical access: Lexical similarity or orthographic redundancy? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18*, 234–254.

Andrews, S. (1997). The effect of orthographic similarity on lexical retrieval: Resolving neighborhood conflicts. *Psychonomic Bulletin & Review, 4*, 439–461.

Armstrong, B. C., Watson, C. E., & Plaut, D. C. (2012). SOS! An algorithm and software for the stochastic optimization of stimuli. *Behavior Research Methods, 44*, 675–705.

Ashburner, J. (2007). A fast diffeomorphic image registration algorithm. *NeuroImage, 38*, 95–113.

Ashburner, J., & Friston, K. J. (2005). Unified segmentation. *NeuroImage, 26*, 839–851.

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language, 59*, 390–412.

Baayen, R. H., Piepenbrock, R., & van Rijn, H. (1993). *The CELEX Lexical Database* [CD-ROM]. Philadelphia: Linguistic Data Consortium.

Bach, S., Brandeis, D., Hofstetter, C., Martin, E., Richardson, U., & Brem, S. (2010). Early emergence of deviant frontal fMRI activity for phonological processes in poor beginning readers. *NeuroImage, 53*, 682–693.

Baciu, M., Boudiaf, N., Cousin, E., Perrone-Bertolotti, M., Pichat, C., Fournet, N., ... Krainik, A. (2016). Functional MRI evidence for the decline of word retrieval and generation during normal aging. *Age, 38*, 3.

Baddeley, A., Logie, R., Nimmo-Smith, I., & Brereton, N. (1985). Components of fluent reading. *Journal of Memory and Language, 24*, 119–131.

Balota, D. A., & Chumbley, J. I. (1984). Are lexical decisions a good measure of lexical access? The role of word frequency in the neglected decision stage. *Journal of Experimental Psychology. Human Perception and Performance, 10*, 340–357.

Balota, D. A., & Ferraro, F. R. (1996). Lexical, sublexical, and implicit memory processes in healthy young and healthy older adults and in individuals with dementia of the Alzheimer type. *Neuropsychology, 10*, 82–95.

Balota, D. A., Cortese, M. J., Sergent-Marshall, S. D., Spieler, D. H., & Yap, M. (2004). Visual word recognition of single-syllable words. *Journal of Experimental Psychology: General, 133*, 283–316.

Baltes, P. B., & Lindenberger, U. (1997). Emergence of a powerful connection between sensory and cognitive functions across the adult life span: A new window to the study of cognitive aging? *Psychology and Aging, 12*, 12–21.

Barr, D. J. (2013). Random effects structure for testing interactions in linear mixed-effects models. *Frontiers in Psychology, 4,* 328.

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: keep it maximal. *Journal of Memory and Language, 68,* 255–278.

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2014). lme4: Linear mixed-effects models using Eigen and S4. R package version 1.

Bergmann, J., & Wimmer, H. (2008). A dual-route perspective on poor reading in a regular orthography: evidence from phonological and orthographic lexical decisions. *Cognitive Neuropsychology, 25*, 653–676.

Berlingeri, M., Danelli, L., Bottini, G., Sberna, M., & Paulesu, E. (2013). Reassessing the HAROLD model: Is the hemispheric asymmetry reduction in older adults a special case of compensatory-related utilisation of neural circuits? *Experimental Brain Research, 224,* 393–410.

Bertram, L., Böckenhoff, A., Demuth, I., Düzel, S., Eckardt, R., Li, S. C., ... Steinhagen-Thiessen, E. (2013). Cohort profile: The Berlin Aging Study II (BASE-II). *International Journal of Epidemiology, 43*, 703–712.

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*, 2767–2796.

Bitan, T., Cheon, J., Lu, D., Burman, D. D., Gitelman, D. R., Mesulam, M. M., & Booth, J. R. (2007). Developmental changes in activation and effective connectivity in phonological processing. *NeuroImage, 38*, 564–575.

Boisgueheneuc, F. d., Levy, R., Volle, E., Seassau, M., Duffau, H., Kinkingnehun, S., ... Dubois, B. (2006). Functions of the left superior frontal gyrus in humans: A lesion study. *Brain, 129*, 3315–3328.

Bollen, K. A. (1989). A new incremental fit index for general structural equation models. *Sociological Methods & Research, 17*, 303–316.

Booth, J. R., Burman, D. D., Meyer, J. R., Gitelman, D. R., Parrish, T. B., & Mesulam, M. M. (2004). Development of brain mechanisms for processing orthographic and phonologic representations. *Journal of Cognitive Neuroscience, 16,* 1234–1249.

Borella, E., Ghisletta, P., & De Ribaupierre, A. (2011). Age differences in text processing: The role of working memory, inhibition, and processing speed. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences, 66B,* 311–320.

Boros, M., Anton, J.-L., Pech-Georgel, C., Grainger, J., Szwed, M., & Ziegler, J. C. (2016). Orthographic processing deficits in developmental dyslexia: Beyond the ventral visual stream. *NeuroImage 128*, 316–327.

Borowsky, R., & Besner, D. (1993). Visual word recognition: A multistage activation model. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 19,* 813–840.

Borowsky, R., Cummine, J., Owen, W. J., Friesen, C. K., Shih, F., & Sarty, G. E. (2006). FMRI of ventral and dorsal processing streams in basic reading processes: insular sensitivity to phonology. *Brain Topography, 18*, 233–239.

Bower, G., & Morrow, D. (1990). Mental models in narrative comprehension. *Science, 247*, 44–48.

Bowles, N. L., & Poon, L. W. (1981). The effect of age on speed of lexical access. *Experimental Aging Research, 7*, 417–425.

Braun, M., Hutzler, F., Münte, T. F., Rotte, M., Dambacher, M., Richlan, F., & Jacobs, A. M. (2015). The neural bases of the pseudohomophone effect: phonological constraints on lexico-semantic access in reading. *Neuroscience, 295,* 151–163.

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

Braun, M., Jacobs, A. M., Hahne, A., Ricker, B., Hofmann, M., & Hutzler, F. (2006). Model-generated lexical activity predicts graded ERP amplitudes in lexical decision. *Cognitive Brain Research, 107,* 431–439.

Brett, M., Anton, J. L., Valabregue, R., & Poline, J. B. (2002). Region of interest analysis using an SPM toolbox [abstract]. Presented at the 8th International Conference on Functional Mapping of the Human Brain, June 2–6, 2002, Sendai, Japan. *NeuroImage, 16*, 497.

Briesemeister, B. B., Hofmann, M. J., Tamm, S., Kuchinke, L., Braun, M., & Jacobs, A. M. (2009). The pseudohomophone effect: evidence for an orthography–phonology-conflict. *Neuroscience Letters, 455,* 124–128.

Brinley, J. F. (1965). Cognitive sets, speed and accuracy of performance in the elderly. In T. Welford & J. E. Birren (Eds.), *Behavior, Aging and the Nervous System* (pp.114–149). Springfield, IL: Charles C Thomas.

Broadbent, D. E. (1967). Word-frequency effect and response bias. *Psychological Review, 74*, 1–15.

Brown, T. A. (2006). *Confirmatory factor analysis for applied research.* New York, NY: Guilford Publications.

Brysbaert, M., Buchmeier, M., Conrad, M., Jacobs, A. M., Bölte, J., & Böhl, A. (2011). The word frequency effect: A review of recent developments and implications for the choice of frequency estimates in German. *Experimental Psychology, 58*, 412–424.

Buckner, R. L., Andrews-Hanna, J. R., & Schacter, D. L. (2008). The brain's default network. *Annals of the New York Academy of Sciences, 1124*, 1–38.

Burke, D. M., & Shafto, M. A. (2008). Language and aging. In F. I. M. Craik & T. A. Salthouse (Eds.), *The Handbook of Aging and Cognition* (pp. 373–443). New York, NY: Psychology Press.

Bush, A. L. H., Allen, P. A., Kaut, K. P., & Ogrocki, P. K. (2007). Infuence of mild cognitive impairment on visual word recognition. *Neuropsychology, Development, and Cognition. Section B, Aging, Neuropsychology and Cognition, 14*, 329–352.

Bush, G., & Shin, L. M. (2006). The Multi-Source Interference Task: an fMRI task that reliably activates the cingulo-frontal-parietal cognitive/attention network. *Nature Protocols, 1*, 308–313.

Button, K. S., Ioannidis, J. P. A., Mokrysz, C., Nosek, B. A., Flint, J., Robinson, E. S. J., & Munafò, M. R. (2013). Power failure: why small sample size undermines the reliability of neuroscience. *Nature Reviews Neuroscience 14*, 365–376.

Byrne, B. M. (2008). Testing for multigroup equivalence of a measuring instrument: A walk through the process. *Psicothema, 20*, 872–882.

Cabeza, R. (2002). Hemispheric asymmetry reduction in older adults: The HAROLD model. *Psychology and Aging, 17*, 85–100.

Cabeza, R., & Dennis, N. A. (2013). Frontal lobes and aging. In D. T. Stuss & R. T. Knight (Eds.), *Principles of frontal lobe function* (pp. 628–652). New York, NY: Oxford University Press.

Cabeza, R., Ciaramelli, E., Olson, I. R., & Moscovitch, M. (2008). The parietal cortex and episodic memory: an attentional account. *Nature Reviews Neuroscience, 9*, 613–625.

Cabeza, R., Daselaar, S. M., Dolcos, F., Prince, S. E., Budde, M., & Nyberg, L. (2004). Task-independent and task-specific age effects on brain activity during working memory, visual attention and episodic retrieval. *Cerebral Cortex, 14*, 364–375.

Carp, J., Park, J., Polk, T.A., Park, D.C. (2011). Age differences in neural distinctiveness revealed by multi-voxel pattern analysis. *NeuroImage, 56*, 736–743.

Carreiras, M., Perea, M., & Grainger, J. (1997). Effects of orthographic neighborhood in visual word recognition: cross-task comparisons. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 23,* 857–871.

Carretti, B., Borella, E., Cornoldi, C., & De Beni, R. (2009). Role of working memory in explaining the performance of individuals with specific reading comprehension difficulties: A meta-analysis. *Learning and Individual Differences, 19*, 246–251.

Cavalli, E., Cole, P., Badier, J. M., Zielinski, C., Chanoine, V., & Ziegler, J. C. (2016). Spatiotemporal dynamics of morphological processing in visual word recognition. *Journal of Cognitive Neuroscience, 28,* 1228–1242.

Cavanna, A. E., & Trimble, M. R. (2006). The precuneus: a review of its functional anatomy and behavioural correlates. *Brain, 129*, 564–583.

Caza, N., & Moscovitch, M. (2005). Effects of cumulative frequency, but not of frequency trajectory, in lexical decision times of older adults and patients with Alzheimer's disease. *Journal of Memory and Language, 53*, 456–471.

Cheung, G. W., & Rensvold, R. B. (2002). Evaluating goodness-of-fit indexes for testing measurement invariance. *Structural Equation Modeling, 9*, 233–255.

Cho, Y. W., Song, H. J., Lee, J. J., Lee, J. H., Lee, H. J., Yi, S. D., … Chang, Y. (2012). Age-related differences in the brain areas outside the classical language areas among adults using category decision task. *Brain and Language, 120*, 372–380.

Cohen-Shikora, E. R., & Balota, D. A. (2016). Visual word recognition across the adult lifespan. *Psychology and Aging, 31,* 488–502.

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

Coltheart, M., Curtis, B., Atkins, P., & Haller, M. (1993). Models of reading aloud: Dual-route and parallel-distributed-processing approaches. *Psychological Review, 100*, 589–608.

Coltheart, M., Davelaar E., Jonasson, J. T., & Besner, D. (1977). Access to the internal lexicon. In S. Dornic (Ed.), *Attention and Performance* (pp. 535–555). London, England: Academic Press.

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*, 204–256.

Corbetta, M., Patel, G., & Shulman, G. L. (2008). The reorienting system of the human brain: from environment to theory of mind. *Neuron, 58*, 306–324.

Craik, F. I. (1994). Memory changes in normal aging. *Current Directions in Psychological Science, 3,* 155–158.

Curzietti, M., Bonnefond, A., Staub, B., Vidailhet, P., & Doignon-Camus, N. (2017). The effects of age on visual expertise for print. *Brain and Language, 169*, 48–56.

D'Esposito, M., Jagust, W. J., & Gazzaley, A. (2009). Methodological and conceptual issues in the study of the aging brain. *Imaging the Aging Brain,* 11–26.

Daffner, K. R., Haring, A. E., Alperin, B. R., Zhuravleva, T. Y., Mott, K. K., & Holcomb, P. J. (2013). The impact of visual acuity on age-related differences in neural markers of early visual processing. *NeuroImage, 67*, 127–136.

Dambacher, M., Kliegl, R., Hofmann, M., & Jacobs, A. M. (2006). Frequency and predictability effects on event-related potentials during reading. *Brain Research, 1084,* 89–103.

Damoiseaux, J. S., Beckmann, C. F., Arigita, E. S., Barkhof, F., Scheltens, P., Stam, C. J., ... Rombouts, S. A. R. B. (2007). Reduced resting-state brain activity in the "default network" in normal aging. *Cerebral Cortex, 18*, 1856–1864.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior, 19*, 450–466.

Daneman, M., & Carpenter, P. A. (1983). Individual differences in integrating information between and within sentences. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 9*, 561–584.

Daneman, M., & Merikle, P. M. (1996). Working memory and language comprehension: A meta-analysis. *Psychonomic Bulletin & Review, 3*, 422–433.

Das, T., Padakannaya, P., Pugh, K. R., & Singh, N. C. (2011). Neuroimaging reveals dual routes to reading in simultaneous proficient readers of two orthographies. *NeuroImage, 54,* 1476–1487.

Daselaar, S., Veltman, D. J., Rombouts, S. A. R. B., Raaijmakers, J. G. W., & Jonker, C. (2003). Deep processing activates the medial temporal lobe in young but not in old adults. *Neurobiology of Aging, 24,* 1005–1011.

De Beni, R., Borella, E., & Carretti, B. (2007). Reading comprehension in aging: The role of working memory and metacomprehension. *Aging, Neuropsychology, and Cognition, 14*, 189–212.

De Frias, C. M., Lövdén, M., Lindenberger, U., & Nilsson, L. G. (2007). Revisiting the dedifferentiation hypothesis with longitudinal multi-cohort data. *Intelligence, 35*, 381–392.

De Quervain, D. J.-F., & Papassotiropoulos, A. (2006). Identification of a genetic cluster influencing memory performance and hippocampal activity in humans. *Proceedings of the National Academy of Sciences of the United States of America, 103*, 4270–4274.

DeDe, G., Caplan, D., Kemtes, K., & Waters, G. (2004). The relationship between age, verbal working memory, and language comprehension. *Psychology and Aging, 19,* 601.

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

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.

Demoulin, C. & Kolinsky, R. (2016). Does learning to read shape verbal working memory? *Psychonomic Bulletin and Review, 23,* 703–722.

Dennis, N. A., & Cabeza, R. (2008). Neuroimaging of healthy cognitive aging. *The Handbook of Aging and Cognition, 3*, 1–54.

Dennis, N. A., Daselaar, S., & Cabeza, R. (2007). Effects of aging on transient and sustained successful memory encoding activity. *Neurobiology of Aging, 28*, 1749–1758.

Dimigen, O., Sommer, W., Hohlfeld, A., Jacobs, A. M., & Kliegl, R. (2011). Coregistration of eye movements and EEG in natural reading: Analyses and review. *Journal of Experimental Psychology: General, 140*, 552–572.

Dorot, D., & Mathey, S. (2010). Visual word recognition in young and older adults: A study of cohort effects for lexical variables. *Revue européenne de psychologie appliquée/European Review of Applied Psychology, 60*, 163–172.

Düzel, S., Voelkle, M. C., Düzel, E., Gerstorf, D., Drewelies, J., Steinhagen-Thiessen, E., ... Lindenberger, U. (2016). The Subjective Health Horizon Questionnaire (SHH-Q): Assessing future time perspectives for facets of an active lifestyle. *Gerontology, 62*, 345–353.

Facoetti, A., Zorzi, M., Cestnick, L., Lorusso, M. L., Molteni, M., Paganoni, P., …Mascetti, G. G. (2006). The relationship between visuo-spatial attention and nonword reading in developmental dyslexia. *Cognitive Neuropsychology, 23,* 841–855.

Forster, K. I., & Shen, D. (1996). No enemies in the neighborhood: absence of inhibitory neighborhood effects in lexical decision and semantic categorization. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22,* 696–713.

Forstmann, B. U., Tittgemeyer, M., Wagenmakers, E. J., Derrfuss, J., Imperati, D., & Brown, S. (2011). The speed-accuracy tradeoff in the elderly brain: a structural model-based approach. *Journal of Neuroscience, 31,* 17242–17249.

Fox, J., & Weisberg, S. (2011). *An R Companion to Applied Regression.* Thousand Oaks, CA: Sage.

Fox, M. D., Corbetta, M., Snyder, A. Z., Vincent, J. L., & Raichle, M. E. (2006). Spontaneous neuronal activity distinguishes human dorsal and ventral attention systems. *Proceedings of the National Academy of Sciences, 103*, 10046–10051.

Frederiksen, J. R. (1978). Assessment of lexical decoding and lexical skills and their relation to reading profciency. In A. M. Lesgold, J. W. Pellegrino, S. D. Fokkema & R. Glaser (Eds.), *Cognitive Psychology and Instruction* (pp. 153–169). New York, NY: Plenum.

Frick, A., Wahlin, T. B. R., Pachana, N. A., & Byrne, G. J. (2011). Relationships between the National Adult Reading Test and memory. *Neuropsychology, 25*, 397.

Friston, K. J., Glaser, D. E., Henson, R. N., Kiebel, S., Phillips, C., & Ashburner, J. (2002). Classical and Bayesian inference in neuroimaging: applications. *Neuroimage, 16*, 484–512.

Frith, U., Wimmer, H., & Landerl, K. (1998). Differences in phonological recoding in German- and English-speaking children. *Scientific Studies of Reading, 2*, 31–54.

Froehlich, E., & Jacobs, A. M. (2016). Verändert sich Lesen im Alter? Alterseffekte in der visuellen Worterkennung [Does reading change with age? A review of aging effects on visual word recognition]. *Lernen und Lernstörungen, 5*, 95–109.

Froehlich, E., Liebig, J., Ziegler, J. C., Braun, M., Lindenberger, U., Heekeren, H. R., Jacobs, A. M. (2016). Drifting through Basic Subprocesses of Reading: A Hierarchical Diffusion Model Analysis of Age Effects on Visual Word Recognition. *Frontiers in Psychology, 7*, 1863.

Gaál, Z. A., Bodnár, F., & Czigler, I. (2017). When Elderly Outperform Young Adults—Integration in Vision Revealed by the Visual Mismatch Negativity. *Frontiers in Aging Neuroscience,* 9.

Gelman, A., & Hill, J. (2007). *Data Analysis Using Regression and Multi- Level/Hierarchical Models.* Cambridge: Cambridge University Press.

Gelman, A., & Rubin, D. B. (1992). Inference from iterative simulation using multiple sequences. *Statistical Science, 7,* 457–472.

Glaser, W. R. (1992). Picture naming. *Cognition, 42*, 61–105. Glezer, L. S., Eden, G., Jiang, X., Luetje, M., Napoliello, E., Kim, J., Riesenhuber, M. (2016). Uncovering phonological and orthographic selectivity across the reading network using fMRI-RA. *NeuroImage, 138*, 248–256.

Glezer, L. S., & Riesenhuber, M. (2013). Individual variability in location impacts orthographic selectivity in the “visual word form area”. *Journal of Neuroscience, 33,* 11221–11226.

Gold, B. T., Andersen, A. H., Jicha, G. A., & Smith, C. D. (2009). Aging influences the neural correlates of lexical decision but not automatic semantic priming. *Cerebral Cortex, 19*, 2671–2679.

Grady, C. (2012). The cognitive neuroscience of ageing. *Nature Reviews Neuroscience, 13,* 491–505.

Grady, C. L., & Craik, F. I. (2000). Changes in memory processing with age. *Current Opinion in Neurobiology, 10*, 224–231.

Grainger, J. (1990). Word frequency and neighborhood frequency effects in lexical decision and naming. *Journal of Memory and Language, 29*, 228–244.

Grainger, J., & Holcomb, P. J. (2009). Watching the word go by: On the time-course of component processes in visual word recognition. *Language and Linguistics Compass, 3*, 128–156.

Grainger, J., & Jacobs, A. M. (1996). Orthographic processing in visual word recognition: a multiple read-out model. *Psychological Review, 103,* 518–565.

Grainger, J., & Ziegler, J. C. (2008). A dual-route approach to orthographic processing. *Frontiers in Psychology, 2,* 54.

Grainger, J., O'Regan, J. K., Jacobs, A. M., & Segui, J. (1989). On the role of competing word units in visual word recognition: The neighborhood frequency effect. *Perception & Psychophysics, 45*, 189–195.

Guttentag, R. E., & Madden, D. J. (1987). Adult age differences in the attentional capacity demands of letter matching. *Experimental Aging Research, 13*, 93–99.

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

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. *Psychology of Learning and Motivation, 22*, 193–225.

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

Head, D., Rodrigue, K. M., Kennedy, K. M., & Raz, N. (2008). Neuroanatomical and cognitive mediators of age-related differences in episodic memory. *Neuropsychology, 22*, 491.

Hedden, T., & Gabrieli, J. D. (2004). Insights into the ageing mind: a view from cognitive neuroscience. *Nature Reviews Neuroscience, 5*, 87–96.

Heine, A., Engl, V., Thaler, V. M., Fussenegger, B. & Jacobs, A. M. (2012). *Neuropsychologie von Entwicklungsstörungen schulischer Fertigkeiten.* Göttingen: Hogrefe.

Heister, J., Wuerzner, K. M., Bubenzer, J., Pohl, E., Hanneforth, T., Geyken, A., & Kliegl, R. (2011). dlexDB-A lexical database for the psychological and linguistic research. *Psychologische Rundschau, 62*, 10–20.

Heitz, R. P. (2014). The speed-accuracy tradeoff: history, physiology, methodology, and behavior. *Frontiers in Neuroscience, 8*, 150.

Hertrich, I., Dietrich, S., & Ackermann, H. (2016). The role of the supplementary motor area for speech and language processing. *Neuroscience & Biobehavioral Reviews, 68,* 602–610.

Hertzog, C., Dixon, R. A., Hultsch, D. F., & MacDonald, S. W. (2003). Latent change models of adult cognition: are changes in processing speed and working memory associated with changes in episodic memory?. *Psychology and Aging*, *18*, 755–769.

Hofmann, M. J., & Jacobs, A. M. (2014). Interactive activation and competition models and semantic context: from behavioral to brain data. *Neuroscience & Biobehavioral Review, 46*, 85–104.

Hofmann, M. J., Kuchinke, L., Biemann, C., Tamm, S., & Jacobs, A. M. (2011). Remembering words in context as predicted by an associative read-out model. *Frontiers in Psychology, 2,* 252.

Houdé, O., Rossi, S., Lubin, A., & Joliot, M. (2010). Mapping numerical processing, reading, and executive functions in the developing brain: an fMRI meta-analysis of 52 studies including 842 children. *Developmental Science, 13*, 876–885.

Howes, D. H., & Solomon, R. L. (1951). Visual duration threshold as a function of word-probability. *Journal of Experimental Psychology, 41*, 401–410.

Hoyer, W. J., Stawski, R. S., Wasylyshyn, C., & Verhaeghen, P. (2004). Adult Age and Digit Symbol Substitution Performance: A Meta-Analysis. *Psychology and Aging, 19*, 211–214.

Hu, L. T., & Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling, 6*, 1–55.

Hutzler, F. (2014). Reverse inference is not a fallacy per se: Cognitive processes can be inferred from functional imaging data. *NeuroImage, 84*, 1061–1069.

Hutzler, F., Braun, M., Võ, M. L.-H., Engl, V., Hofmann, M., Dambacher, M., … Jacobs, A. M. (2007). Welcome to the real world: Validating fixation-related brain potentials for ecologically valid settings. *Brain Research, 1172,* 124–129.

Jacobs, A. M. (2011). Neurokognitive Poetik: Elemente eines Modells des literarischen Lesens [Neurocognitive poetics: elements of a model of literary reading]. In R. Schrott & A. M. Jacobs (Eds.), Gehirn und Gedicht: *Wie wir unsere Wirklichkeiten konstruieren* (pp. 492–520). München: Hanser.

Jacobs, A. M. (2015). Neurocognitive poetics: methods and models for investigating the neuronal and cognitive-affective bases of literature reception. *Frontiers in Human Neuroscience. 9,* 186.

Jacobs, A. M., & Grainger, J. (1994). Models of visual word recognition: sampling the state of the art. *Journal of Experimental Psychology:Human Perception & Performance, 20,* 1311–1334.

Jacobs, A. M., & Hofmann, M. J. (2013). Neurokognitive Modellierung. In E. Schröger & S. Koelsch (Eds.), *Theorie und Forschung* (pp. 431–444), Göttingen: Hogrefe.

Jacobs, A. M., & Willems, R. M. (2017). The fictive brain: Neurocognitive correlates of engagement in literature. *Review of General Psychology.*

Jacobs, A. M., & Ziegler, J. C. (2015). Visual word recognition, Neurocognitive psychology of. In J.D. Wright (Ed.), *International Encyclopedia of Social and Behavioral Sciences* (pp. 214–219). Oxford: Elsevier.

Jacobs, A. M., Graf, R., & Kinder, A. (2003). Receiver operating characteristics in the lexical decision task: evidence for a simple signal-detection process simulated by the multiple read-out model. *Journal of Experimental Psychology: Learning, Memory, and Cognition., 29,* 481–488.

Jacobs, A. M., Rey, A., Ziegler, J. C., & Grainger, J. (1998). MROM-P: An interactive activation, multiple read-out model of orthographic and phonological processes in visual word recognition. In J. Grainger & A. M. Jacobs (Eds.), *Localist connectionist approaches to human cognition* (pp 147–187). Mahwah, NJ: Erlbaum.

Jacobs, A. M., Võ, M. L.-H., Briesemeister, B. B., Conrad, M., Hofmann, M. J., Kuchinke, L., ... Braun, M. (2015). 10 years of BAWLing into affective and aesthetic processes in reading: what are the echoes? *Frontiers in Psychology, 6,* 714.

Jacobs, A.M. (2001). The cognitive psychology of literacy. In N.J. Smelser & P.B. Baltes (Eds.), *International Encyclopedia of the Social and Behavioral Sciences* (pp. 8971–8975). Amsterdam: Elsevier.

Jacobs, A.M., & Graf, R., (2005). Wortformgedächtnis als intuitive Statistik in Sprachen mit unterschiedlicher Konsistenz [Word form memory as intutive statistics in languages with different consistencies], *Zeitschrift für Psychologie, 213,* 133–141.

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.

Jobard, G., Vigneau, M., Simon, G., Tzourio-Mazoyer, N. (2011). The weight of skill: Interindividual variability of reading related brain activation patterns in fluent readers. *Journal of Neurolinguistics, 24*, 113–132.

Joubert, S., Beauregard, M., Walter, N., Bourgouin, P., Beaudoin, G., Leroux, J. M., ... Lecours, A. R. (2004). Neural correlates of lexical and sublexical processes in reading. *Brain and Language, 89*, 9–20.

Juphard, A., Carbonnel, S., Ans, B., & Valdois, S. (2006). Length effect in naming and lexical decision: The multitrace memory model's account. *Current Psychology Letters: Behaviour, Brain & Cognition, 19*, 1–13.

Just, M. A., & Carpenter, P. A. (1980). A theory of reading: From eye fixations to comprehension. *Psychological Review, 87*, 329–354.

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: individual differences in working memory. *Psychological Review*, *99,* 122–149.

Kintsch, W., & Van Dijk, T. A. (1978). Toward a model of text comprehension and production. *Psychological Review, 85,* 363–394.Kliegl, R., Dambacher, M., Dimigen, O., Jacobs, A. M., & Sommer, W. (2012). Eye movements and brain electric potentials during reading. *Psychological Research, 76,* 145–158.

Kliegl, R., Grabner, E., Rolfs, M., & Engbert, R. (2004). Length, frequency, and predictability effects of words on eye movements in reading. *European Journal of Cognitive Psychology, 16*, 262–284.

Korkmaz, S., Goksuluk, D., & Zararsiz, G. (2014). MVN: An R package for assessing multivariate normality. *The R Journal, 6*, 151–162.

Kramer, A. F., & Kray, J. (2006). Aging and Attention. In F. Craik & E. Bialystok (Eds.), *Lifespan cognition: Mechanisms of Change* (pp. 57–69). New York, NY: Oxford University Press

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

Kruschke, J. K. (2015). *Doing Bayesian Data Analysis: A Tutorial with R, JAGS, and Stan.* Amsterdam: Elsevier.

Kwong See, S. T., & Ryan, E. B. (1995). Cognitive mediation of adult age differences in language performance. *Psychology and Aging, 10*, 458–468.

Laird, A. R., Fox, P. M., Eickhoff, S. B., Turner, J. A., Ray, K. L., McKay, D. R., ... Fox, P. T. (2011). Behavioral interpretations of intrinsic connectivity networks. *Journal of Cognitive Neuroscience, 23*, 4022–4037.

Lerche, V., & Voss, A. (2016). Model complexity in diffusion modeling: Benefits of making the model more parsimonious. *Frontiers in Psychology, 7,*1324.

Lerche, V., Voss, A., & Nagler, M. (2016). How many trials are required for parameter estimation in diffusion modeling? A comparison of different optimization criteria. *Behavioral Research Methods*, 1–25.

Li, S. C., Lindenberger, U., & Sikström, S. (2001). Aging cognition: From neuromodulation to representation. *Trends in Cognitive Science, 5,* 479–486.

Li, W., Qin, W., Liu, H., Fan, L., Wang, J., Jiang, T., & Yu, C. (2013). Subregions of the human superior frontal gyrus and their connections. *NeuroImage, 78*, 46–58.

Liebig, J, Froehlich, E, Ziegler, J. C., Morawetz, C., Braun, M., Heekeren, H. R., & Jacobs, A. M. (2017). Neurofunctionally dissecting the reading system in children. *Developmental Cognitive Neuroscience*, *27*, 45–57.

Lindenberger, U. (2014). Human cognitive aging: Corriger la fortune?. *Science, 346,* 572–578.

Lindenberger, U., & Baltes, P. B. (1994). Sensory functioning and intelligence in old age: A strong connection. *Psychology and Aging, 9*, 339–355.

Lindenberger, U., Burzynska, A. Z., Nagel, I. E. (2013). Heterogeneity in frontal lobe aging. In D. T. Stuss & R. T. Knight (Eds.), *Principles of frontal lobe function* (pp. 609–627). New York, NY: Oxford University Press.

Lindenberger, U., Nagel, I. E., Chicherio, C., Li, S. C., Heekeren, H. R., & Bäckman, L. (2008). Age-related decline in brain resources modulates genetic effects on cognitive functioning. *Frontiers in Neuroscience, 2*, 234.

Little, T. D., Rhemtulla, M., Gibson, K., & Schoemann, A. M. (2013). Why the items versus parcels controversy needn’t be one. *Psychological Methods, 18*, 285–300.

Logothetis, N. K., & Wandell, B. A. (2004). Interpreting the BOLD Signal. *Annual Review of Physiology, 66*, 735–769.

Lundstrom, B. N., Ingvar, M., & Petersson, K. M. (2005). The role of precuneus and left inferior frontal cortex during source memory episodic retrieval. *NeuroImage, 27*, 824–834.

Lustig, C., Snyder, A. Z., Bhakta, M., O'Brien, K. C., McAvoy, M., Raichle, M. E., …Buckner, R. L. (2003). Functional deactivations: Change with age and dementia of the Alzheimer type. *Proceedings of the National Academy of Sciences, 100*, 14504–14509.

MacDonald, S. W. S., & Stawski, R. S. (2016). Methodological Considerations for the Study of Adult Development and Aging. In K. W. Schaie & S. L. Willis (Eds.), *Handbook of the Psychology of Aging* (pp. 15–40). New York, NY: Academic Press.

Madden, D. J. (1989). Visual word identification and age-related slowing. *Cognitive Development, 4,* 1–29.

Madden, D. J., Langley, L. K., Denny, L. L., Turkington, T. G., Provenzale, J. M., Hawk, T. C., & Coleman, R. E. (2002). Adult age differences in visual word identification: Functional neuroanatomy by positron emission tomography. *Brain and Cognition, 49*, 297–321.

Madden, D. J., Pierce, T. W., & Allen, P. A. (1993). Age-related slowing and the time course of semantic priming in visual word identification. *Psychology and Aging, 8,* 490–507.

Madden, D. J., Spaniol, J., Whiting, W. L., Bucur, B., Provenzale, J. M., Cabeza, R., …Huettel, S. A. (2007). Adult age differences in the functional neuroanatomy of visual attention: a combined fMRI and DTI study. *Neurobiology of Aging, 28,* 459–476.

Maillet, D., & Schacter, D. L. (2016). Default network and aging: Beyond the task-negative perspective. *Trends in Cognitive Sciences, 20,* 646–648.

Martin, A., Schurz, M., Kronbichler, M., & Richlan, F. (2015). Reading in the brain of children and adults: A meta-analysis of 40 functional magnetic resonance imaging studies. *Human Brain Mapping, 36*, 1963–1981.

Matsunaga, M. (2008). Item parceling in structural equation modeling: A primer. *Communication Methods and Measures, 2*, 260–293.

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,* 375–407.

McDonald, R. P., & Ho, M. H. R. (2002). Principles and practice in reporting structural equation analyses. *Psychological Methods, 7*, 64–82.

McGinnies, E., Comer, P. B., & Lacey, O. L. (1952). Visual-recognition thresholds as a function of word length and word frequency. *Journal of Experimental Psychology, 44*, 65–69.

McNorgan, C., Chabal, S., O'Young, D., Lukic, S., & Booth, J. R. (2015). Task dependent lexicality effects support interactive models of reading: A meta-analytic neuroimaging review. *Neuropsychologia, 67,*148–158.

Mei, L., Xue, G., Chen, C., Xue, F., Zhang, M., & Dong, Q. (2010). The "visual word form area" is involved in successful memory encoding of both words and faces. *NeuroImage, 52*, 371–378.

Mevel, K., Chételat, G., Eustache, F., & Desgranges, B. (2011). The default mode network in healthy aging and Alzheimer's disease. *International Journal of Alzheimer's Disease*, *2011*, 1–9.

Meyer, B. J. F., & Pollard, C. K. (2006). Applied learning and aging: A closer look at reading. In J. E. Birren & K. W. Schaie (Eds.), *Handbook of the Psychology of Aging* (pp. 233–260). New York, NY: Academic Press.

Miyake, A., Just, M. A., & Carpenter, P. A. (1994). Working memory constraints on the resolution of lexical ambiguity: Maintaining multiple interpretations in neutral contexts. *Journal of Memory and Language, 33*, 175–202.

Meyer, B. J. F., Marsiske, M., & Willis, S. L. (1993). Text processing variables predict the readability of everyday documents read by older adults. *Reading Research Quarterly, 28*, 235–248.

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.

Nagel, I. E., Preuschhof, C., Li, S. C., Nyberg, L., Bäckman, L., Lindenberger, U., & Heekeren, H.R. (2011). Load modulation of BOLD response and connectivity predict working memory performance in younger and older adults. *Journal of Cognitive Neuroscience, 23*, 2030–2045.

Nazir, T. A., O'Regan, J. K., & Jacobs, A. M. (1991). On words and their letters. *Bulletin of the Psychonomic Society, 29,* 171–174.

Nelson, H. (1982). *National adult reading test (NART): Test manual.* Windsor: Nfer-Nelson.

Nelson, H., & Willison, J. (1991). *The revised national adult reading test–test manual.* Windsor: NFER-Nelson.

New, B., Ferrand, L., Pallier, C., & Brysbaert, M. (2006). Reexamining the word length effect in visual word recognition: New evidence from the English Lexicon Project. *Psychonomic Bulletin & Review, 13*, 45–52.

Newman, R. L., & Joanisse, M. F. (2011). Modulation of brain regions involved in word recognition by homophonous stimuli: an fMRI study. *Brain Research, 1367*, 250–264.

Newman, S. D., Malaia, E., Seo, R., & Cheng, H. (2013). The effect of individual differences in working memory capacity on sentence comprehension: an fMRI study. *Brain Topography, 26*, 458–467.

Norris, D. (2009). Putting it all together: A unified account of word recognition and reaction-time distributions. *Psychological Review, 116*, 207–219.

Nuthmann, A., Engbert, R., & Kliegl, R. (2006). Messung von Blickbewegungen. In J. Funke & P. A. Frensch (Eds.), *Handbuch der Allgemeinen Psychologie–Kognition* (pp. 705–711). Göttingen: Hogrefe.

O'Regan, J. K., & Jacobs, A. M. (1992). Optimal viewing position effect in word recognition: A challenge to current theory. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 185–197.

Oganian, Y., Froehlich, E., Schlickeiser, U., Hofmann, M. J., Heekeren, H. R., & Jacobs, A. M. (2016). Slower perception followed by faster lexical decision in longer words: a diffusion model analysis. *Frontiers in Psychology, 6,* 1958.

Ogawa, S., Lee, T. M., Kay, A. R., & Tank, D. W. (1990). Brain magnetic resonance imaging with contrast dependent on blood oxygenation. *Proceedings of the National Academy of Sciences*, *87*, 9868–9872.

Olulade, O. A., Flowers, D. L., Napoliello, E. M., Eden, G. F. (2013). Developmental differences for word processing in the ventral stream. *Brain and Language, 125,* 134–145.

Otten, L. J., Henson, R. N., & Rugg, M. D. (2001). Depth of processing effects on neural correlates of memory encoding. *Brain, 124*, 399–412.

Paap, K. R., McDonald, J. E., Schvaneveldt, R. W., & Noel, R. W. (1987). Frequency and pronounceability in visually presented naming and lexical decision tasks. In M. Coltheart (Ed.), *Attention and performance XII: The Psychology of Reading* (pp. 221–243). Hillsdale, NJ: Lawrence Erlbaum Associates.

Perry, C., Ziegler, J. C., & Zorzi, M. (2007). Nested incremental modeling in the development of computational theories: The CDP+ model of reading aloud. *Psychological Review, 114*, 273–315.

Perry, C., Ziegler, J. C., & Zorzi, M. (2010). Beyond single syllables: Large-scale modeling of reading aloud with the connectionist dual process (CDP++) model. *Cognitive Psychology, 61*, 106–151.

Perry, C., Ziegler, J. C., & Zorzi, M. (2013). A Computational and Empirical Investigation of Graphemes in Reading. *Cognitive Science, 37*, 800 –828.

Plaut, D. C., McClelland, J. L., Seidenberg, M. S., & Patterson, K. (1996). Understanding normal and impaired word reading: computational principles in quasi-regular domains. *Psychological Review, 103*, 56–115.

Poldrack, R. A. (2011). Inferring mental states from neuroimaging data: from reverse inference to large-scale decoding. *Neuron, 72*, 692–697.

Poldrack, R. A., Wagner, A. D., Prull, M. W., Desmond, J. E., Glover, G. H., & Gabrieli, J. D. (1999). Functional specialization for semantic and phonological processing in the left inferior prefrontal cortex. *NeuroImage, 10*, 15–35.

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,* 816–847.

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

Price, C. J., & Devlin, J. T. (2011). The interactive account of ventral occipitotemporal contributions to reading. *Trends in Cognitive Sciences, 15*, 246–253.

R Core Team (2015). *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing.

Radach, R., Günther, T., & Huestegge, L. (2012). Blickbewegungen beim Lesen, Leseentwicklung und Legasthenie. *Lernen und Lernstörungen, 1*, 185–204.

Radvansky, G. A., & Dijkstra, K. (2007). Aging and situation model processing. *Psychonomic Bulletin & Review, 14*, 1027–1042.

Raichle, M. E., MacLeod, A. M., Snyder, A. Z., Powers, W. J., Gusnard, D. A., & Shulman, G. L. (2001). A default mode of brain function. *Proceedings of the National Academy of Sciences, 98*, 676–682.

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.

Ratcliff, R. (1978). A theory of memory retrieval. *Psychological Review, 85*, 59–108.

Ratcliff, R. (2008). Modeling aging effects on two-choice tasks: Response signal and response time data. *Psychology and Aging, 23*, 900.

Ratcliff, R., & McKoon, G. (2008). The diffusion decision model: Theory and data for two-choice decision tasks. *Neural Computation, 20*, 873–922.

Ratcliff, R., & Rouder, J. N. (1998). Modeling response times for two-choice decisions. *Psychological Science, 9,* 347–356.

Ratcliff, R., & Smith, P. L. (2010). Perceptual discrimination in static and dynamic noise: the temporal relation between perceptual encoding and decision making. *Journal of Experimental Psychology General, 139*, 70–94.

Ratcliff, R., & Tuerlinckx, F. (2002). Estimating parameters of the diffusion model: approaches to dealing with contaminant reaction times and parameter variability. *Psychonomic Bulletin and Review, 9,* 438–481.

Ratcliff, R., Gomez, P., & McKoon, G. (2004a). A diffusion model account of the lexical decision task. *Psychological Review, 111*, 159–182.

Ratcliff, R., McKoon, G., & Verwoerd, M. (1989). A bias interpretation of facilitation in perceptual identification. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15*, 378–387.

Ratcliff, R., Spieler, D., & McKoon, G. (2004b). Analysis of group differences in processing speed: where are the models of processing? *Psychonomic Bulletin and Review, 11*, 755–769.

Ratcliff, R., Thapar, A., & McKoon, G. (2001). The effects of aging on reaction time in a signal detection task. *Psychology and Aging, 16*, 323–341.

Ratcliff, R., Thapar, A., & Mckoon, G. (2003). A diffusion model analysis of the effects of aging on brightness discrimination. *Perception & Psychophysics, 65*, 523–535.

Ratcliff, R., Thapar, A., & McKoon, G. (2004d). A diffusion model analysis of the effects of aging on recognition memory. *Journal of Memory and Language, 50*, 408–424.

Ratcliff, R., Thapar, A., Gomez, P., & McKoon, G. (2004c). A diffusion model analysis of the effects of aging in the lexical-decision task. *Psychology and Aging, 19*, 278–289.

Raykov, T., & Marcoulides, G. A. (1999). On desirability of parsimony in structural equation model selection. *Structural Equation Modeling, 6,* 292–300.

Reuter-Lorenz, P. A., & Cappell, K. A. (2008). Neurocognitive aging and the compensation hypothesis. *Current Directions in Psychological Science, 17*, 177–182.

Reuter-Lorenz, P. A., Jonides, J., Smith, E. E., Hartley, A., Miller, A., Marshuetz, C., & Koeppe, R. A. (2000). Age differences in the frontal lateralization of verbal and spatial working memory revealed by PET. *Journal of Cognitive Neuroscience, 12*, 174–187.

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*, 8239–8247.

Richlan, F., Kronbichler, M., & Wimmer, H. (2009). Functional abnormalities in the dyslexic brain: A quantitative meta-analysis of neuroimaging studies. *Human Brain Mapping, 30*, 3299–3308.

Risse, S. & Kliegl, R. (2011). Investigating age differences in the perceptual span with the N+2-boundary paradigm. *Psychology and Aging, 26,* 451–460.

Robert, C., & Mathey, S. (2007). Aging and lexical inhibition: the effect of orthographic neighborhood frequency in young and older adults. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences., 62*, 340–342.

Rolls, E. T., Joliot, M., & Tzourio-Mazoyer, N. (2015). Implementation of a new parcellation of the orbitofrontal cortex in the automated anatomical labeling atlas. *NeuroImage, 122,* 1–5.

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*, 3–18.

Rosseel, Y. (2012). lavaan: An R package for structural equation modeling. *Journal of Statistical Software, 48*.

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review, 103*, 403–428.

Salthouse, T. A. (2003). Memory aging from 18 to 80. *Alzheimer Disease & Associated Disorders, 17*, 162–167.

Salthouse, T. A. (2009). When does age-related cognitive decline begin?. *Neurobiology of Aging, 30*, 507–514.

Salthouse, T. A., Mitchell, D. R., Skovronek, E., & Babcock, R. L. (1989). Effects of adult age and working memory on reasoning and spatial abilities. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15*, 507.

Samanez-Larkin, G. R., & D'Esposito, M. (2008). Group comparisons: Imaging the aging brain, *Social Cognitive and Affective Neuroscience, 3*, 290–297.

Satorra, A., & Bentler, P. M. (2001). A scaled difference chi-square test statistic for moment structure analysis. *Psychometrika, 66*, 507–514.

Schlaggar, B. L., & McCandliss, B. D. (2007). Development of Neural Systems for Reading. *Annual Review of Neuroscience, 30*, 475–503.

Schrott, R., & Jacobs, A. M. (2011). *Gehirn und Gedicht: Wie wir unsere Wirklichkeiten konstruieren* [Brain and Poetry: How we Construct our Realities]. München: Hanser.

Schurz, M., Kronbichler, M., Crone, J., Richlan, F., Klackl, J., & Wimmer, H. (2014). Top-down and bottom-up influences on the left ventral occipitotemporal cortex during visual word recognition: an analysis of effective connectivity. *Human Brain Mapping, 35,* 1668–1680.

Seymour, P. H., Aro, M., & Erskine, J. M. (2003). Foundation literacy acquisition in European orthographies. *British Journal of Psychology, 94*, 143–174.

Shafto, M. A., Burke, D. M., Stamatakis, E. A., Tam, P. P., & Tyler, L. K. (2007). On the tip-of-the-tongue: neural correlates of increased word-finding failures in normal aging. *Journal of Cognitive Neuroscience, 19*, 2060–2070.

Shaywitz, B. A., Skudlarski, P., Holahan, J. M., Marchione, K.E., Constable, R. T., Fulbright. R. K., … & Shaywitz, S. E. (2007). Age-related changes in reading systems of dyslexic children. *Annals of Neurology, 61,* 363–370.

Siegel, L. S. (1994). Working memory and reading: A life-span perspective. *International Journal of Behavioral Development, 17*, 109–124.

Spaniol, J., Madden, D. J., & Voss, A. (2006). A diffusion model analysis of adult age differences in episodic and semantic long-term memory retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32,* 101–117.

Spieler, D. H., & Balota, D. A. (2000). Factors influencing word naming in younger and older adults. *Psychology and Aging, 15*, 225–231.

Stadtlander, L. M. (1995). Age differences in orthographic and frequency neighborhoods. In P. A. Allen & Th. R. Bashore (Eds.), *Age differences in word and language processing* (pp. 72–86). Amsterdam: Elsevier.

Steinmetz, H. (2014). Lineare Strukturgleichungsmodelle. München: Rainer Hampp Verlag.

Sugiura, M. (2016). Functional neuroimaging of normal aging: Declining brain, adapting brain. *Ageing Res Rev, 30,* 61–72.

Tainturier, M. J., Tremblay, M., & Lecours, A. R. (1989). Aging and the word frequency effect: A lexical decision investigation. *Neuropsychologia, 27,* 1197–1203.

Tainturier, M. J., Tremblay, M., & Lecours, A. R. (1992). Educational level and the word frequency effect: A lexical decision investigation. *Brain and Language, 43,* 460–474.

Taler, V., & Jarema, G. (2007). Lexical access in younger and older adults: The case of the mass/count distinction. *Canadian Journal of Experimental Psychology, 61*, 21–34.

Taylor, J. S., Rastle, K., & Davis, M. H. (2012). Can cognitive models explain brain activation during word and pseudoword reading? A meta-analysis of 36 neuroimaging studies. *Psychological Bulletin, 139,* 766–791.

Thapar, A., Ratcliff, R., & McKoon, G. (2003). A diffusion model analysis of the effects of aging on letter discrimination. *Psychology and Aging, 18,* 415–429.

Thornton, R., & Light, L. L. (2006). Language comprehension and production in normal aging. In J. E. Birren & K. W. Scharie (Eds.), *Handbook of the Psychology of Aging* (pp. 261–287). New York, NY: Academic Press.

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

Tzourio-Mazoyer, N., Landeau, B., Papathanassiou, D., Crivello, F., Etard, O., Delcroix, N., ... Joliot, M. (2002). Automated anatomical labeling of activations in SPM using a macroscopic anatomical parcellation of the MNI MRI single-subject brain. *NeuroImage, 15*, 273–289.

Vallesi, A., McIntosh, A. R., & Stuss, D. T. (2009). Temporal preparation in aging: a functional MRI study. *Neuropsychologia 47,* 2876–2881.

Van den Heuvel, M. P., & Hulshoff Pol, H. E. (2010). Exploring the brain network: A review on resting-state fMRI functional connectivity. *European Neuropsychopharmacology, 20*, 519–534.

Van Der Linden, M., Hupet, M., Feyereisen, P., Schelstraete, M. A., Bestgen, Y., Bruyer, R., ...Seron, X. (1999). Cognitive mediators of age-related differences in language comprehension and verbal memory performance. *Aging, Neuropsychology, and Cognition, 6*, 32– 55.

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

Vandekerckhove, J., Tuerlinckx, F., & Lee, M. D. (2011). Hierarchical diffusion models for two-choice response times. *Psychol. Methods, 16,* 44–62.

Vandekerckhove, J., Verheyen, S., & Tuerlinckx, F. (2010). A crossed random effects diffusion model for speeded semantic categorization decisions. *Acta Psychologica, 133,* 269–282.

Verhaeghen, P. (2003). Aging and vocabulary score: A meta-analysis. *Psychology and Aging, 18*, 332–339.

Vigneau, M., Beaucousin, V., Hervé, P. Y., Jobard, G., Crivello, F., Mellet, E., ... Tzourio-Mazoyer, N. (2009). Right Hemisphere Contribution to Phonological, Lexico-Semantic and Sentence/text Processing: A Meta-Analysis. *NeuroImage, 47*, S164.

Voss, A., Nagler, M., & Lerche, V. (2013). Diffusion models in experimental psychology: A practical introduction. *Experimental Psychology 60,* 385–402.

Wagenmakers, E. J., Ratcliff, R., Gomez, P., & McKoon, G. (2008). A diffusion model account of criterion shifts in the lexical decision task. *Journal of Memory and Language,* 58, 140–159.

Wagner, A. D., Schacter, D. L., Rotte, M., Koutstaal, W., Maril, A., Dale, A. M., ... Buckner, R. L. (1998). Building memories: remembering and forgetting of verbal experiences as predicted by brain activity. *Science, 281*, 1188–1191.

Wechsler, D. (1997). *Wechsler Memory Scale - Third edition.* San Antonio: The Psychological Corporation.

Weekes, B. S. (1997). Differential effects of number of letters on word and nonword naming latency. *The Quarterly Journal of Experimental Psychology A, 50*, 439–456.

Weiber, R., & Mühlhaus, D. (2014). Strukturgleichungsmodellierung. Berlin, Heidelberg: Springer Gabler.

Welcome, S. E., & Joanisse, M. F. (2012). Individual differences in skilled adult readers reveal dissociable patterns of neural activity associated with component processes of reading. *Brain and Language, 120,* 360–371.

Whiting, W. L., Madden, D. J., Langley, L. K., Denny, L. L., Turkington, T. G., Provenzale, J. M… Coleman, R. E. (2003). Lexical and sublexical components of age-related changes in neural activation during visual word identification. *Journal of Cognitive Neuroscience, 15*, 475–487.

Wiecki, T. V., Sofer, I., & Frank, M. J. (2013). HDDM: Hierarchical Bayesian estimation of the drift-diffusion model in python. *Frontiers in Neuroinformatics, 7,* 14.

Wierenga, C. E., Benjamin, M., Gopinath, K., Perlstein, W. M., Leonard, C. M., Rothi, L. J. G., ... Crosson, B. (2008). Age-related changes in word retrieval: role of bilateral frontal and subcortical networks. *Neurobiology of Aging, 29*, 436–451.

Willems, R., & Jacobs, A. M. (2016). Caring about Dostoyevsky: the untapped potential of studying literature. *Trends in Cognitive Science, 20,* 243–245.

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

Wingfield, A., & Grossman, M. (2006). Language and the aging brain: Patterns of neural compensation revealed by functional brain imaging. *Journal of Neurophysiology, 96,* 2830–2839.

Wolf, M. (2007). *Proust and the Squid–The Story and Science of the Reading Brain*. New York, NY: Harper Perennial.

Wydell, T. N., Vuorinen, T., Helenius, P., & Salmelin, R. (2003). Neural correlates of letter-string length and lexicality during reading in a regular orthography. *Journal of Cognitive Neuroscience, 15,* 1052–1062.

Zacks, R., & Hasher, L. (1997). Cognitive gerontology and attentional inhibition: A reply to Burke and McDowd. *The Journals of Gerontology. Series B: Psychological Sciences and Social Sciences, 52*, 274–283.

Zeman, A., Milton, F., Smith, A., & Rylance, R. (2013). By heart: an fMRI study of brain activation by poetry and prose. *Journal of Consciousness Studies, 20,* 132–158.

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

Ziegler, J. C., & Goswami, U. (2006). Becoming literate in different languages: Similar problems, different solutions. *Developmental Science, 9*, 429–436.

Ziegler, J. C., & Jacobs, A. M. (1995). Phonological information provides early sources of constraint in the processing of letter strings. *Journal of Memory and Language,* 34, 567–593.

Ziegler, J. C., Bertrand, D., Lété, B., & Grainger, J. (2014). Orthographic and phonological contributions to reading development: Tracking developmental trajectories using masked priming. *Developmental Psychology, 50,*1026–1036.

Ziegler, J. C., Bertrand, D., Tóth, D., Csépe, V., Reis, A., Faísca, L. ... Blomert, L. (2010). Orthographic depth and its impact on universal predictors of reading: A cross-language investigation. *Psychological Science, 21*, 551–559.

Ziegler, J. C., Castel, C., Pech-Georgel, C., George, F., Alario, F. X., & Perry, C (2008). Developmental dyslexia and the dual route model of reading: Simulating individual differences and subtypes. *Cognition, 107,* 151–178.

Ziegler, J. C., Jacobs, A. M., & Klüppel, D. (2001a). Pseudohomophone effects in lexical decision: Still a challenge for current word recognition models. *Perception, 27*, 547–559.

Ziegler, J. C., Perry, C., Jacobs, A. M., & Braun, M. (2001b). Identical Words are Read Differently in Different Languages. *Psychological Science*, *12*, 379–384.

Ziegler, J. C., Rey, A., & Jacobs, A. M. (1998). Simulating individual word identification thresholds and errors in the fragmentation task. *Memory & Cognition, 26,* 490–501.

Zoccolotti, P., Luca, M., Filippo, G., Judica, A., & Martelli, M. (2008). Reading development in an orthographically regular language: Effects of length, frequency, lexicality and global processing ability. *Reading and Writing, 22,* 1053–1079.

Zorzi, M., Houghton, G., & Butterworth, B. (1998). Two routes or one in reading aloud? A connectionist dual-process model. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1131–1161.

Zwaan, R. A. (2015). Situation models, mental simulations, and abstract concepts in discourse comprehension. *Psychonomic Bulletin & Review*, 1–7.

Appendices

A Supplementary Material Study 1: Verändert sich Lesen im Alter? Alterseffekte in der visuellen Worterkennung [Does reading change with age? A review of aging effects on visual word recognition]

A.1. Extended abstract

Background: Reading is a highly automatized, complex mental process that, once acquired, functions efficiently for most people. Text comprehension as well as reflective or aesthetic processes (e.g., in poetry reception) can only be performed effortlessly at a high level when the underlying single word recognition runs smoothly. In fact, single word recognition appears as important for developing key concepts in cognitive psychology and psycholinguistics as the cell in biology. While factors influencing reading acquisition as well as reading processes in young adults have been extensively investigated across different languages, only a small number of studies focused on developmental aspects of visual word recognition over the life span, i.e. on changes that might occur during aging and/or in old age. Considering that handling words, speech, and texts recruits cognitive processes that are all marked by a decline in neurochemical, neuroanatomical and functional resources with increasing age this seems rather astonishing, even more so as this deficiency was already noted 17 years ago.

Aims: The aim of this review is threefold. First, we give a summary of the research on visual word recognition in young adult readers. This includes describing common paradigms, major findings regarding key variables and methods, as well as a short description of popular mo-dels of word recognition. Second, we summarize findings of studies investigating age effects on visual word recognition and provide an overview on the current state of affairs within that field. Third, we discuss chief findings and their implications for future research.

Methods: As the lexical decision task is explicitly recommended to investigate single word recognition only studies using this task entered the review. To determine whether age affects processing on the whole word level or on a sublexical level (e.g., syllables) we looked at frequency and orthographic neighborhood effects (word level), as well as at length effects (sublexical level) and their interaction with age. We were able to identify 16 studies that met the selection criteria. Only results obtained from healthy, normal reading adults are reported. The age span covered by this review ranges from 17 to 88 years.

Results: By far, most studies concentrated on frequency effects as a function of age. From 15 studies addressing this topic, 12 reported no significant interaction of age and frequency, i.e. there is no evidence for any differences between young and older participants. Both age groups responded equally faster to high frequency than to low frequency words. Only two studies found larger frequency effects for older than for younger adults with one of these two studies reporting that result for both the lexical decision task and naming task, yet not for the lexical decision task alone. One study reported no interaction between frequency and age at first but reported larger frequency effects for younger than for older adults after adjusting the young subjects' latency data to that of the older ones. Length effects as a function of age were addressed in six studies. Two of them found significant interactions between word length and age. Larger length effects were reported for older participants than for younger participants. Two studies did not find any differences between the age groups. Two other studies reported a significant word length disadvantage for older adults but only after adjusting the younger subjects' latency data to that of the old ones; without adjustment no interaction between word length and age could be found. Only three studies could be identified that looked into orthographic neighborhood effects as a function of age. While one study reported no effects of orthographic neighborhood for both the younger and older adults two studies found smaller neighborhood effects for older participants than for younger participants: Older adults tended to respond more slowly to words with a high neighborhood density than did younger adults, younger adults responded more slowly to words with a high neighborhood frequency whereas older adults showed no such effect. Neuronal effects of word frequency and word length as a function of age were addressed in only one study by means of cerebral blood flow. Solely for older participants, frequency effects were found in Brodmann Areas (BA) 17, 18 and 37 in the left hemisphere. The slower they responded to low frequent words, the more activation older adults produced in these areas. Likewise, only older adults showed word length effects in BA 17 with activity being larger the less influence word length had on reaction time. No neuronal effects of word frequency and word length were obtained for the younger age group.

Discussion: There is a variety of reasons that can generally account for the variability in findings which every researcher in the field of age effects in language processing should be aware of. First, there is an ongoing debate whether vocabulary scores of older and younger adults should be matched or not. Naturally, older adults should have an advantage over younger adults in vocabulary knowledge due to their prolonged exposure to language. However, matching the scores might confound results. Second, besides vocabulary there are further important variables such as time of formal education and acuity that should be taken into account. Especially acuity seems to have an enormous effect in recognition tasks, but information on this issue is omitted in a number of studies of this review. Third, as a rule, reaction times of older participants are longer than those of younger participants, making special analyses necessary: Yet, there are different approaches taken by different research groups. Furthermore, aging per se is an extremely heterogeneous process leaving some older participants operate on a fairly high level, while others show clear signs of cognitive decline. As a consequence, variance in data is larger in the older age group than in the younger. When it comes to differences in results reported for frequency effects as a function of age three explanations are brought forward. First, objective frequency measures correspond more to the lexicon of older adults than to that of younger adults. Second, when comparing older and younger participants with similar vocabulary scores chances are, that these older participants are more likely to be less competent readers. Less competent readers, in turn, tend to produce larger frequency effects than competent ones. Third, the level of education influences the magnitude of the frequency effect as well. Less educated subjects produce a more pronounced frequency effect than do educated ones. Yet, all three explanations do not fully account for the reported results. Differences in results concerning the length effect as a function of age might be due to characteristics of the stimulus material. But as not all details describing the stimuli are given in the studies this conclusion remains speculative. Results concerning orthographic neighborhood point towards decreased lexical activation and inhibition in older adults. Neuronally, findings suggest that older and younger adults process frequency and word length differently.

Conclusion: To answer the question whether reading changes with age one obviously has to consider the different subprocesses of reading. Lexical processing which is crucial for word recognition seems to be only partially affected by age. The lack of an interactive effect of frequency and age suggests visual word recognition to be relatively stable over the lifetime. Yet, results reported for orthographic neighborhood point towards a change in lexical inhibition and activation processes in older adults. Age-dependent changes in reading seem to emerge most notably at the sublexical level as findings concerning word length effects indicate.

A.2. Summary of the effects of frequency, word length and orthographic neighborhood on eye movements, EEG and brain activation.

A.2.1. Erkenntnisse aus der Blickbewegungsforschung. Beim Lesen eines Textes fixieren die Augen einen Großteil der Wörter. Dabei werden entweder die Buchstaben zwischen dem Anfang und der Mitte eines Wortes (bevorzugte Blickposition; Rayner, 1979) fixiert oder aber eine Stelle, die näher zur Wortmitte liegt und die Erkennungszeit des Wortes minimiert (optimale Blickposition; O'Regan & Jacobs, 1992). Manche Wörter werden mehrmals fixiert (Refixation) oder ganz übersprungen. Die Blickbewegungen zwischen den Fixationen sind meist sowohl räumlich als auch zeitlich unterschiedlich lang. Im Regelfall werden diese sogenannten Sakkaden von links nach rechts ausgeführt, es kommt aber auch vor, dass sich Blickbewegungen gegen den Lesefluss bewegen und bereits gelesene Wörter erneut fixiert werden (Regression). Während jeder Fixation werden visuelle Informationen aus deren Umfeld aufgenommen. Die Größe dieser Wahrnehmungsspanne wird mit 3-4 Schriftzeichen links der Fixation und bis zu maximal 15 Zeichen rechts der Fixation angegeben (Rayner & Fisher, 1987; Radach et al., 2012). Zahlreiche Faktoren beeinflussen die Fixationsparameter eines Wortes: visuelle (z.B. Wortlänge; z.B. Kliegl et al., 2004), sublexikalische (z.B. Silbenfrequenz; Conrad, Carreiras, Tamm, & Jacobs, 2009) sowie lexikalische (z.B. Wortfrequenz, Wortbedeutung oder Kontextbezug; Rayner, 1998). In der Regel werden niederfrequente Wörter und solche mit hoher Buchstabenanzahl länger fixiert als hochfrequente kurze (Inhoff & Rayner, 1986; Just & Carpenter, 1980; Pollatsek, Juhasz, Reichle, Machacek, & Rayner, 2008; Rayner & Duffy, 1986). Ebenso führt eine hohe Anzahl orthographischer Nachbarn dazu, dass ein Wort insgesamt länger betrachtet wird (Pollatsek, Perea, & Binder, 1999). Im Kontext der Einzelworterkennung und der klinisch orientierten Neurolinguistik hat die Blickbewegungsforschung eine Vielzahl von Erkenntnissen bezüglich normaler und gestörter Leseprozesse geliefert (für eine detaillierte Betrachtung siehe Radach et al., 2012).

A.2.2. Zeitlicher Verlauf der visuellen Worterkennung. Lesen ist ein hochautomatisierter, aber zeitlich verteilter Prozess (Jacobs, 2006). Innerhalb eines Sekundenbruchteils werden Buchstaben oder Worte aus einer Menge hoch ähnlicher Symbole identifiziert, diesen Bedeutung zugewiesen und das Ergebnis in einen Kontext eingeordnet (Hauk, Coutout, Holden, & Chen, 2012). Spätestens 150ms nach Präsentation erfolgt die Analyse einzelner Buchstaben bzw. Buchstabengruppen. Etwa weitere 100ms später werden diese mit phonologischen Informationen zu Ganzwortrepräsentationen verknüpft. Der sogenannte lexikalische Zugriff erfolgt nach weiteren ca. 50ms (Grainger & Holcomb, 2009). Effekte semantischer Prozesse und höherer Verarbeitungsstufen (z.B. Einbettung in den Satzkontext) werden stabil, unabhängig von der Darbietungsmodalität, ab ca. 400ms nachgewiesen (z.B. Filik & Leuthold, 2008; Grainger & Holcomb, 2009; Hagoort, Hald, Bastiaansen, & Petersson, 2004; Kutas & Hillyard, 1980). Da die der Worterkennung zugrundeliegenden Prozesse interagieren, zeitlich überlappen und oftmals mit sehr unterschiedlichen Paradigmen operationalisiert und untersucht werden (Grainger & Holcomb, 2009), steht der genaue zeitliche Ablauf und Grad der Überschneidung weiterhin zur Diskussion (Hauk et al., 2012). Einige Forscher finden bereits nach ca. 100ms Anzeichen für einen lexikalischen Zugriff (z.B., Hauk, Davis, Ford, Pulvermüller, & Marslen-Wilson, 2006; Pulvermüller, Assadollahi, & Elbert, 2001; Sereno, Rayner, & Posner, 1998) und gehen entsprechend von einer Überschneidung orthographischer und semantischer Prozesse aus. Innerhalb der späteren Verarbeitungsprozesse ist nicht geklärt, ob Effekte, die nach 400ms auftreten, semantische Verarbeitung per se darstellen oder auf kontextuelle Einflüsse zurückzuführen sind, da Anzeichen für (affektiv-)semantische Verarbeitung bereits in einem Zeitfenster unterhalb 200ms nachgewiesen wurden (Hauk et al., 2012; 2006; Hofmann, Kuchinke, Tamm, Võ, & Jacobs, 2009; Ponz et al., 2013).

A.2.3. Neuronale Korrelate der visuellen Worterkennung. Während des Lesens werden im Gehirn mindestens zwei verschiedene Wortverarbeitungssysteme aktiviert: Das dorsale System, das vorwiegend mit phonologischer Verarbeitung assoziiert ist und das auf orthographische Verarbeitung spezialisierte, ventrale System, das sensorische/visuelle Einheiten mit lexikalischen Repräsentationen verknüpft. Während die Verarbeitung im dorsalen System weitgehend linkshemisphärisch abläuft, soll die Verarbeitung im ventralen System beide Hemisphären rekrutieren (Poeppel, 2011). Neuroanatomisch setzt sich das dorsale System aus einem anterioren und einem posterioren Teil zusammen. Der posteriore Teil besteht aus dem angularen und supramarginalen Gyrus sowie dem linken superioren temporalen Gyrus. Es wird angenommen, dass dieser Teil eine integrative Rolle für die Verknüpfung von orthographischen mit phonologischen Prozessen spielt. Zum anterioren Teil des dorsalen Systems wird der inferiore Frontalgyrus gezählt, der sich bis in den dorsalen prämotorischen Kortex ausdehnt. Dieser Teil des dorsalen Systems wird unter anderem mit der Sprachproduktion und der aktiven Analyse phonologischer Elemente assoziiert (Schlaggar & McCandliss, 2007). Das ventrale System umfasst die linken inferioren okzipitotemporalen/fusiformen Areale (Sandak et al., 2004) inklusive des sogenannten visuellen Wortformsystems (VWFS; Cohen et al., 2002; Dehaene et al., 2002). Das VWFS scheint spezifische neuronale Mechanismen für die Verarbeitung von Buchstaben zu bergen (z.B. Binder, Medler, Westbury, Liebenthal, & Buchanan, 2006; Cohen et al., 2000; Cohen et al., 2002; Dehaene et al., 2002), was jedoch nicht impliziert, dass es ausschließlich Buchstaben verarbeitet (Bookheimer et al., 1995; Dehaene & Cohen, 2007; Price & Devlin, 2003). Gerade die fortlaufende Debatte über die funktionale Bedeutung des VWFS verdeutlicht, dass nach 20 Jahren intensiver Forschung und dutzenden publizierten Studien weiterhin Klärungsbedarf darüber besteht, wie die funktionalen Beziehungen der am Lesenetzwerk beteiligten Areale untereinander aussehen und was dies für die Annahmen der im Folgenden skizzierten theoretischen Modelle bedeutet (Danelli et al., 2013).

B Supplementary Material Study 2: Drifting through Basic Subprocesses of Reading: A Hierarchical Diffusion Model Analysis of Age Effects on Visual Word Recognition

B.1. Supplementary tables and figures

Table B.1.1

Mean item characteristics and standard deviations (SD) for the single item reading tasks

	LIT		LDT		PDT		SDT	
	Target	Non-target	Target	Non-target	Target	Non-target	Target	Non-target
Length	5.00 (.00)	5.00 (.00)	4.53 (.51)	4.48 (.51)	4.45 (.50)	4.43 (.50)	4.50 (.51)	4.53 (.51)
WF	- -	- -	1.31 (.82)	1.41 (.83)	1.37 (.75)	1.33 (.93)	1.27 (1.03)	1.22 (1.10)
BF	3.89 (.74)	3.81 (.69)	4.42 (.27)	4.43 (.27)	4.37 (.31)	4.35 (.28)	4.42 (.24)	4.41 (.25)
ON	- -	- -	23.4 (14.1)	20.2 (13.6)	20.4 (12.6)	19.4 (16.1)	24.4 (14.9)	23.8 (10.7)

Note. LIT = letter identification task; LDT = lexical decision task; PDT = phonological decision task; SDT = semantic decision task; Length = number of letters; WF = normalized lemma frequency of the word or base word (PDT); BF = bigram frequency; ON = orthographic neighborhood density.

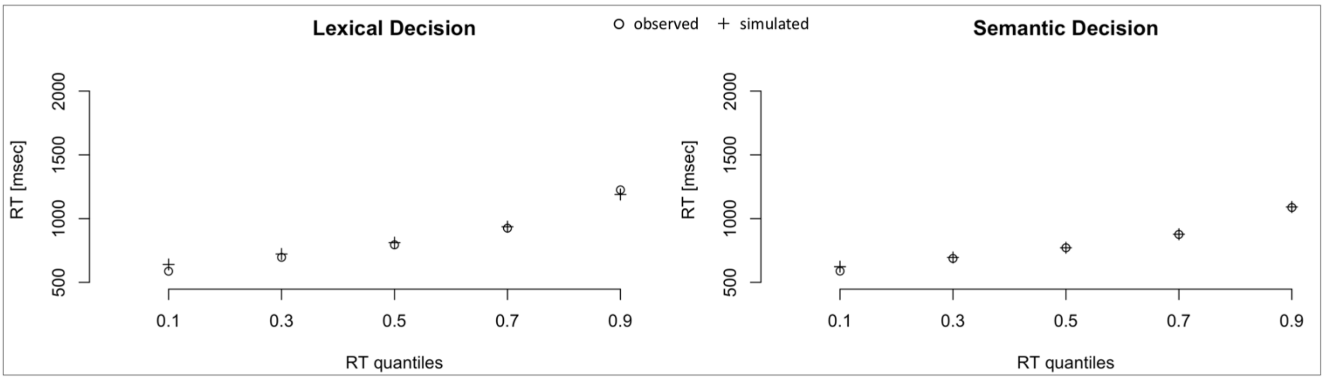

Figure B.1.1. Plot of RT quantiles (0.1, 0.3, 0.5, 0.7, 0.9) for correct responses based on observed and simulated data.

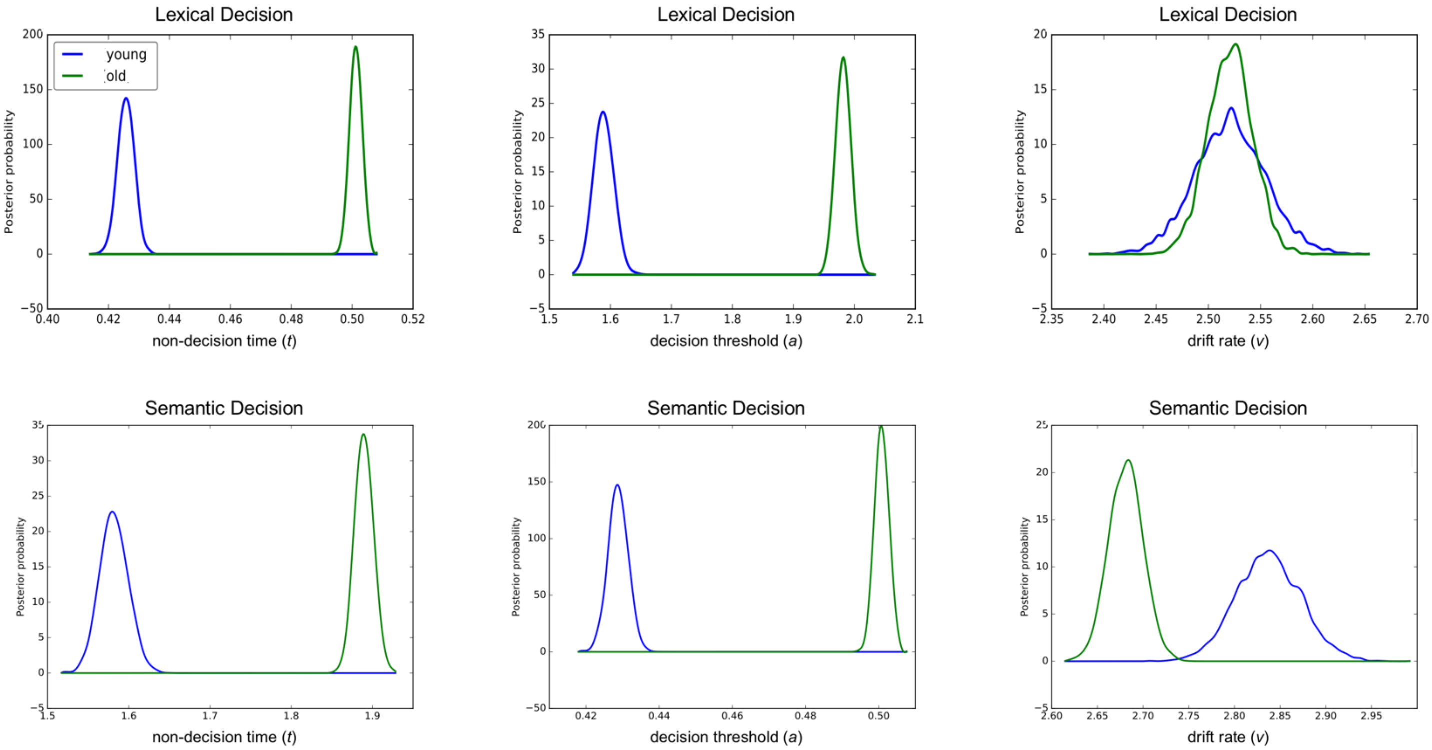

Figure B.1.2. Posterior density plots of group means of the parameters non-decision time *t* (first column), decision threshold *a* (second column) and drift rate *v* (third column).

B.2. Additional hierarchical diffusion model analyses on orthographic and lexico-semantic processing with older adults being binned into one large group (N = 1,423)

B.2.1. Model set-up. For the additional analyses, we estimated the posterior distributions of a total of 12 parameters across the lexical and lexico-semantic decision task: four non-decision time parameters (*t*), four threshold parameters (*a*) with the upper threshold being the correct response and the lower threshold being the incorrect response and four drift rate parameters (*v*; for *t, a,* and *v* one for each age group within each of the two tasks).

B.2.2. Assessment of convergence and model fit. No drifts nor large jumps were observed when inspecting the traces of the posterior distributions for each of the two models separately. Furthermore, we observed no parameter values above 1.02 within the R-hat statistic which indicates successful convergence for both the orthographic and the lexico-semantic model. The models fitted the data well as correlations between model RT quantiles and the observed data was $r = .94$ in the lexical decision task, and $r = .96$ in the semantic decision task (Figure B.1.1.).

B.2.3. Model parameter analysis of posterior estimates. Older adults obtained larger posterior estimates for non-decision time (t) and decision threshold (a) than young adults with a probability of 1, as assessed via Bayesian hypothesis testing, for both the lexical decision and the semantic decision task (Figure B.1.2.). Estimates for drift rates (v) were smaller for older compared to young adults in the semantic decision task (again exhibiting a probability of 1). Within the lexical decision task, however, the probability of drift rates being larger for younger than for older adults was only .50.

C Supplementary material study 3: Same, same but different: Processing words in the aging brain

Table C.1

Summary of linear mixed-effect regression analyses of RT data across (full model; interactions not shown) and within all five in-scanner tasks

Predictor	*b*	*SE*	*t-value*
Full model			
Intercept	907.5	10.9	83.5
Baseline task[1]	-241.4	10.9	-22.1
Letter identification[2]	-130.5	12.3	-10.6
Semantic decision[3]	-108.6	10.3	-10.6
Lexical decision[4]	-122.0	10.5	-11.6
Younger adults[5]	-55.1	9.93	-5.55
Baseline task			
Intercept	666.0	11.0	60.7
Younger adults[5]	-48.3	9.92	-4.87
Letter identification			
Intercept	837.4	14.4	58.1
Younger adults[5]	-84.1	13.1	-6.42
Lexical decision			
Intercept	944.0	18.8	50.2
Younger adults[5]	-40.5	13.7	-2.97
Phonological decision			
Intercept	1,187.7	20.4	58.4
Younger adults[5]	-73.6	15.4	-4.77
Semantic decision			
Intercept	902.9	15.1	59.9
Younger adults[5]	-28.6	11.9	-2.39

Note. *b* = beta-estimate; *SE* = Standard Error; [1]compared to all other tasks; [2]compared to lexical, phonological and semantic decision; [3]compared to lexical and phonological decision; [4]compared to phonological decision; [5]compared to older adults. For each task, the main effect of age was significant, $\chi^2_{baseline\ task}(1) = 23.7, p < .001$, $\chi^2_{letter\ identification}(1) = 41.2, p < .001$, $\chi^2_{lexical\ decision}(1) = 8.81, p < .01$, $\chi^2_{phonological\ decision}(1) = 22.8, p < .001$, $\chi^2_{semantic\ decision}(1) = 5.73$, $p < .05$.

Table C.2

Summary of logistic mixed-effect regression analyses of accuracy data across (full model; interactions not shown) and within all five in-scanner tasks

Predictor	*b*	*SE*	*z-value*
Full model			
Intercept	3.88	.11	36.4
Baseline task[1]	1.52	.20	7.51
Letter identification[2]	.48	.15	3.20
Semantic decision[3]	.40	.12	3.26
Lexical decision[4]	.58	.11	5.36
Older adults[5]	.12	.10	1.21
Baseline task			
Intercept	664.2	10.7	61.9
Older adults[5]	-48.1	9.76	-4.93
Letter identification			
Intercept	836.3	14.4	58.1
Older adults[5]	-85.4	13.1	-6.50
Lexical decision			
Intercept	943.5	18.8	50.3
Older adults[5]	-40.4	13.8	-2.93
Phonological decision			
Intercept	1,187.3	20.5	58.0
Older adults[5]	-74.9	15.5	-4.84
Semantic decision			
Intercept	901.4	15.1	59.8
Older adults[5]	-29.0	11.9	-2.44

Note. *b* = beta-estimate; *SE* = Standard Error; [1]compared to all other tasks; [2]compared to lexical, phonological and semantic decision; [3]compared to lexical and phonological decision; [4]compared to phonological decision; [5]compared to younger adults. Only for semantic decision, the main effect of age was significant, $\chi^2_{baseline\ task}(1) = 2.24, p = .13$, $\chi^2_{letter\ identification}(1) = 1.47, p = .23$, $\chi^2_{lexical\ decision}(1) = .28, p = .60$, $\chi^2_{phonological\ decision}(1) = .00, p = 1.0$, $\chi^2_{semantic\ decision}(1) = 3.95, p < .05$.

Table C.3

Brain regions showing significant BOLD signal increases in younger adults during the four reading-related tasks (contrasts: reading task > baseline task)

			MNI coordinates					
Brain region	BA	Hemisphere	x	y	z	T	P_{FWE}	k
Letter identification								
Inferior occipital gyrus	17	LH	-24	-96	-6	7.90	.000	339
Inferior occipital gyrus	37	LH	-39	-63	-9	4.31		LM
Inferior occipital gyrus	19	LH	-39	-75	-9	4.04		LM
Superior parietal gyrus	7	LH	-24	-69	39	4.88	.020	105
Lexical decision								
Inferior temporal gyrus	37	LH	-45	-54	-12	5.08	.038	88
Phonological decision								
Inferior frontal gyrus, opercular part	9	LH	-48	9	27	9.16	.000	1.236
Precentral	-	LH	-45	6	30	8.98		LM
Inferior frontal gyrus, triangular part	46	LH	-42	30	15	8.97		LM
Insula	47	LH	-33	24	0	8.93		LM
Inferior temporal gyrus	37	LH	-45	-57	-9	8.58	.000	445
Inferior occipital gyrus	18	LH	-24	-99	-6	8.58		LM
Supplementary motor area	8	LH	-6	18	48	6.51	.002	169
Midcingulate gyrus	9	RH	12	27	33	4.09		LM
Insula	47	RH	33	24	0	6.50	.003	158
Inferior parietal gyrus	40	LH	-42	-42	45	5.71	.000	471
Middle occipital gyrus	19	LH	-24	-69	36	5.58		LM
Inferior parietal gyrus	19	LH	-54	-33	45	5.47		LM
Superior parietal gyrus	7	LH	-27	-63	45	5.16		LM
Semantic decision								
Inferior occipital gyrus	18	LH	-24	-99	-6	6.83	.013	117
Inferior frontal gyrus, triangular part	46	LH	-42	27	18	5.64	.000	576
Inferior frontal gyrus, triangular part	-	LH	-45	30	15	5.59		LM
Precentral	9	LH	-48	12	30	5.38		LM
Inferior frontal gyrus, opercular part	9	LH	-36	12	27	5.26		LM
Inferior frontal gyrus, triangular part	47	LH	-48	39	-3	4.28		LM
Inferior frontal gyrus, triangular part	47	LH	-36	24	-3	4.09		LM

Table C.3 (continued)

Brain region	BA	Hemisphere	MNI coordinates x	y	z	T	P_{FWE}	k
Semantic decision (continued)								
Inferior temporal gyrus	37	LH	-45	-54	-12	5.40	.002	180
Fusiform gyrus	-	LH	-36	-45	-21	4.86		LM

Note. Peaks were identified using MNI coordinates. Brodmann areas (BA) were identified using NeuroElf version 1.1 (http://neuroelf.net). At the whole-brain level, a significance statistical threshold of $p < .05$ cluster-wise FWE-corrected for multiple comparisons has been used (voxel-level uncorrected at $p < .001$) with minimum clusters of 105 (letter identification), 88 (lexical decision), 158 (phonological decision) and 117 (semantic decision). k = cluster size (number of voxels), LH = left hemisphere, RH = right hemisphere, LM = local maxima.

Table C.4

Brain regions showing significant BOLD signal increases in older adults during the four reading-related tasks (contrasts: reading task > baseline task)

Brain region	BA	Hemisphere	MNI coordinates			T	P_{FWE}	k
			x	y	z			
Letter identification								
Inferior occipital gyrus	18	LH	-30	-90	-9	10.4	.000	2,056
Inferior occipital gyrus	-	LH	-24	-93	-9	10.0		LM
Inferior occipital gyrus	19	LH	-39	-66	-9	8.01		LM
Middle occipital gyrus	19	LH	-30	-87	21	7.42		LM
Superior parietal gyrus	7	LH	-24	-66	39	7.23		LM
Superior parietal gyrus	7	LH	-24	-60	48	6.94		LM
Middle occipital gyrus	19	LH	-30	-75	24	6.62		LM
Fusiform gyrus	-	LH	-36	-39	-24	6.33		LM
Fusiform gyrus	-	LH	-39	-42	-21	6.26		LM
Vermis7	-	-	0	-75	-24	5.40		LM
Cerebellum crus1	-	LH	-45	-63	-33	3.70		LM
Lingual gyrus	19	LH	-24	-54	-12	3.60		LM
Inferior occipital gyrus	18	RH	36	-90	-3	9.22	.000	998
Inferior occipital gyrus	18	RH	27	-90	-6	8.80		LM
Superior parietal gyrus	7	RH	24	-54	51	5.22		LM
Middle occipital gyrus	19	RH	30	-75	30	5.00		LM
Superior parietal gyrus	7	RH	30	-72	54	4.86		LM
Superior parietal gyrus	7	RH	27	-63	51	4.83		LM
Cerebellum	19	RH	33	-72	-21	3.54		LM
Precentral gyrus	9	LH	-45	6	33	5.57	.002	178
Inferior frontal gyrus, opercular part	9	LH	-54	18	33	3.87		LM
Inferior frontal gyrus, triangular part	45	LH	-45	24	21	3.37		LM
Inferior frontal gyrus, opercular part	9	RH	45	9	33	5.41	.008	131
Insula	47	RH	33	24	0	5.08	.003	160
Insula	47	RH	36	21	-18	4.11		LM
Superior temporal gyrus, temporal pole	38	RH	54	12	-9	3.69		LM
Posterior orbital gyrus	38	RH	51	18	-12	3.68		LM
Posterior orbital gyrus	-	RH	48	21	-15	3.57		LM
Lexical decision								
Inferior occipital gyrus	18	LH	-30	-93	-9	9.07	.000	828
Inferior occipital gyrus	-	LH	-27	-96	-6	8.84		LM
Inferior temporal gyrus	37	LH	-42	-60	-9	6.51		LM
Fusiform gyrus	-	LH	-39	-42	-21	6.09		LM
Cerebellum crus1	-	LH	-36	-75	-30	4.31		LM
Cerebellum crus1	-	LH	-36	-42	-33	3.23		LM

Table C.4 (continued)

Brain region	BA	Hemi-sphere	MNI coordinates x	y	z	T	P_{FWE}	k
Lexical decision (continued)								
Inferior occipital gyrus	18	RH	33	-87	-6	8.79	.000	440
Cerebellum	-	RH	33	-69	-24	3.75		LM
Precentral	9	LH	-45	6	33	5.94	.000	1,180
Inferior frontal gyrus, opercular part	-	LH	-48	9	27	5.77		LM
Inferior frontal gyrus, triangular part	47	LH	-39	24	0	5.63		LM
Inferior frontal gyrus, triangular part	46	LH	-51	39	12	5.34		LM
Inferior frontal gyrus, orbital part	11	LH	-36	33	-12	5.09		LM
Inferior frontal gyrus, triangular part	46	LH	-48	30	18	5.07		LM
Inferior frontal gyrus, triangular part	-	LH	-51	33	21	5.07		LM
Inferior frontal gyrus, opercular part	9	LH	-54	18	33	4.99		LM
Inferior frontal gyrus, orbital part	-	LH	-33	36	-9	4.97		LM
Superior frontal gyrus	-	LH	-24	45	-3	3.21		LM
Inferior frontal gyrus, triangular part	46	RH	54	33	18	5.60	.000	761
Inferior frontal gyrus, triangular part	-	RH	54	33	24	5.51		LM
Insula	47	RH	33	27	0	5.41		LM
Inferior frontal gyrus, orbital part	11	RH	30	36	-12	4.64		LM
Inferior frontal gyrus, opercular part	9	RH	42	12	33	4.37		LM
Anterior orbital gyrus	-	RH	27	39	-9	4.28		LM
Superior temporal gyrus, temporal pole	47	RH	54	18	-6	4.245		LM
Inferior frontal gyrus, opercular part	45	RH	54	18	9	3.98		LM
Inferior frontal gyrus, orbital part	47	RH	48	24	-12	3.91		LM
Inferior frontal gyrus, opercular part	13	RH	42	18	6	3.62		LM
Superior frontal gyrus, medial segment	8	RH	3	27	48	5.15	.000	446
Midcingulate gyrus	9	RH	6	33	30	4.12		LM

Table C.4 (continued)

Brain region	BA	Hemi-sphere	MNI coordinates x	y	z	T	P_{FWE}	k
Lexical decision (continued)								
Superior frontal gyrus, medial segment	9	RH	3	48	30	3.47		LM
Superior frontal gyrus, medial segment	9	LH	-3	54	24	3.40		LM
Superior frontal gyrus, medial segment	6	LH	-6	48	36	3.33		LM
Superior parietal gyrus	7	LH	-24	-66	39	4.58	.000	240
Superior parietal gyrus	7	LH	-24	-63	51	4.29		LM
Thalamus	-	RH	12	-3	3	4.25	.031	93
Pallidum	-	RH	15	9	0	3.91		LM
Phonological decision								
Inferior occipital gyrus	18	LH	-30	-93	-9	11.11	.000	1,977
Inferior occipital gyrus	18	RH	27	-93	-6	9.92		LM
Inferior occipital gyrus	18	RH	36	-90	-3	9.82		LM
Inferior temporal gyrus	37	LH	-48	-60	-9	8.93		LM
Cerebellum	-	RH	33	-72	-24	7.49		LM
Cerebellum crus1	-	RH	12	-81	-27	7.44		LM
Cerebellum crus1	-	LH	-9	-81	-27	7.08		LM
Cerebellum crus1	-	LH	-33	-75	-24	6.41		LM
Fusiform gyrus	-	LH	-39	-45	-24	6.14		LM
Fusiform gyrus	-	LH	-42	-48	-21	6.02		LM
Cerebellum	-	LH	-18	-54	-30	3.95		LM
Inferior temporal gyrus	-	LH	-45	-33	-12	3.92		LM
Cerebellum	-	LH	-12	-48	-21	3.71		LM
Middle occipital gyrus	19	LH	-36	-87	18	3.44		LM
Precentral	9	LH	-42	6	30	10.83	.000	7,165
Insula	47	LH	-33	24	0	10.39		LM
Inferior frontal gyrus, triangular part	-	LH	-39	24	0	10.32		LM
Inferior frontal gyrus, triangular part	46	LH	-42	33	9	10.27		LM
Insula	47	RH	33	24	-3	10.11		LM
Inferior frontal gyrus, triangular part	46	LH	-45	30	18	9.97		LM
Superior frontal gyrus, medial segment	8	RH	6	27	45	9.29		LM
Supplementary motor area	8	LH	-6	15	54	8.91		LM
Inferior frontal gyrus, opercular part	9	LH	-54	18	33	8.85		LM
Inferior frontal gyrus, triangular part	46	RH	54	33	24	8.52		LM

Table C.4 (continued)

Brain region	BA	Hemi-sphere	MNI coordinates x	y	z	T	P_{FWE}	k
Phonological decision (continued)								
Inferior frontal gyrus, opercular part	9	RH	45	12	33	7.37		LM
Midcingulate gyrus	9	RH	9	33	33	7.33		LM
Middle frontal gyrus	47	RH	39	39	-12	7.17		LM
Inferior frontal gyrus, triangular part	13	RH	45	21	9	7.08		LM
Thalamus	-	RH	12	-9	-3	6.84		LM
Precentral	6	LH	-48	0	54	6.83		LM
Middle frontal gyrus	10	RH	36	54	3	5.80		LM
Thalamus	-	LH	-6	-21	0	5.62		LM
Thalamus	-	RH	6	-21	0	5.27		LM
Middle frontal gyrus, orbital part	-	RH	42	51	-9	5.23		LM
Middle frontal gyrus	-	LH	-36	51	18	5.16		LM
Thalamus	-	LH	-6	-9	9	4.95		LM
Middle frontal gyrus	6	RH	42	3	60	4.84		LM
Middle frontal gyrus	-	RH	27	12	48	4.09		LM
Anterior cingulate gyrus	-	LH	-9	30	27	3.93		LM
Caudate	-	LH	-18	3	18	3.91		LM
Putamen	-	LH	-27	57	-3	3.85		LM
Middle frontal gyrus	-	RH	30	21	57	3.59		LM
Middle frontal gyrus	-	RH	33	3	54	3.47		LM
Superior frontal gyrus	-	LH	-21	0	63	3.45		LM
Superior parietal gyrus	7	LH	-27	-60	48	7.45	.000	872
Superior parietal gyrus	7	LH	-24	-66	39	7.11		LM
Inferior parietal gyrus	40	LH	-45	-42	48	5.82		LM
Inferior parietal gyrus	7	LH	-39	-57	60	5.29		LM
Inferior parietal gyrus	40	LH	-54	-36	42	4.98		LM
Superior parietal gyrus	7	RH	33	-66	51	5.38	.000	325
Middle occipital gyrus	39	RH	30	-63	36	4.56		LM
Supramarginal gyrus	40	RH	42	-42	42	4.12		LM
Inferior parietal gyrus	-	RH	33	-54	45	4.04		LM
Semantic decision								
Inferior occipital gyrus	17	LH	-24	-96	-6	9.98	.000	1,296
Cerebellum crus1	-	RH	12	-84	-27	7.33		LM
Inferior temporal gyrus	20	LH	-51	-51	-12	6.94		LM
Fusiform gyrus	-	LH	-39	-42	-21	6.35		LM
Cerebellum crus1	-	LH	-9	-81	-27	5.68		LM
Cerebellum crus1	-	RH	36	-75	-24	5.38		LM
Middle temporal gyrus	22	LH	-57	-45	3	4.77		LM
Middle temporal gyrus	22	LH	-51	-36	3	4.25		LM

Table C.4 (continued)

Brain region	BA	Hemi-sphere	MNI coordinates			T	P_{FWE}	k
			x	y	z			
Semantic decision (continued)								
Middle temporal gyrus	21	LH	-51	-21	-6	3.57		LM
Inferior frontal gyrus, triangular part	46	LH	-45	36	12	8.91	.000	1,956
Inferior frontal gyrus, triangular part	46	LH	-51	30	18	8.15		LM
Inferior frontal gyrus, orbital part	11	LH	-39	33	-9	7.89		LM
Middle frontal gyrus	9	LH	-36	9	33	7.71		LM
Inferior frontal gyrus, opercular part	9	LH	-54	18	33	7.64		LM
Insula	47	LH	-36	24	0	7.41		LM
Inferior frontal gyrus, triangular part	-	LH	-42	21	24	7.4		LM
Middle frontal gyrus	10	LH	-45	48	0	7.35		LM
Inferior frontal gyrus, orbital part	-	LH	-51	30	-6	7.12		LM
Middle frontal gyrus	6	LH	-36	6	51	4.76		LM
Middle frontal gyrus	6	LH	-36	18	57	4.65		LM
Middle frontal gyrus	6	LH	-39	6	60	3.87		LM
Inferior occipital gyrus	18	RH	27	-93	-3	8.20	.000	225
Superior frontal gyrus, medial segment	8	LH	-3	27	51	7.69	.000	875
Superior frontal gyrus, medial segment	9	LH	-3	48	33	4.59		LM
Superior frontal gyrus, medial segment	-	LH	-3	54	27	4.44		LM
Superior frontal gyrus	8	LH	-12	51	36	4.36		LM
Midcingulate gyrus	6	RH	12	30	36	4.14		LM
Superior frontal gyrus	8	LH	-12	48	48	4.11		LM
Inferior frontal gyrus, triangular part	46	RH	57	33	18	7.56	.000	972
Insula	47	RH	33	24	-3	6.32		LM
Middle frontal gyrus	9	RH	39	15	36	4.68		LM
Anterior orbital gyrus	11	RH	33	36	-15	4.63		LM
Posterior orbital gyrus	47	RH	30	27	-15	4.44		LM
Middle frontal gyrus	8	RH	48	21	45	3.31		LM

Table C.4 (continued)

Brain region	BA	Hemisphere	MNI coordinates x	y	z	T	P_{FWE}	k
Semantic decision (continued)								
Inferior parietal gyrus	7	LH	-30	-75	48	5.07	.001	193
Inferior parietal gyrus	7	LH	-42	-60	57	3.82		LM

Note. Peaks were identified using MNI coordinates. Brodmann areas (BA) were identified using NeuroElf version 1.1 (http://neuroelf.net). At the whole-brain level, a significance statistical threshold of $p < .05$ cluster-wise FWE-corrected for multiple comparisons has been used (voxel-level uncorrected at $p < .001$) with minimum clusters of 131 (letter identification), 93 (lexical decision), 325 (phonological decision) and 193 (semantic decision). k = cluster size (number of voxels), LH = left hemisphere, RH = right hemisphere, LM = local maxima.

Table C.5

Brain regions showing significant age-related differences in BOLD signal in any of the four reading-related tasks (F-contrast)

Brain region	BA	Hemi-sphere	MNI coordinates			F	P_{FWE}	k
			x	y	z			
Inferior occipital gyrus	18	LH	-21	-96	-6	127.6	.000	12,623
Inferior occipital gyrus	18	RH	36	-90	-3	96.0	.000	LM
Inferior occipital gyrus	18	RH	24	-93	-3	89.8	.000	LM
Precentral gyrus	9	LH	-48	3	33	43.3	.000	3,670
Supplementary motor area	6	LH	-3	3	57	32.3	.000	LM
Insula	47	LH	-33	24	0	28.4	.000	LM
Middle frontal gyrus	9	LH	-30	33	39	15.9	.000	152
Superior frontal gyrus	8	RH	27	33	42	15.3	.000	168
Middle temporal gyrus	21	RH	60	-6	-18	14.4	.000	135
Middle temporal gyrus, temporal pole	21	RH	54	6	-24	10.4	.000	LM
Putamen	-	RH	27	-3	12	14.1	.000	255
Putamen	-	RH	27	0	3	12.0	.000	LM
Thalamus	-	RH	18	-9	12	10.0	.000	LM
Postcentral gyrus	4	LH	-36	-18	42	11.5	.000	42
Supramarginal gyrus	13	LH	-51	-36	24	10.9	.000	48
Cerebellum crus1	-	RH	12	-81	-27	10.5	.000	12
Middle temporal gyrus	21	LH	-60	-3	-15	9.72	.000	14
Middle temporal gyrus	21	LH	-63	-45	-3	9.39	.000	13
Insula	13	RH	39	-12	-3	9.05	.000	20
Insula	13	RH	42	-6	-12	8.50	.000	LM
Superior frontal gyrus	9	LH	-12	54	36	8.74	.000	10
Middle frontal gyrus	46	RH	45	42	18	8.28	.000	27

Note. Peaks were identified using MNI coordinates and anatomically labelled with the aal and aal2 toolboxes (Tzourio-Mazoyer et al., 2002; Rolls et al., 2015). Brodmann areas (BA) were identified using NeuroElf version 1.1 (http://neuroelf.net). At the whole-brain level, a significance statistical threshold of $p < .05$ cluster-wise FWE-corrected for multiple comparisons has been used (voxel-level uncorrected at $p < .001$) with minimum clusters of 10 voxels. k = cluster size (number of voxels), RH = right hemisphere, LH = left hemisphere, LM = local maxima.

D Supplementary material study 4: Age-related differences in the subprocesses of reading and sentence comprehension: The impact of working and episodic memory

D.1. Results

Reading Performance.

Accuracy. Mean percentage accuracy rates are shown in Table D2.1. A 4 x 2 (task: letter identification vs. lexical decision vs. phonological decision vs. semantic decision x age: young vs. old) mixed-effect model yielded a main effect of task, $\chi^2(3) = 210.4$, $p < .001$ and the significant interaction of task and age, $\chi^2(3) = 21.7$, $p < .001$. Planned comparisons which were directly encoded in the model showed that highest accuracy rates were obtained for the letter identification task, $b = .56$, $SE = .11$, $z = 5.11$. Responses in semantic decision were more accurate than in lexical and phonological decision, $b = .64$, $SE = .10$, $z = 6.15$ and the lexical decision task received more accurate judgements than the phonological decision task, $b = 1.08$, $SE = .09$, $z = 12.0$, all p's < .001. Additional analyses indicated that older participants responded more accurately than younger participants within the letter identification task, $\chi^2(1) = 11.5$, whereas the opposite pattern was found within the phonological decision task, $\chi^2(1) = 8.52$, all p's < .01. No age-related differences in accuracy rates were observed within the lexical and the semantic decision task (see Table D.2.2 for a detailed summary).

Response times. Mean RTs are shown in Table S1. A 4 x 2 (task: letter identification vs. lexical decision vs. phonological decision vs. semantic decision x age: young vs. old) mixed-effect model yielded a main effect of task, $\chi^2(3) = 818.8$, $p < .001$ and age, $\chi^2(1) = 352.2$, $p < .001$ as well as the significant interaction of both factors, $\chi^2(3) = 11.2$, $p < .05$. Planned comparisons, directly encoded in the model showed that shortest RTs were obtained in letter identification, $b = -215.9$, $SE = 14.6$, $t = -14.8$. RTs in semantic decision were shorter, $b = -200.6$, $SE = 13.7$, $t = -14.6$ than in lexical and phonological decision and again RTs in lexical decision were shorter than in phonological decision, *b* = -247.5, *SE* = 12.1, *t* = -20.5. RTs between tasks differed significantly from each other considering the size of the data set and all absolute t-values being well above a value of 2 (*cf.* Baayen et al., 2008). Younger participants responded faster than older participants, *b* = -83.3, *SE* = 4.44, *t* = -18.8. This general pattern was also observed within all four reading tasks (see Table D.2.3 for a detailed summary).

Sentence comprehension. Mean scores in sentence comprehension are displayed in Table S1. Younger adults differed from older adults with younger adults scoring higher (*M* = 60.9; *SD* = 10.2) than older adults (*M* = 54.7; *SD* = 10.8), *t*(494.3) = -9.42, *p* < .001, 95% CI [-7.43, -4.87] with an effect size of *d* = .58.

Memory performance.

Working memory performance. Mean working memory scores are shown in Table D.2.1. Younger participants scored higher in spatial updating (32.9; 6.41) than older participants (21.1; 8.86). The difference was significant, t(624.1) = -26.2, p < .001, 95% CI [-12.6, -10.8] with an effect size of d = 1.39. The same pattern was observed for letter updating (46.3 vs. 39.2; 9.0 vs. 10.3), t(513.6) = -11.7, p < .001, 95% CI [-8.19, -5.84] with an effect size of d = .69 and the number-n-back task (.89 vs. .69; .13 vs. .17), t(585.7) = -22.0, p < .001, 95% CI [-.22, -.18], d = 1.21.

Episodic memory performance. Mean episodic memory scores are shown in Table D.2.1. Compared to older participants, younger adults obtained higher scores in scene encoding (.38 vs. .28; .15 vs. .14), *t*(443.8) = -10.3, *p* < .001, 95% CI [-.12, -.08], *d* = .70. Likewise, younger adults scored higher in verbal learning (60.5 vs. 43.2; 10.75 vs. 13.3), face-profession (.54 vs. .27; .19 vs. .21), and object location (16.3 vs. 13.3; 5.30 vs. 3.82). All differences between the age groups were significant: $t_{\text{verbal learning}}$(569.6) = -24.1, 95% $\text{CI}_{\text{verbal}}$

$_{\text{learning}}$ [-18.8, -15.9], $d_{\text{verbal learning}} = 1.35$; $t_{\text{face-profession}}(508.5) = -21.9$, 95% $\text{CI}_{\text{face-profession}}$ [-.29, -.25], $d_{\text{face-profession}} = 1.32$; $t_{\text{object location}}(381.1) = -9.18$, 95% $\text{CI}_{\text{object location}}$ [-3.62, -2.34], $d_{\text{object location}} = .72$, all p's < .001.

Processing Speed Performance. Mean processing speed results are shown in Table D.2.1. As expected, younger adults responded faster than older adults in basic pattern recognition (501 vs. 649; 60.9 vs. 90.7), $t(688.2) = 33.8$, $p < .001$, 95% CI [139, 156], $d = 1.72$) and in the control trials of the multi-source interference task (462 vs. 656; 46.1 vs. 95.4), $t(1007.3) = 50.7$, $p < .001$, 95% CI [186, 201], $d = 2.21$). They also scored higher in both test sessions of the digit symbol substitution test than did older adults (session 1: 43.2 vs. 65.4; 11.3 vs. 9.62, $t(409.1) = -31.0$, $p < .001$, 95% CI [-23.6, -20.8], $d = 2.23$/session 2: 45.0 vs. 63.4; 10.1 vs. 8.30, $t(398.6) = -28.7$, $p < .001$, 95% CI [-19.6, -17.1], $d = 2.11$).

D.2. Supplementary tables

Table D.2.1

Accuracy (%), mean RTs (ms) for the four single word reading tasks, mean scores for memory and processing speed tasks as well as standard deviations (SD) as a function of age

	Younger Adults	Older Adults
Reading Measures		
Accuracy (*SD)*		
Letter identification	97.3 (16.3)	97.8 (14.8)
Lexical decision	95.7 (20.2)	97.0 (17.0)
Phonological decision	89.0 (31.3)	86.6 (34.1)
Semantic decision	96.3 (19.0)	96.9 (17.2)
RTs *(SD)*[1]		
Letter identification	605 (145)	783 (203)
Lexical decision	748 (261)	907 (310)
Phonological decision	1,226 (464)	1,398 (497)
Semantic decision	706 (192)	851 (233)
Sentence comprehension[1]	60.9 (10.2)	54.7 (10.7)
Working Memory (*SD*)		
Spatial updating	32.9 (6.41)[a]	21.1 (8.86)[b]
Letter updating	46.3 (9.0)[c]	39.2 (10.3)[b]
Number-n-back	.89 (.13)[a]	.69 (.17)[b]
Episodic Memory (*SD*)		
Scene encoding	.38 (.15)	.28 (.14)[d]
Verbal learning	60.5 (10.8)[e]	43.2 (13.3)[f]
Face-profession	.54 (.19)	.27 (.21)[f]
Object location	16.3 (5.30)[c]	13.3 (3.82)[g]
Processing Speed (*SD*)		
Basic pattern recognition	501 (60.9)[h]	649 (90.7)[i]
Multiple interference	462 (46.1)[j]	656 (95.4)[k]
Digit symbol[2]	65.4 (11.3)[l]	43.2 (9.62)[m]
	63.4 (10.1)[n]	45.0 (8.30)[o]

Note. SD = standard deviation; [1]measures were parceled into three indicators per task before entering analyses; [2]two measures per subject from two sessions one week apart; prior to entering CFA and SEM RTs, sentence comprehension, memory and processing speed scores were z-standardized; [a]*n* = 303; [b]*n* = 1,210; [c]*n* = 301; [d]*n* = 1,222; [e]*n* = 308; [f]*n* = 1,221; [g]*n* = 1,208; [h]*n* = 305; [i]*n* = 1,197; [j]*n* = 302; [k]*n* = 1196; [l]*n* = 293; [m]*n* = 1,130; [n]*n* = 294; [o]*n* = 1,153.

Table D.2.2

Summary of logistic mixed-effect regressions for accuracy within the four single item reading tasks

Predictor	*b*	*SE*	*z*-value	*p*-value
Letter identification task				
Intercept	4.31	.11	38.1	< .001
Age[1]	.12	.04	3.40	< .001
Lexical decision task				
Intercept	4.42	.15	29.5	< .001
Age[1]	.08	.06	1.22	.22
Phonological decision task				
Intercept	2.51	.11	22.2	< .001
Age[1]	-.13	.05	-2.92	< .01
Semantic decision task				
Intercept	4.25	.13	32.6	< .001
Age[1]	.11	.06	1.95	.05

Note. *b* = beta-estimate; *SE* = standard error; [1]older adults compared to younger adults; The main effect of age was significant only within letter identification and phonological decision, $\chi^2_{letter\ identification}(1) = 11.5, p < .001, \chi^2_{phonological\ decision}(1) = 8.52, p < .01$.

Table D.2.3

Summary of linear mixed-effect regressions for RTs within the four single item reading tasks

Predictor	*b*	*SE*	*t-value*
Letter identification task			
Intercept	694.5	7.10	97.9
Age[1]	-88.9	4.16	-21.4
Lexical decision task			
Intercept	835.2	14.7	56.9
Age[1]	-79.1	6.14	-12.9
Phonological decision task			
Intercept	1,330.2	28.9	46.0
Age[1]	-92.6	8.90	-10.4
Semantic decision task			
Intercept	781.7	9.66	80.9
Age[1]	-72.7	4.69	-15.5

Note. *b* = beta-estimate; *SE* = standard error; [1]young adults compared to older adults; Within each task, the main effect of age was highly significant, $\chi^2_{letter\ identification}(1) = 456.8, p < .001, \chi^2_{lexical\ decision}(1) = 166.1, p < .001, \chi^2_{phonological\ decision}(1) = 108.2, p < .001, \chi^2_{semantic\ decision}(1) = 240.4, p < .001$.