Idioms in the Aging Brain
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1 General discussion

This thesis investigated to what extent age-related cognitive decline goes hand in hand with changes in healthy elderly adults’ language processing. Research on young adults shows that successful language processing depends on executive functions such as working memory and inhibition (e.g., Daneman & Carpenter, 1980; Fedorenko et al., 2006; Gadsby et al., 2008; Gunter et al., 2003; Hoenig & Scheef, 2009; Hsu & Novick, 2016; Huettig & Janse, 2016; January et al., 2009; Palladino et al., 2001; Salisbury, 2004; Vos et al., 2001; Ye & Zhou, 2008). However, these executive functions typically decline with age, even in the absence of a neurodegenerative disease (e.g., Bopp & Verhaeghen, 2005; Hasher et al., 1997; Hasher & Zacks, 1988; Hultsch et al., 1992; Park et al., 2002; Salthouse, 2009; Singh-Manoux et al., 2012; Van Hooren et al., 2007). One would therefore expect that a decrease in working memory and inhibition skills has direct repercussions for our ability to process language (Eyigoz, Mathur, Cecchi, & Naylor, 2020). So far, however, data on this subject have been sparse.

To shed light on the effects of cognitive aging on language processing, this thesis presented four empirical studies that investigate how young, middle-aged, and elderly adults process Dutch idiomatic expressions, such as tegen de lamp lopen (literally: ‘to walk against the lamp, figuratively: ‘to get caught’). To understand an idiom, readers or listeners have to resolve the ambiguity between an idiom’s literal and figurative meaning, which may explain why successful idiom processing and comprehension has been found to depend on executive functions such as working memory and inhibition (Cacciari et al., 2018; Galinsky & Glucksberg, 2000). At the same time, these executive functions are known to decline with age. Therefore, idioms serve as the ideal testing ground for investigating how language processing changes due to age-related cognitive decline. Together, our findings aim to increase the existing knowledge on language abilities across the adult lifespan. Additionally, by providing more insight in the language abilities of healthy elderly adults, this thesis sets a baseline for research and interventions on language impairments in patients suffering from neurodegenerative diseases, such as Alzheimer’s dementia.

The studies presented in Chapters 2 - 5 each investigate the effects of cognitive aging on idiom processing from a different angle. Below, I will discuss how the various results contribute to the central research question of this thesis and how they add to our understanding of cognitive aging and idiom processing in general. This chapter will be concluded by some suggestions for future research.
Chapter 2: Elderly adults’ processing of idioms in context

The ERP study presented in Chapter 2 investigated whether the ability to benefit from linguistic context when processing idioms changes with age. Do young and elderly readers benefit from predictive context in the same way, or does cognitive decline hamper elderly adults’ ability to retain context information and use it to facilitate the processing of subsequent idioms by predicting and pre-activating their figurative meaning?

Effects were measured in the N400, which has been shown to be sensitive to context information (e.g., Federmeier & Kutas, 2005; Kutas & Federmeier, 2011), as well as to the facilitated processing of idioms (Laurent et al., 2006; Paulmann et al., 2015; Rommers et al., 2013; Strandburg et al., 1993). Additionally, we investigated effects in the P600, which has been argued to reflect the effort involved in the integration of word meanings to construct a sentence meaning (Brouwer et al., 2017; Brouwer & Hoeks, 2013). This process may be facilitated by predictive context information.

Our findings in the N400 showed that there is no difference between young and elderly adults with respect to the way in which they quickly resolve the ambiguity between an idiom’s literal and figurative meaning, and subsequently retrieve the figurative meaning from the mental lexicon. Both young and elderly adults show an idiom advantage: the processing of idiomatic sentences is facilitated relative to literal sentences, because an idiom’s figurative meaning can be retrieved as a whole in a word-like manner. In contrast, in literal sentences the meaning of each word has to be retrieved separately and these word meanings have to be combined compositionally. We also found that young and elderly adults do not differ in the way in which they benefit from predictive context information to facilitate the retrieval of upcoming words in literal and idiomatic sentences.

In contrast to our findings in the N400, our findings in the P600 showed a difference between young and elderly adults with regard to the way in which they integrate the meanings of words that were retrieved earlier to compute a sentence meaning. Specifically, we found that young adults complete this process without relying on context information, whereas elderly adults depend on context information to construct the meaning of literal, but not idiomatic sentences. The difference between elderly adults’ processing of literal and idiomatic sentences suggests that the idiom advantage for lexical retrieval also facilitates the higher-level process of sentence meaning computation, which allows elderly adults to construct the meaning of idiomatic sentences without relying on context information. However, the word-by-word retrieval and integration that is required in literal sentences may be more effortful and computationally too demanding for elderly adults. To compensate for this, they use context information to predict and pre-activate word meanings, which makes it easier to combine these words into a sentence if the words that they predicted actually appear.
Despite the fact that previous studies have underlined the importance of working memory capacity for the use of context in sentence processing (e.g., Federmeier & Kutas, 2005; Light & Capps, 1986; Van Petten et al., 1997), elderly adults’ lower working memory capacity did not affect their ability to benefit from context information in the retrieval of upcoming words, nor did it explain elderly adults’ increased reliance on linguistic context in the word-by-word computation of literal sentence meanings. Likewise, although young adults’ idiom comprehension has been found to rely on inhibition skills (Cacciari et al., 2018; Galinsky & Glucksberg, 2000), elderly adults’ reduced inhibition skills did not prevent them from showing the same idiom advantage as young adults. Only verbal fluency performance showed to be predictive of young and elderly adults’ use of context in literal and idiomatic sentence processing.

With regard to retrieval processes, we found that strong verbal fluency is associated with facilitated lexical retrieval. The relation between verbal fluency and sentence meaning integration is less clear than the relation between verbal fluency and lexical retrieval: strong verbal fluency was associated with increased effort in the computation of sentence meaning, whereas it was actually expected to be associated with a facilitation of this process. Possibly, the increased effort involved in the computation of sentence meaning, was driven by sentences containing a violation. It is conceivable that people with strong verbal fluency skills show efficient retrieval of word meanings, but also detect violations of meaning more easily when they have to combine the meanings of the words they have retrieved. As a result, strong verbal fluency skills could be associated with efficient error detection rather than increased effort in sentence meaning computation. Nevertheless, as verbal fluency scores did not differ between young and elderly adults, it is difficult to draw conclusions about the relationship between verbal fluency and the computation of sentence meaning in young compared with elderly adults.

Taken together, the study presented in Chapter 2 shows that the ability to use linguistic context to facilitate lexical retrieval during reading is remarkably stable across the adult lifespan. In contrast to our expectations, it is not affected by the age-related decline in working memory capacity. In addition, the idiom advantage also remains stable and is unaffected by age-related decline in inhibition skills. However, cognitive aging seems to affect the integration of word meanings, in the sense that elderly adults need to rely on additional context information when sentence processing is effortful. Specifically, literal sentence processing was found to be more effortful for elderly adults than the processing of idiomatic sentences. Thus, our findings indicate that idiom knowledge, which has been shown to increase steadily until old age (Sprenger et al., 2019), contributes to the cognitive reserve in elderly readers (Baum & Titone, 2014).
Chapter 3: Longitudinal effects of cognitive aging on idiom processing

The longitudinal ERP study discussed in Chapter 3 tested the same elderly adults as in Chapter 2, but now three years later. It investigated whether elderly adults' ability to benefit from context information in idiom processing remains stable or whether it declines over time due to the longitudinal effects of cognitive aging. Three years after comparing young and elderly adults' use of context in idiom processing, we measured the brain responses of the same elderly adults again with the same experimental set-up in order to map the cognitive and linguistic changes during old age within our elderly participants. In addition to measuring their N400 and P600 responses, verbal fluency scores were collected in both studies to measure longitudinal changes in cognitive processing.

The findings in the N400 and P600 indicated that elderly adults’ ability to benefit from context information in sentence processing, as well as the idiom advantage for lexical retrieval, are preserved over the three years between testing. The same held for their cognitive abilities. The longitudinal preservation of elderly adults' language processing abilities may have resulted from the protective effect of their superior verbal knowledge (e.g., Brysbaert et al., 2016), including knowledge of idioms (Sprenger et al., 2019). Especially the idiom advantage for lexical retrieval may benefit from language experience, as idiom familiarity has been found to play an important role in the facilitated processing of idioms relative to literal sentences. (Carrol & Conklin, 2020; Carrol & Littlemore, 2020). Thus, in addition to our findings in Chapter 2, which suggested that idiom knowledge contributes to the cognitive reserve of elderly readers when measured cross-sectionally, our longitudinal data indicate that idiom knowledge may also serve as a buffer against the longitudinal effects of cognitive aging on elderly adults’ language abilities.

An alternative explanation for the longitudinal preservation of elderly adults’ processing of idioms in context was that the elderly participants, who had a mean age of 71 at the time of the follow-up study, were too young to show a longitudinal decline in language processing abilities. Based on the literature, we expected decline in cognitive abilities to start between the age of 60-65 (e.g., Hatta et al., 2020; Hultsch et al., 1992; Schaie, 2013), approximately five years younger than the participants in the follow-up study. This expected longitudinal decline in elderly adults’ cognitive skills was predicted to affect their language processing abilities. Therefore, the fact that we found that elderly adults' processing of idioms in context was preserved over time was unexpected. However, a recent longitudinal study by Vonk et al. (2020) showed that verbal fluency, which we used as a measure of cognitive processing, does not decline longitudinally until the age of 73. Based on this finding, we suggest that the second study was possibly conducted too early in the participants’ lifespan to detect significant changes in verbal fluency, and that verbal fluency is too coarse a measure to detect cognitive decline on this time scale.
This conclusion is supported by the EEG data, in which we observed significant changes across the three years: the general N400 effect decreased, whereas the general P600 effect increased in strength. The longitudinal decrease in the N400 effect was suggested to result from age-related changes in the brain’s architecture that alter the timing or strength of neural signals. This may slow down the activation and retrieval of word meanings, and thereby the detection of words that introduce a semantic violation in the sentence. Furthermore, given the fact that the P600 has been argued to reflect processes of semantic integration (Brouwer et al., 2017; Brouwer & Hoeks, 2013), the longitudinal increase in the P600 effect was suggested to indicate a change in elderly adults’ processing strategy in which the allocation of neural resources is shifted from lexical retrieval processes to processes related to the integration of word meanings to construct a representation for the entire sentence or discourse (Dave et al., 2018). In other words, cognitive aging may lead elderly adults to focus more heavily on higher-level language processing.

In sum, Chapter 3 contributes to our main research question by providing insight in the slope of decline in language abilities due to cognitive aging. Specifically, Chapter 3 showed that elderly adults’ ability to benefit from context information and from the idiom advantage in sentence processing does not significantly decline over the course of three years. Thus, whereas the findings from previous studies on longitudinal changes in cognition led us to expect a corresponding decline in language abilities in elderly adults, both language abilities and cognitive abilities showed to be surprisingly stable when measured over the course of three years. As longitudinal changes in language processing were investigated within the same group of elderly adults, our findings cannot be attributed to individual differences in cognitive abilities, education, socio-economic status or genetics that may bias findings from studies comparing language processing in different age groups cross-sectionally. Finally, the findings in Chapter 3 contribute to the general research question by pointing to the role that elderly adults’ language experience may play in compensating for the longitudinal effects of age-related cognitive decline on language processing abilities.

Chapter 4: Literal word meaning suppression in idiom processing across the adult lifespan

Chapter 4 presented an ERP study examining the relationship between cognitive aging and the suppression of literal word meanings during idiom processing. Specifically, we investigated how the time course of literal word meaning suppression during idiom processing changes across the adult lifespan due to age-related cognitive decline. To this aim, the brain responses of adults between the age of 20 and 80 were recorded while they read sentences containing an idiom. We focused on the amplitude of the N400 to measure the extent to which the literal
meaning of an idiom's final noun is activated. Furthermore, we examined whether the degree to which readers have suppressed the literal meaning of an idiom's final noun depends on how much they have seen of the idiom. This determines the extent to which they have had the chance to activate the idiom’s figurative meaning, and therefore the need for inhibition of literal word meanings. This was manipulated by presenting the idioms in Subject-Verb-Object order (SVO) and in Subject-Object-Verb order (SOV). In Dutch, both word orders can express the same meaning. The activation of the literal meaning of the idiom’s final noun was expected to vary with its position in the sentence.

Previous studies on literal sentence processing have shown that, relative to the N400 elicited by unexpected words, the N400 is smaller when readers or listeners encounter expected words, but also when they encounter words that are semantically related to the expected word (Federmeier et al., 2002; e.g., Federmeier & Kutas, 1999). These findings indicate that pre-activation of predicted words spreads through the mental lexicon from the expected word to semantically associated words. However, when investigating idiom processing in young adults, Rommers et al. (2013) found that words that are semantically related to the literal meaning of an idiom constituent do not lead to the same N400 reduction as the same words presented in a literal context. Based on these findings, Rommers et al. (2013) argued that idiom processing does not require the word-by-word integration of the literal meanings of idiom constituents, as the figurative meaning of the idiom can be retrieved from the mental lexicon as a whole. Consequently, the literal meanings of idiom constituents are not activated anymore by the time the reader reaches the idiom’s final word.

Our study further elaborates on those findings. We find that the time course of literal meaning suppression in idiom processing critically depends on age and the position of an idiom constituent in the sentence. Specifically, we show that the speed at which the literal meanings of idiom constituents are suppressed slows down gradually with increasing age. Young adults are faster in suppressing literal word meanings than middle-aged and elderly adults. Furthermore, the gradual age-related delay in literal word meaning suppression is most apparent at the offset of the idiom. Before reading the idiom’s last word, literal word meanings were still active in all participants, but after reading the idiom’s last word, only young adults had suppressed its literal word meaning. Taken together, we find that already from middle-age on, literal word meanings are suppressed less quickly in idiom processing. Such a slow-down in ambiguity resolution is in line with Burke et al.’s (1991) observation that the speed of signals in the neural network generally slows down with age. With regard to idiom processing, the delay in middle-aged and elderly adults’ transfer of neural signals through the network could slow down the activation of the lemma containing the idiom’s figurative meaning, which in turn slows down the suppression of the literal meanings of the idiom constituents. Therefore, the fact that literal word meanings are suppressed at idiom offset in
young adults, but not in middle-aged and elderly adults, may reflect an overall effect of cognitive aging on language processing.

In sum, Chapter 4 shows how the time course of resolving ambiguity between an idiom’s literal and figurative meaning within the sentence changes gradually across the adult lifespan. Crucially, Chapter 4 shows that age-related changes already start in middle-age, around age 40, thereby underlining the importance of investigating the effects of aging on language across the entire adult lifespan.

Chapter 5: Cognitive aging delays figurative interpretation in idiom processing

The study presented in Chapter 5 consisted of a picture-selection task carried out in a visual-word eye-tracking paradigm (Cooper, 1974; Tanenhaus et al., 1995). It investigated the effects of cognitive aging on the time course of selecting the figurative meaning of idioms. Additionally, to examine the relationship between the time course of idiom activation and cognitive aging, age-related differences in the time course of selecting an idiom’s figurative meaning over its literal phrase meaning were related to individuals’ performance on offline tests of executive control, inhibition skills, and sustained attention.

Young and elderly adults were equally good at selecting the correct picture. However, the time course of gaze allocation revealed that elderly adults were affected more strongly by competition from pictures of the idiom’s literal meaning. This is consistent with the findings of Westbury and Titone (2011), who observed that elderly adults have more difficulties with judging whether an idiom can be interpreted literally when there is strong competition between the idiom’s literal and figurative meaning. Yet, contrary to what we had expected, the delay in elderly adults’ activation of the idiom’s figurative meaning was not predicted by their reduced performance on the tests of executive control and inhibition, despite previous studies showing that young adults’ idiom processing and comprehension depend on inhibitory capacities (Cacciari et al., 2018; Galinsky & Glucksberg, 2000). Possibly, the type of inhibition that is measured by the Stroop task, which we used in the present study, does not match the type of inhibition that is involved in resolving ambiguity between an idiom’s literal and figurative meaning. Cacciari et al. (2018) related successful idiom processing and comprehension to inhibition skills measuring the number of intrusions in a Listening span task, whereas Galinsky and Glucksberg (2000) measured inhibition by investigating to what extent the activation of the figurative meaning of metaphors and idioms leads to negative priming of their literal meanings. Thus, both Cacciari et al. (2018) and Galinsky and Glucksberg (2000) measured inhibition in a linguistic task. Therefore, it is conceivable that the type of inhibition involved in idiom processing is specific for
language. This hypothesis would be in line with recent work suggesting that language processing and domain-general cognitive processing are separate constructs (e.g., Diachek et al., 2020; Shain et al., 2020; Wehbe et al., 2020). Thus, even though elderly adults showed a delay in the inhibition of an idiom’s literal meaning as well as reduced performance on offline cognitive tasks, and this is highly suggestive of a shared mechanism, it may also simply reflect a parallel decline in two independent systems. Therefore, future studies should include both linguistic and non-linguistic inhibition tasks to examine how age effects on idiom processing are related to age-related decline in both types of inhibition skills.

In conclusion, the study presented in Chapter 5 provides insight in the effects of cognitive aging on language abilities by showing that cognitive aging delays the activation of the figurative meaning. Furthermore, the discrepancy between elderly adults’ preserved offline idiom comprehension and the delay in their time course of idiom processing underlines the importance of using online research methods when studying the effects of cognitive aging on language abilities. Finally, it is argued that non-invasive online research methods such as eye-tracking have the potential of improving early detection of language difficulties in elderly adults suffering from neurodegenerative diseases such as Alzheimer’s dementia (e.g., Eyigoz et al., 2020). The findings presented in Chapter 5 provide a baseline for such future studies.

2 Theoretical implications

The findings discussed in this thesis have implications for theories of cognitive aging, as well as for theories of idiom processing. Below the implications for each field will be discussed.

2.1 Cognitive aging

Theories of cognitive aging have attributed age-related changes in cognitive and linguistic abilities to multiple factors. As successful idiom processing and comprehension have been shown to depend on working memory capacity and inhibition skills in young adults (Cacciari et al., 2018; Galinsky & Glucksberg, 2000), elderly adults’ ability to resolve the ambiguity between an idiom’s literal and figurative meaning during sentence processing was expected to be affected by the typical age-related decline in these cognitive abilities (e.g., Bopp & Verhaeghen, 2005; Craik & Salthouse, 2011; Hasher et al., 1997; Hasher & Zacks, 1988; Hultsch et al., 1992; Park et al., 2002; Salthouse et al., 1988; Van Hooren et al., 2007). Thus, we hypothesized that the findings of this thesis would be in line with theories that attribute the effects of cognitive aging to a decline in working memory capacity (e.g., Baddeley, 1986; Engle et al., 1999) or inhibition skills (e.g., Hasher et al., 1997;
However, none of the studies presented in this thesis reported a direct link between age-related changes in idiom processing and a reduction in elderly adults’ working memory capacity or inhibition skills: either age effects in idiom processing occurred in the absence of reductions in inhibition skills (Chapter 4) or elderly adults’ reduced working memory capacity and inhibition skills did not predict their increased dependency on linguistic context for the computation of literal sentence meaning (Chapters 2 and 3), nor the delay in elderly adults’ activation of an idiom’s figurative meaning (Chapter 5). Therefore, this thesis does not provide support for theories explaining age-related changes in language abilities by a decline in working memory capacity or inhibition skills.

Instead, the age-related delay that was found in elderly adults’ suppression of the literal meanings of idiom constituents (Chapter 4), the delay in elderly adults’ activation of an idiom’s figurative meaning over its literal meaning (Chapter 5), and the longitudinal reduction in the strength of elderly adults’ general N400 effect (Chapter 3) are in line with theories of cognitive aging that attribute age-related cognitive decline to a reduced transmission of neural signals through the network (Burke et al., 1991). As previous studies show that literal word meanings are activated in initial stage of idiom processing (Beck & Weber, 2016; Cacciari & Tabossi, 1988; Holsinger & Kaiser, 2013; Kessler et al., 2020; Konopka & Bock, 2009; Laurent et al., 2006; Peterson et al., 2001; Sprenger et al., 2006; Swinney & Cutler, 1979; Titone & Connine, 1999, 1994), we expected activation to spread from the literal meanings of the idiom constituents to the lexical node representing the meaning of the idiom as a whole (e.g., its superlemma, Sprenger et al., 2006). Once the idiom’s figurative meaning is activated, the literal meanings of the idiom constituents need to be inhibited. An age-related slow-down in the speed of neural signals, consistent with Burke’s account (1991), would not only explain a delay in the activation of the idiom constituents, but also that of the subsequent activation of the idiom’s figurative meaning (Chapter 5) and the suppression of literal word meanings (Chapter 4).

A reduced transmission of signals through the mental lexicon could also explain why elderly adults have been found to be less likely than young adults to revise their interpretation of ambiguous words (Meyer & Federmeier, 2010), as there may be a delay in the flow of activation from the lexical node of the initial interpretation to the lexical node of the revised interpretation. Thus, Burke’s account of cognitive aging (1991) cannot only explain age effects in the processing of idioms, but also in the processing of other forms of ambiguous constructions, such as lexical ambiguities.

Finally, the idiom advantage for lexical retrieval that was found in young as well as elderly adults (Chapters 2 and 3) and the longitudinal preservation of elderly adults’ ability to benefit from context information in sentence processing (Chapter 3) suggest an important role for language experience as a protective factor against the effects of cognitive aging on language abilities. These observations are in line...
with the work by Ramscar and colleagues (Ramscar et al., 2014, 2017; Wulff et al., 2019). Their account states that age-related changes in cognitive performance should not be considered a result of cognitive decline, but rather a logical consequence of the fact that the accumulated verbal knowledge that elderly adults have acquired over the years (e.g., Brysbaert et al., 2016; Verhaeghen, 2003) increases competition between nodes in the mental lexicon. This increased competition is argued to explain elderly adults’ reduced performance on tasks measuring inhibition skills. This is a positive view on cognitive aging, as it sees age-related changes in cognitive performance not as decline, but as a learning effect. Nevertheless, more research is needed to investigate how the large amount of verbal knowledge that elderly adults have collected throughout their lives interacts with changes in domain-general cognitive abilities and high-level language processes, such as sentence processing or the resolution of ambiguity in sentence processing (Baum & Titone, 2014). Idioms may provide an ideal testing ground for future studies on this topic, as idioms have a long learning curve that reaches its peak in old age (Sprenger et al., 2019). At the same time, idiom processing depends on cognitive abilities such as inhibition skills (Cacciari et al., 2018). However, before idioms can be used to test accounts of cognitive aging, idiom models need further specification with regard to the way in which activation of the idiom’s literal and figurative meaning may change with age. Therefore, the theoretical implications of our findings for models of idiom processing across the adult lifespan are discussed below.

2.2 Idiom processing

An important question for models of idiom processing is what role literal word meanings play in the processing of idioms. Although comparing models of idiom processing was not the goal of the studies presented in this thesis, the findings do contribute to the discussion.

First, the processing advantage for idioms that we found in both young and elderly adults (Chapters 2 and 3) is in line with previous findings on young adults (e.g., Carrol & Conklin, 2020; Carrol & Littlemore, 2020; Conklin & Schmitt, 2008; Siyanova-Chanturia et al., 2011; Swinney & Cutler, 1979; Underwood et al., 2004) and extends them to the elderly population. Furthermore, this idiom advantage for lexical retrieval supports idiom models arguing that the figurative meaning of an idiom has its own lexical node in the mental lexicon and is therefore retrieved in a word-like manner (e.g., Bobrow & Bell, 1973; Cutting & Bock, 1997; Gibbs, 1980; Sprenger et al., 2006). According to this view, the idiom advantage is a consequence of the fact that the idiom’s figurative meaning can be retrieved from the mental lexicon as a whole.

Second, the findings in Chapters 4 and 5 showed that literal meanings are activated during idiom processing. Therefore, these findings contradict models of
idiom processing that state that an idiom’s figurative meaning is retrieved from the mental lexicon without activating its literal word meanings (Bobrow & Bell, 1973; Gibbs, 1980) and support models that incorporate the activation of literal meaning as part of idiom processing (e.g., Cacciari & Tabossi, 1988; Cutting & Bock, 1997; Holsinger & Kaiser, 2013; Libben & Titone, 2008; Sprenger et al., 2006).

Third, within the set of idiom models assuming literal meaning activation, the models differ with respect to the extent to which literal meaning activation takes place. The findings in Chapter 4 showed that the degree to which literal meaning activation takes place is a function of how much of the idiom the reader has seen. This variability in the degree of literal meaning activation, and in turn the activation of the idiom, argues against the existence of a idiom key (Cacciari & Tabossi, 1988). An idiom key is a specific word in the idiom after which the idiom is recognized as such, and after which the reader or listener switches from processing the idiom’s literal, compositional meaning to processing the idiom’s figurative meaning. Instead, the findings in Chapter 4 support hybrid models of idiom processing in which the activation can flow bi-directionally between the lexical nodes representing the literal meanings of the idiom constituents and the lexical node representing the idiom’s figurative meaning (Sprenger et al., 2006). The more idiom constituents have been encountered, the more likely it is that the activation of the idiom lemma surpasses the activation level of the single lemmas representing the idiom constituents, leading to the retrieval of the idiom’s figurative meaning. In this view, idiom activation is a gradual process, rather than the result of a sudden change of interpretation. The advantage of the hybrid approach is that it can explain facilitating context effects within the same framework.

Finally, the findings in this thesis expand existing theories of idiom processing by providing insight in the way in which idiom processing is modulated the age of readers or listeners. Specifically, Chapters 4 and 5 showed that the point at which readers or listeners switch from processing the idiom’s literal, compositional meaning to processing its figurative meaning is a function of age and the number of idiom constituents that a reader has seen. The best candidates for incorporating these findings on idiom processing in old age are hybrid models of idiom processing. Unlike models arguing that the figurative meaning of an idiom is retrieved without activating the literal meanings of idiom constituents (Bobrow & Bell, 1973; Gibbs, 1980), hybrid models assume that idiom processing also involves the activation of literal word meanings, at least in initial stage of processing (e.g., Cacciari & Tabossi, 1988; Cutting & Bock, 1997; Sprenger et al., 2006; Titone & Connine, 1999). This means that at some point during the processing of the idiom, readers or listeners need to switch between the idiom’s two meanings. The findings in Chapter 4 and 5 could be explained by expanding hybrid models of idiom processing with the notion that the timing of the switch between an idiom’s literal and figurative meaning is a function of age.
The effect of age on the switch between the processing of an idiom’s literal and figurative meaning can be explained particularly well by a subset of hybrid models that specify the way in which the lexical nodes of idiom constituents are connected to the lexical node of the idiom as a whole (Cutting & Bock, 1997; Sprenger et al., 2006). The specification of these connections enables the formulation of hypotheses on how the connection and the flow of activation between the nodes is influenced by non-linguistic factors, such as age. In this way, these hybrid models of idiom processing could be linked to Burke’s account of cognitive aging (1991), which holds that age-related cognitive decline is driven by a slow-down in the transmission of signals between nodes in the neural network, which reduces the efficiency of cognitive processing in elderly adults. In idiom processing, a similar slow-down in the speed of neural signals could explain why figurative meaning activation, and relatedly literal word meaning suppression is delayed in elderly adults. In this way, the studies on the effects of cognitive aging on idiom processing that are presented in this thesis establish a link between the processing of language and domain-general cognitive processing.

3 Future directions

Using idioms as a paradigm for ambiguity processing during language comprehension, the work discussed in this thesis shows that the online processing of language changes across the adult lifespan. The empirical studies not only show a difference between young and elderly adults’ processing of idioms with and without preceding context information, but also reveal that age-related changes in idiom processing already occur as early as middle age, and that they do not correlate with measures of the degree of the readers’ or listeners’ cognitive decline. Taken together, the findings presented in this thesis provide several avenues for further research.

First, the fact that a change in language processing was found to already start in middle-aged adults from the age of 40 underlines the importance of studying language across the entire adult lifespan. In addition to comparing groups of young adults to groups of elderly adults, studies could also include the middle age range to gain insight in language abilities across the full adult age spectrum. Moreover, to achieve a full understanding of language processing across the lifespan and to shed light on the point at which changes in the processing of different types of linguistic constructions start to appear, research would benefit from studying age as a continuous factor. An additional advantage of examining gradual changes across the lifespan is that it enables researchers to identify or rule out factors that potentially modulate age effects in language processing, such as cognitive abilities, education, socio-economic status, or genetics. By including individuals of all ages, the present thesis has shown that age-related changes in the time course of language processing
and the time course of cognitive processing do not progress at the same pace. This discrepancy would not have been discovered if language processing and cognitive processing were only investigated in adults at two points of the age spectrum, for example young adults and elderly adults.

The findings of this thesis indicate that the relationship between the mechanism underlying age-related changes in language abilities and those underlying age-related changes in cognitive processing needs further investigation. Although we show that language processing changes with age, no direct links were found between online measures of language processing and offline performance on neuropsychological tests. Here, we propose two possible methodologies to test the connection between age-related changes in linguistic and cognitive processing. The first possibility would be to study both language processing and cognitive processing using online measures, such as event-related potentials. Specifically, researchers could correlate components reflecting inhibition mechanism, such as those in response to an ERP-version of the Stroop task (e.g., West, 2004; Zurron, Lindín, Galdo-Alvarez, & Díaz, 2014), to components reflecting language processing, such as the N400 and P600 that were studied in this thesis. A second possibility would be to use cross-task paradigms in which tasks of domain-general cognitive functioning are integrated in a language task to test the dependency of the linguistic processes under investigation on general cognitive processing. For example, in a visual-world eye-tracking study by Hsu and Novick (2016) trials testing the processing of temporarily ambiguous sentences were alternated with trials testing cognitive control abilities by means of a Stroop task. Hsu and Novick (2016) showed that when Stroop trials preceded the language trials, activation of the cognitive control mechanisms supporting performance on the Stroop trials also facilitated individuals’ revision or erroneous interpretations in the processing of temporarily ambiguous sentences. Based on their findings, they argue that the general cognitive control mechanisms underlying error detection on incongruent Stroop trials also support reinterpretation mechanisms in language processing. Both the paradigm used by Hsu and Novick (2016), as well as a combined event-related potential paradigm for cognitive and language processing could provide a starting point for linking domain-general cognitive functions to the successful processing of linguistic constructions that may depend on these cognitive abilities.

Future studies testing the connection between linguistic and cognitive processing across the lifespan would also benefit from paying specific attention to individual differences. While the studies presented in this thesis were based on the hypothesis that successful language processing depends on domain-general cognitive abilities, recent neuro-imaging research has revealed no overlap between regions that are responsible for domain-general cognitive processing and those that support language tasks (Diachek et al., 2020), leading the authors to conclude that domain-general cognitive processing does not play a role in sentence comprehension. Importantly, Diachek et al. investigated activation patterns that
were defined for each individual participant, thereby accounting for individual differences in linguistic and cognitive processing. The idea that linguistic processing and domain-general cognitive processing are supported by separate cognitive processes explain why we found that language processing changes gradually with age, but that these changes cannot be traced back to a decline in elderly adults’ performance on offline cognitive tasks. Applying Diachek et al.’s view to the investigation of language processing across the adult lifespan would lead to the idea that domain-general abilities and language abilities can decline separately from one another, each at their own pace. To gain more insights in the relationship between cognitive processing and linguistic processing, future studies could follow the approach by Diachek et al. (2020) and focus on the role that individual differences play in this relationship. Concretely, this could imply that language processing should be studied in a more diverse population. The adults who participated in the studies discussed in this thesis all had a high level of education. A starting point for future studies could therefore be to investigate the relationship between language processing and cognitive abilities in adults with a more diverse range of education levels.

Finally, the findings in this thesis show that future research can benefit from the use of statistical analysis techniques such as Generalized Additive Mixed-effects Modelling that enable researchers to make better use of the high temporal precision of online research methods, such as event-related potentials and eye-tracking. Specifically for the investigation of language processing across the lifespan GAMMs provide multiple benefits: 1) they avoid the arbitrary selection of time windows and take into account age-related changes in timing of effects, and 2) they enable researchers to model effects against the continuous effect of age, thereby avoiding the creation of artificial age groups and providing an opportunity to discover changes in the slope of age effects. It should be noted that GAMMs are often applied in studies with a relatively simple task design, such as those investigating young adults’ auditory discrimination of syllables in an oddball paradigm (e.g., Boll-Avetisyan et al., 2018) or young adults’ ability to detect the direction of a moving object (e.g., Boehm, Van Maanen, Forstmann, & Van Rijn, 2014). Therefore, the use of GAMMs for the analysis of data collected in more complex designs involving higher-level cognitive processing, such as sentence processing, needs further specification and development. Nevertheless, the use of advanced statistical analysis techniques will ultimately benefit research by providing a clearer picture of the way in which the time course of language processing changes across the lifespan and how this process is influenced by individual differences.
4 Conclusions

Together, the results discussed in this thesis provide insight in which aspects of language processing remain relatively stable across the adult lifespan and which language abilities change in healthy elderly adults.

A first aspect of language processing that did not differ between young and elderly adults is the idiom advantage for lexical retrieval. Thus, elderly adults are as able as young adults to benefit from the fixed character of idioms in the retrieval of meanings in sentence processing. Furthermore, we found no differences in young and elderly adults’ ability to benefit from context information to facilitate the processing of lexical retrieval in both literal and idiomatic sentences. Moreover, we showed that elderly adults’ ability to use context in sentence processing does not decline over the course of three years, suggesting that linguistic decline in healthy aging progresses relatively slowly.

A difference between young and elderly adults’ language processing was found in the computation of sentence meanings. We found that elderly adults, but not young adults use context information for the processing of literal sentences. This supports the idea that the idiom advantage for lexical retrieval reduces processing effort, while literal sentence processing is effortful. Furthermore, despite the robustness of the idiom advantage against the effects of cognitive aging, we found that the time course of idiom processing changes across the adult lifespan. Specifically, the suppression of literal word meanings was found to decline gradually with age. Notably, age-related changes already start to occur in middle-age around age 40. In line with the gradual age-related decrease in literal word meaning suppression during idiom processing, elderly adults’ selection of an idiom’s figurative meaning over its literal phrase meaning was found to be delayed in comparison with young adults. These findings suggest that elderly adults need more time to switch from the literal interpretation of the idiom to a figurative interpretation. Finally, although elderly adults’ use of context in idiomatic and literal sentence processing did not change over the course of three years, we found longitudinal changes in general patterns of language processing in the brain that may indicate a change in elderly adults’ processing strategies. Specifically, elderly adults may shift the allocation of neural capacity from processes related to prediction and lexical retrieval to the integration of word meanings with the aim of constructing a sentence meaning.

In sum, the work in this thesis shows that certain aspects of language processing change in healthy aging and that these changes already start as early as age 40. At the same time, the absence of longitudinal decline in elderly adults’ language processing abilities indicates that a large part of the effects of age on language processing already takes place in middle age and that the curve of decline flattens into old age. Although the delay in online idiom processing did not lead to impairments in elderly adults’ offline idiom comprehension, an important question
is to what extent subtle delays in online language processing can cause communication difficulties in real-life settings. This can be expected, as conversation partners typically do not wait until the listeners has resolved potential ambiguities in the spoken message. In the future, findings on changes in elderly adults' language processing should be connected to the ways in which language is used in actual discourse settings, to create a clearer picture of potential communication difficulties in healthy aging.

Finally, the present thesis showed that it is not easy to trace back age effects in online language processing to age-related changes in offline measures of cognitive performance. On the one hand, this finding adds fuel to the general discussion on the dependency of language processing on domain-general cognitive processing. On the other hand, the fact that we found that language processing changes across the adult lifespan supports the idea that there is a connection between language processing and cognitive processing. However, the nature of this connection remains to be determined. Future studies may need to take a broader perspective on language processing by considering factors that may compensate for age effects in language processing, such as language experience, education, and socio-economic status. In other words, studying the interaction between cognitive aging and sentence processing calls for a holistic approach that accounts for the complexity of the phenomena under investigation.