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Syntactic Processing in Older Adults

A Review of Studies and Theories from 1980 to the Present

Abstract: In the past 40 years, there has been a growing body of research using different methods investigating whether syntactic processing declines with age. To date, however, studies have provided conflicting results. Here we present a review of the relevant studies and theories, in chronological order, to illustrate the development of focus, methods, and models across the four decades. From this review, one can see that older adults' syntactic processing involves a complex process which may be influenced by many factors, such as syntactic complexities, individual differences, and languages. And the interpretation of syntax is difficult to separate from other cognitive factors such as working memory. But similar neural changes found in imaging studies suggest that, with advanced technologies and better research designs, researchers do not have far to go to find out the nature of age-related syntactic processing. In addition, the recently devised comprehensive model, based on all previous studies about cognition, shows a systematic illustration of the change in cognition across age and provides suggestions for the prevention of cognitive decay. This model is enlightening for age-related syntactic processing, although it still needs the support of further evidence from syntactic studies.

Keywords: age; behavioral studies; neurocognitive studies; syntax; theoretical models

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1 Introduction

In 2019, one of the ten key findings of the UN 2019 Revision of World Population Prospects was that the world's population is aging, with people over age 65 being the fastest-growing age group: "By 2050, one in six people in the world will be over age 65 (16%), up from one in 11 in 2019 (9%)" (UN: 2019). Obviously, the gradual increase in the number of older adults in the world has become an indisputable fact, and the world is entering an era of population aging. People have realized that the increase of older adults in the population should be accompanied by efficient policies, medical technologies, and services. Language, whose quality shapes both the psychological and physical health of older adult individuals (Keaton & Giles 2016), has therefore become an active research area in the investigations of older adults. However, knowledge about the development of older adults' syntactic knowledge is still under debate (Zhu et al. 2018) and needs further attention. The present study aims to review the studies on older adults' syntactic processing in chronological order, specifically, from 1980 to the present and then to illustrate the relevant theories.

2 Studies from 1980 to the Present

In general, studies on the syntactic comprehension of aging adults can be basically divided into two stages: the first period is the time before 2000, mainly including the 1980s and 1990s, during which the syntactic abilities of aging people were mainly examined through behavioral methods; the second period is from 2000 to the present, with advanced technologies such as event-related potentials (ERPs) and fMRI being applied in the relevant studies. Despite the fast development in the research methods, the existing results are not consistent in answering the question of whether there is a decline with age in the ability to process sentences syntactically. In the following section, we will introduce the relevant studies in terms of the two different periods.

2.1 Behavioral Research Stage

The studies on the syntactic processing of aging people began in 1980 and developed slowly in the first two decades. Yet the studies during this period laid a good foundation for the flourishing of research after 2000. There are mainly two trends for the studies in this stage: the beginning of offline studies in the 1980s and the attempts at online studies in 1990s.

2.1.1 Offline Studies in the 1980s

In the 1980s, people began to pay attention to older adults' linguistic abilities. Emery (1985, 1986), Kemper (1986, 1987), and Kemper et al. (1989) all found that aging led to less syntactic complexity in production, although this result might be moderated by other factors such as memory and education (Kemper et al. 1989). Comparatively, however, there were fewer studies on syntactic comprehension, and studies at this period were usually offline, taking accuracy as the main measurement standard of the results. Nonetheless, these few studies had varied findings about whether syntactic comprehension would decline in normal aging.

Feier and Gerstman (1980) tested different age groups' comprehension ability in listening for four types of relative clauses, in which the subjects were asked to act out sentences they heard. The results showed that people's performance began to decline in their 60s. Later, Davis and Ball (1989) presented subjects with spoken sentences and asked them questions about "what is doing what" in the relative sentences in different plausibilities and claimed the same decline trend as in Feier and Gerstman (1980) in older people's comprehension results. However, the contrary was concluded by Lieberman et al. (1989), who used the Rhode Island Test of Language Structure to examine 29 elderly people with an average age of 80.8 years by using a sentence–picture matching task, and found that there was decreasing comprehension of syntax with increasing age, but a further analysis with the removal of nonnative speakers revealed no age effect on the subjects' performance.

It is worth noting that there were factors other than aging that played roles in drawing the conclusions in these studies, such as memory, sentence type, plausibility, and so on. According to Feier and Gerstman (1980), the subjects' accuracy was found to correlate with their performance in vocabulary and digit span, and in the oldest group, in which people were 74–80 years old, education was found to lead to a significant difference in the results. Furthermore, Feier and Gerstman found no correlation between age and the various types of relativized sentences, although performance was worse on all relativized sentences compared to conjoined sentences. Davis and Ball (1989), however, showed that aging did not affect the results concerning the semantic component, but it worsened the comprehension of syntactic questions in implausible sentences. Also, for those aged in their 70s, distance played a role in their understanding of both center-embedded and right-branching sentences, which meant that cognitive factors such as working memory might modify language comprehension. Thus, Davis and Ball concluded that instead of affecting a certain component of the language system, normal aging may lead to alterations in the correlation between components. Lieberman et al. (1989) found, however, if the language background was considered, the result is different, as they found that nonnative speakers made more errors in the tasks. Moreover, this study included a small discussion on individual disease processes which were also considered as a possible account for the result.

The conclusion that we can draw from these few attempts in the 1980s is that aging may lead to a decline in syntactic comprehension, yet the reasons for this deterioration in linguistic processing are complex, and we can hardly attribute the results to the syntactic ability itself.

2.1.2 Online Studies in the 1990s

In the 1990s, researchers began to focus on online processing, in which reaction time was taken as an additional factor for the comprehension results. In this period, researchers realized that they should test and discuss the cognitive factors involved in older adults' syntactic processing. Nonetheless, the deterioration of syntactic comprehension in normal aging has still not been confirmed. While some people claimed there was a decay in syntactic comprehension in normal aging, others came to different conclusions.

Obler et al. (1991) and Baum (1993), for example, confirmed a decline in the syntactic interpretation abilities of older people and attributed it to a specific language disease. Obler and colleagues tested the comprehension of six syntactic structures across four age groups (30s, 50s, 60s, 70s) with word-monitoring tasks, and the results showed that both errors and reaction times increased with age, especially for more complex syntactic types and implausible sentences. In addition, it was found that neuropsychological factors such as mental control, verbal memory, and sustained attention contributed minimally to an age-related decline in comprehension, suggesting that the subtle breakdown seen in syntactic processing may be a language-specific impairment. In addition, Baum (1993) explored the processing of relative clause structures by normal elderly adults in two experiments, a lexical decision task and a sentence repetition task. The results of the lexical decision task revealed longer reaction times and somewhat different patterns of performance for the older subjects as compared to the young subjects; on the repetition task, the oldest subjects performed more poorly. Overall, the author concluded that there was a reduction in computational capacity accompanying normal aging, which may account for the observed decrements in the syntactic processing of the elderly subjects.

However, some other researchers came to a different conclusion. Baum (1991), for example, found that three age groups exhibited the same reliable sensitivity to ungrammaticality. He assessed the online syntactic processing abilities of three groups of adults (60–69 years, 70–79 years, 80–89 years) via the same paradigm as Obler et al. (1991). Sensitivity to syntactic violations in stimuli, including both local (within-clause) and long-distance (across-clause) dependencies, was examined through error analyses and reaction time measures. The results revealed no general decline in online syntactic processing, as there was no statistically significant difference across the subject groups. Nor was there a correlation between age and reaction time. Baum thus agreed with Lieberman et al. (1989), who claimed that a decline in syntactic performance was not a natural feature associated with normal aging, but rather that individual differences in aging and disease processes yielded an age-related decline in syntactic processing.

Zurif and colleagues (1995) used a cross-modal lexical priming study to investigate older adults' gap-filling processing in subject- and object-relative sentences. They found that older adults showed the expected priming effects in subject-relative sentences and short object relatives but not in object-relative sentences with longer antecedent-gap distances. The authors therefore concluded that older adults' sentence-processing deficits were due to a decline in working-memory capacity. However, Zurif et al. (1995) reached this conclusion based only on old adults' performance, instead of directly comparing older and younger adults, making the results less convincing.

Later, Kemtes and Kemper (1997) designed a better study. They examined younger and older adults' online processing of the main verb and relative clause sentences in a self-paced word-by-word reading task, in which three different measures were applied to collect all participants' composite working-memory capacities. The results showed that declines in syntactic processing were not specific to all older adults. Working-memory span, type of syntactic ambiguity (ambiguous vs. unambiguous), and type of syntactic ambiguity resolution (main verb vs. relative clause) interacted with each other to influence younger and older adults' online reading times and offline sentence comprehension. This finding provided support for an individual-differences approach to older adults' syntactic processing.

In summary, the studies in this period attempted to explore syntactic comprehension in aging through online tasks. Even though they still failed to obtain a consistent conclusion, the studies during this stage involved more consideration of multiple factors in older adults' syntactic processing, such as working memory, syntactic types, and individual difference, which was enlightening for the later studies.

2.2 Online and Neurocognitive Research Stage

From 2000 to 2020, more and more studies set out to explore syntactic processing in aging with more varied methods. One main trend for studies in this period was that many online studies attempted to uncover the role of working memory in age-related syntactic processing (e.g. Stine-Morrow et al. 2000; Waters and Caplan 2001; DeDe et al. 2004; Caplan et al. 2011; Kemper and Herman 2006; Payne et al. 2014). Another trend is that some researchers try to detect the neural changes in language processing across lifespan by applying advanced neurocognitive technique, such as ERPs (Kemmer et al. 2004; Leckey and Federmeier 2017; Zhu et al. 2018; Alatorre-Cruz et al. 2018) and functional magnetic resonance imaging (fMRI) (e.g. Grossman et al. 2002; Tyler et al. 2009; Davis et al. 2014; Campbell et al. 2016). Although there are still discrepancies on the issue about age-related changes in syntactic processing, these further online studies did make much progress compared to previous studies in the last two decades.

2.2.1 Aging and Working Memory in Syntactic Processing

Working memory literally refers to the memory needed by the brain to temporarily work on cognitive tasks. More precisely, it is a cognitive capacity which can store information and keep it active for a limited time, so as to achieve a certain goal in cognitive processing (Baddeley 1992; Engle 2001). This important ability, however, has widely been proved to decline with age (see Carpenter et al. 1994 for a review). Given its important role in the cognitive system, many researchers believed that cognitive changes with age may be attributed to a weakness in working-memory capacity (Salthouse 1991). The relation between language processing and working memory, for example, is one of the issues arousing great interest in language studies (Just and Carpenter 1992; DeDe et al. 2004; Kemper et al. 2004; Kemper and Liu 2007; Caplan et al. 2011). To date, however, there is still no unified answer to the question about whether working-memory decline leads to deterioration in language comprehension, especially in online syntactic processing (e.g. Just and Carpenter 1992; Caplan and Waters 1999; Caplan and Waters 2013).

Many studies claimed that older adults' syntactic processing is independent of their working-memory capacity. In one study, Stine-Morrow et al. (2000) compared the reading time and the comprehension for subject-relative and object-relative constructions among younger and older readers. The results showed that younger adults rather than older adults, needed more time on reading object-relative constructions. And older adults demonstrated lower accuracy in comprehending object-relative sentences. Thus, it is suggested that the ability to interpret is not modulated and it is intact with age, but age-related changes in working-memory capacity may compromise sentence comprehension.

Waters and Caplan (2001) tested 127 individuals who ranged from 18 to 90 years old on a reading span test and on measures of online and offline sentence-processing efficiency. Older participants had reduced working-memory spans compared with younger participants. While older participants showed comparable effects of syntactic complexity with younger adults in the online tasks, they were found to be more affected by syntactic complexity on the offline measures. The results support the hypothesis that online processes involved in recognizing linguistic forms and determining the literal, preferred, discourse-coherent meaning of sentences constitute a domain of language processing that relies on its own processing resource or working-memory system.

DeDe et al. (2004) used a structural modeling approach to examine the relationships between age, verbal working memory (vWM), and three types of language measures: online syntactic processing, sentence comprehension, and text comprehension. The best-fit model for the online-processing measure revealed a direct effect of age on online sentence processing, but no effect mediated through vWM. The best-fit models for sentence and text comprehension included an effect of age mediated through vWM and no direct effect of age. These results indicated that the relationship among age, vWM, and comprehension differed depending on the measure of language processing and supported the view that individual differences in vWM did not affect individuals' online syntactic processing.

Later, Caplan et al. (2011), in order to make a more convincing and comprehensive investigation on the relationship among aging, working memory, processing speed, and syntactic comprehension, recruited a larger population sample including two hundred participants ranging from 20–90 years old. The participants were divided into four age groups (19–29, 30–49, 50–69, 70–90), and were required to finish two self-paced reading tasks, one adopting simple relative clause (cleft subject, cleft object, subject-subject, subject-object) while the other involved sentential complements containing a relative clause or a doubly-embedded relative clause. Older participants were found to be less accurate in comprehension, and there was age-related slowing in online processing, indicating a decrease in the efficiency of parsing and interpretation. Speed of processing and working memory were positively correlated with online processing times in experiment 2, suggesting that different tasks may need different speeds of processing and working memory. Working memory was not predictable for the reading times in more complex sentences, suggesting that general working memory is not critically involved in online syntactic processing. In addition, older individuals' slower online processing and poorer comprehension performance reflected their inefficiency in processing the most demanding point of the most complex sentences.

Yoo and Dickey (2017) examined the effect of healthy aging on comprehending garden-path sentences involving minimal attachment ambiguity in experiment 1 and late closure ambiguity in experiment 2. The results showed that older adults were significantly slower than younger adults in online processing at the disambiguating verb, indicating that older adults felt more difficulty in the reanalysis of garden-path sentences. While the offline performance was successfully predicted by working-memory capacity, the processing difficulty of older adults in real-time processing was still unknown. The authors declared that there was an age-related decline in comprehending challenging, syntactically ambiguous sentences.

However, there were some studies, such as those by Kemper and Herman (2006) and Payne et al. (2014), supporting the important role of working memory in online syntactic processing. In the study by Kemper and Herman (2006), subjects needed to remember a noun phrase (NP) while they read sentences varying in syntactic complexity. The NPs were proper names or definite descriptions for occupations or roles (e.g. the thief). The sentences for the reading task were subject-extracted versus object-extracted cleft sentences using either descriptions or proper names as both the sentence subject and the sentence object. It was found that young adults slowed their reading in complex sentences compared to simpler sentences, especially when the NPs in memory load were matched with those in the sentences, whereas for older adults, there was a general reduction in processing because of memory load, with no correlation with the syntactic complexity or memory-load matching. Kemper and Herman suggested that the results for the younger adults meant working memory can affect online processing, consistent with the single source model of memory. Payne et al. (2014) investigated the role of age, working memory, and literacy reading in the resolution of reflexives in sentences with relative clauses. In their study, 91 participants ranging from 18 to 81 were asked to read self-paced sentences word by word and make a judgement on whether the reflexive was bound by NP1 or NP2 (e.g. *The son* (NP1) *of the princess* (NP2) *who scratched himself/herself in public was humiliated*). The results showed NP2-attachment advantage on average, whereas older adults were observed with a lower acceptability for NP2 compared to young adults. However, this disadvantage of NP2 attachment in older subjects was modulated by working memory in both online and offline results. In addition, more print exposure was found to be beneficial for older adults' online processing as well as younger adults' offline comprehension.

Additionally, there was relevant evidence from languages other than English, such as German. Reifegerste and colleagues (Reifegerste et al. 2017; Reifegerste and Felser 2017) showed interest in German natives and observed that older adults had greater difficulty in syntactic processing with demanding working-memory capacity. In one study, Reifegerste et al. (2017) tested older and younger adults' susceptibility to agreement attraction errors in German with two experiments (experiment 1: timed grammaticality judgment; experiment 2: self-paced reading + working memory test). It was found that there were longer reading latencies and judgment reaction times (RTs) for older adults. Further, working memory was found to compromise older adults' reading latencies and accuracy in ungrammatical sentences. The author ascribed older adults' difficulty in blocking intervening nouns from interfering in processing subject-verb agreement to the decline in working memory and inhibitory control ability. In another study, Reifegerste and Felser (2017) investigated the effect of normal aging on pronoun resolution through the manipulation of gender and sentence length in two experiments. They found that older participants were less sensitive than younger people in mismatching licit antecedents and were more distracted by the linearly closer antecedent. Reifegerste and Felser ascribed older adults' vulnerability in processing demanding tasks to executive functions, such as interference control. But it was confusing that they discussed the effect of working memory in short sentences but ignored the role of working memory in more complex sentences.

Moreover, evidence from eye-tracking studies also supported the role of working memory in online syntactic processing. Kemper et al. (2004) used eye-tracking to examine resolution of temporary syntactic ambiguity in reduced relative clause sentences (e.g. *The experienced soldiers warned about the dangers conducted the midnight raid*). They found that older adults paid more attention to the first noun in ambiguous sentences with more regressions, yet their time spent in reading had no significant difference to the young adults, suggesting that older adults tried to confirm their understanding with more regressions, but did not engage in significant reanalysis of the sentence. In order to make clear the role of working memory in syntactic processing, they did a second experiment in which they tested two age groups, both divided into high and low reading span. The results showed that low-span readers, like older adults in the first experiment, made many regressions on the first noun, and the high-span group, mirroring the young adults in experiment one, could resolve the ambiguity by relying on information from the working memory. Moreover, no effect of age was found in experiment two. The findings supported the idea that working memory affects syntactic comprehension. Similarly, Kemper and Liu (2007) used eye-tracking to investigate young and older adults' processing of cleft sentences and relative clauses. When reading cleft sentences with no ambiguities (experiment 1), older adults made more regressions on cleft object sentences and object-relative clauses, resulting in increased regression path fixation times and total fixation times. In experiment two, subjects were asked to read sentences with object-relative clauses but without the complementizer *that*, leading to syntactic ambiguities. The older adults with smaller working memory were found to have significantly more leftward regressions in processing these ambiguous sentences. The results indicated that individual and age group differences in working memory modulated the syntactic analysis of cleft object and object-relative clause sentences.

Different from other studies with sentences involving demanding working-memory capacity, Poulisse et al. (2019) adopted sentences with only two words (e.g. *I cook*) to detect the effect of age on syntactic processing. The speed and accuracy were measured, and results showed older adults were slower and less accurate than younger adults in detecting syntactic agreement errors for both real and pseudo-verb sentences, suggesting there was age-related decline in syntactic comprehension. The age-related decline in accuracy was smaller for the pseudo-verb sentences, and the decline in speed was larger for the pseudo-verb sentences, compared to real verb sentences. It was suggested that syntactic comprehension decline was stronger in the absence of semantic information, which caused older adults to produce slower responses in order to make more accurate decisions. In line with these findings, performance for older adults was positively related to a measure of processing speed capacity. Taken together, the author claimed that elementary syntactic processing abilities declined in healthy aging.

To summarize, the studies after 2000 began to focus on the specific relations between syntactic processing and other cognitive factors, among which the effect of working memory attracted most attention. Although researchers cannot reach a unified conclusion, their studies provide further evidence for the importance of individual factors in older adults' language interpretation.

2.2.2 Neural Changes in Older Adults' Syntactic Processing

In addition to the more and more online self-paced studies mentioned above, advanced neurocognitive techniques such as fMRI and ERPs have also been applied to examine the relation between aging and syntactic ability, and it was often found that older adults would activate some brain regions different from those that young adults would activate in performing the same task. Although the nature or the cause of the different brain activities across age is still under discussion, the neural studies provide direct evidence of neurobiological changes in language processing, avoiding some errors caused by inferring conclusions from behavioral results as previous studies do.

The existing fMRI studies were varied in their findings in detail, but they have provided something in consensus. For example, there was a consistent finding that aging brains were able to activate the core syntactic regions, like the younger brains (Grossman et al. 2002; Peelle et al. 2009; Tyler et al. 2009; Antonenko et al. 2013). Grossman et al. (2002) applied fMRI to monitor regional brain activity in 13 younger subjects and 11 healthy seniors in reading sentences with varied grammatical features (subject-relative vs. object-relative subordinate clause) and verbal working memory (vWM) demands (short vs. long antecedent noun-gap linkage). It was found that young and old subjects had both similarities and differences in the recruitment of networks. On the one hand, the two groups both involved the left posterolateral temporal and bilateral occipital cortex for all sentences, and ventral portions of the left inferior frontal cortex for object-relative sentences with a larger working-memory demand. On the other hand, compared to younger subjects, seniors had less activity in left parietal recruitment but greater recruitment in the left premotor cortex, and dorsal portions of the left inferior frontal cortex. In addition, for sentences with a long noun-gap linkage, older subjects recruited the right parietal cortex in addition to the right posterolateral temporal cortex. The findings were consistent with the hypothesis that the neural basis for sentence comprehension included dissociable but interactive large-scale neural networks and related cognitive resources involved in working memory. Seniors were able to achieve comparable accuracy with young adults by up-regulating portions of the neural substrate for higher working-memory demand in sentence processing. Peelle et al. (2009) made a similar study with blood oxygen level-dependent functional magnetic resonance imaging. They investigated the age-related change in the cortical network underlying spoken language comprehension using short sentences differing in syntactic complexity and speech rate. Both young and older adults activated a core sentence-processing network in the comprehension of syntactically complex sentences. However, older adults were found to show reduced recruitment of the inferior frontal regions but increased activity in the frontal regions, suggesting a compensatory effect. Moreover, older adults showed reduced coherence and limited coordination ability between activated regions in a functional connectivity analysis, which may be contributed to older adults' difficulty in comprehending challenging sentences, as the recruitment efficiency was predictable for the accuracy. And Tyler et al. (2009) used a word-monitoring task to investigate whether syntax is preserved in aging by recruiting other brain regions to compensate for neural atrophy. The behavioral results revealed that the older group maintain preserved performance despite their gray matter loss by increasing neural activities in the right hemisphere frontotemporal regions, whereas the young group activated the frontotemporal network in the left hemisphere. The authors thus attributed the preserved syntactic processing in aging to the compensatory bilateral functional language network. In addition, Antonenko et al. (2013) adopted a comprehensive assessment of behavioral performance, task-independent functional connectivity, and structural brain connectivity to examine the effect of age in the syntactic processing of native Germans. It was observed that older adults exhibited lower accuracy in comprehension compared to young adults, which was associated with their decreased functional connectivity within the mainly left-lateralized syntax network. Moreover, older adults' syntactic ability was associated with the structural integrity of ventral fibers, whereas young adults relied more on the dorsal tract. The authors proposed that, to successfully accomplish a syntactic task, the aging brain, like children, would depend on the existing structural prerequisites as well as the recruitment of alternative connections.

However, the above studies often involved cognitive tasks other than pure syntactic processing. Davis et al. (2014) and Campbell et al. (2016), therefore, figured out a way to distinguish those confounding factors from syntactic processing. They both adopted two experiments, one of which was natural listening without any explicit task, aiming to detect processes specific to language comprehension, and the other of which was listening to the same sentences and rating them on sentence acceptability, which was to examine functional connectivity in general task demands. Davis et al. (2014) scanned 50 healthy native British English speakers with a broad range of ages (20–80 years old) in processing sentences with or without local ambiguous phrases (e.g. Landing planes are/is…). It was observed that in both tests, there was consistent activation of the left-lateralized frontotemporal network which was associated with syntactic analysis. But the task condition elicited extra activity in the opercular, frontoparietal, and bilateral prefrontal cortex (PFC). And only the PFC, which showed stronger activation with age, was strongly mediated by gray matter health. In Campbell et al. (2016), a larger sample with 111 participants ranging from 22 to 87 years old was investigated using fMRI with materials similar to Davis et al. (2014). Moreover, they pretested all subjects' crystal intelligence and further examined how age and task demands affected functional connectivity both within and between the relevant networks. The analysis showed that all age groups activated the same auditory and frontotemporal syntax networks in task-free language comprehension, but older people were found to be with gray matter loss and reduced connectivity to task-related networks. Therefore, the author declared no reduced specialization or compensation with age. Moreover, they found aging adults' preserved performance in overt tasks was related to crystallized knowledge, suggesting that older adults were able to make up for decreased between-network connectivity by richer language knowledge.

Furthermore, Samu et al. (2017) applied fMRI to investigate how healthy aging affected different cognitive domains in 98 participants aged 23–87 years old. In the study, participants were required to complete three cognitive tasks: a fluid intelligence task, a picture naming task, and a sentence comprehension experiment. The first two found an age-related decrease, while the online syntactic processing of spoken language observed age-related preservation. It was reported that the age-related cognitive decrease in both declining tasks could be accounted for by the age-related decrease in the responsiveness of the task-positive components and in the suppression of the DM components in default mode (DM). And in syntactic processing, performance and task-positive functional responsiveness were preserved with age, and DM components showed neither a baseline suppression effect nor any age-related difference in responsivity. The authors claimed that the ability to recruit task-specific networks and suppress task-irrelevant DM regions in certain contexts could help facilitate successful cognition across the adult lifespan, as well as account for differences in age-related cognitive decline or preservation.

ERP studies have also provided evidence for brain change with age. For example, Kemmer et al. (2004) applied ERPs to record the age-related changes in comprehending grammatical number violations. The older adults were found to have less accuracy but comparable P600 amplitude and latency in violations. However, the P600 effect in seniors was less asymmetric and more frontal than in younger adults. The authors suggested that aging is accompanied with changes in brain activity. Similarly, Leckey and Federmeier (2017) tested 24 right-handed older adults' neural response in subject-verb number agreement and reflexive pronoun-antecedent number agreement with ERPs and observed that the asymmetric pattern changes with age, such that P600 responses elicited both hemispheres with either left-hemisphere-biased or right-hemisphere-biased presentations.

Additionally, Alatorre-Cruz et al. (2018) examined younger and older Spanish adults' syntactic ability in processing adjective-noun agreements with varied working-memory demands. Both groups were asked to read sentences and detect grammatical errors. The results showed that the two groups were equal in behavioral performance, but a different pattern of ERP components was observed in older adults. That is, they showed smaller amplitude of LAN, P600a, and P600b effects when the distance between nouns and adjectives was enlarged, suggesting an age-related decrement in processing syntactic knowledge demanding a large working memory.

Zhu et al. (2018) investigated the syntactic processing of older and younger Chinese adults with ERPs. In the study, participants needed to read sentences containing *ba* or *bei* constructions, special structures in Chinese which have a strict word order, namely, NP1-*ba/bei*-NP2-VP (verb phrase). The verb in the sentence was substituted with a semantically incongruent transitive verb or a noun to realize semantic violations and semantic plus syntactic violations. The syntactic processing was made by comparison between the two violations. Subjects' reaction to the critical word was recorded by ERPs. The results showed lower accuracy in older adults but comparable P600s between the two age groups. But there was a negative correlation between the behavioral data and the neural reaction data in older adults, which indicated less efficiency in older adults' syntactic processing. The authors thus demonstrated that there was a decline in older Chinese adults' syntactic processing of simple sentences.

In sum, studies in the recent two decades reveal that it is still arguable whether syntactic processing ability declines with age and whether older adults' poorer performance in interpretating complex sentences is led by the decay of their working-memory capacity. Despite the inconsistent results in previous studies, the advanced technology, such as fMRI and ERPs, provided some relevant new views for the issue, and it can be deduced that with the development of technology, these unanswered questions will be answered in the very near future.

3 Relevant Theories

It is obvious that studies on syntactic processing in aging adults place their focus on two main questions. The first of these is a) whether age has an effect on syntactic interpretation, and to answer this question, researchers must separate the syntactic processing ability from other cognitive capacities in which working memory was most discussed. Hence the second question is b) whether older adults' decline in syntactic processing, if there is one, is due to the effect of other individual factors. Along with the development of relevant studies as well as the unanswered questions, several models of syntactic processing across the human lifespan were put forward, mainly including psycholinguistic models, neurocognitive models, and a combinational model.

3.1 Psycholinguistic Models: Modular and Interactive

At the very beginning, for the nature of syntactic processing, especially whether syntactic processing is independent of other processing or resources, there are two related models: the modular model and the interactive model.

The modular model is based on the modularity theory of mind (Fodor 1982), which assumes that the human mind consists of several independent modules. These modules are domain-specific, dealing with specific cognitive functions, and they are information-encapsulated, as only the information in the modules can affect their functions. According to the modular model, language processing takes place in steps and is hierarchic. Syntactic processing, as a part of sentence processing, is an input process, which runs automatically in the modular model and is an interpretative process. It is not affected by other processes (such as semantics) or nonlinguistic resources. Syntactic parsing is assumed to be a fast and obligatory method to compute the linguistic form of utterances. Scholars who support this theory cite some data to show that the computation of syntactic structures is not affected by semantic constraints, so as to demonstrate that syntactic processing embodies the characteristics of "information encapsulation" (Stine-Morrow et al. 2000: 316). Based on this theory, some studies have suggested that the elderly's syntactic processing ability is stable and will not decline with age (e.g. Caplan and Waters 1999). The fact that many studies have found a deterioration of the elderly's syntactic abilities may be due to their failing to separate syntactic processing from other cognitive resources.

However, relevant fMRI studies have found that the neural substrates of phonetics/phonology, the lexicon, syntax, and meaning do not recruit a single neural area in their processing. Instead, the processing of each involves a broadly distributed network or processing stream (for reviews, see Binder et al. 2009; Hickok 2009; Hickok and Poeppel 2007; Kaan and Swaab 2002; Blumstein and Myers 2013). Therefore, it is suggested that the brain should not be divided into independently functional "linguistic" modules.

These findings are consistent with the interactive model, which assumes that the numerous computational tasks involved in language comprehension operate in parallel, and they can affect each other, for example, under some circumstances, the construction of the syntactic representation can be influenced by semantic constraints (Taraban and McClelland 1988). Meanwhile, all these computations compete for limited nonlinguistic cognitive resources (Just and Carpenter 1992; Just et al. 1996), such as attention, memory, and inhibition control ability. As aging may bring particular difficulties in cognitive abilities such as in self-initiating processing (Craik 1986), older adults may have different ways of allocating the limited resources, which may be the cause for their different performance compared to young people. Therefore, from this interactionist perspective, aging-related difficulties in syntactic performance may be attributed to a declining ability in allocating processing resources effectively and adequately to the syntactic computations needed for language interpretation (Stine-Morrow et al. 2000).

Based on the interactive model, several cognitive aging models have been proposed for language processing, such as resource theory, general slowing theory, and working memory theory. All these models suggest that the decline of older adults' performance in a specific cognitive task is not a sign of the deterioration of the tested cognitive ability, but a result of the effect of some other recognized decline in cognitive capacity. For example, for the general reduced performance of older adults, the resource theory assumes that older people have less resources than younger people, and that some tasks demand the use of more resources for older people than for younger adults, which consequently causes age-related decline in performance (Craik and Byrd 1982; McCoy et al. 2005; Murphy et al. 2000), while according to the general slowing theory (Salthouse 1996), some cognitive operations may be executed too slowly to be completed successfully within the available time, which will lead to an increase in speech comprehension errors. The working memory theory suggests that the decline of working memory in the elderly limits their ability to understand and produce complex semantic content and complex syntax (Kemper and Kemtes 1999).

3.2 Neurocognitive Models: Compensation and Dedifferentiation

Neurocognitive models have been proposed based on findings in neurocognitive studies. Many imaging studies contrasting the performance of healthy young adults with older adults have shown a major difference in observed patterns of neural activation when young adults and older adults are asked to perform the same cognitive task, such as syntactic comprehension (Grossman et al. 2002; Peelle et al. 2009; Tyler et al. 2009; Antonenko et al. 2013). In general, there is a shift from more focal activation in young adults to more widespread patterns of activation in older adults (e.g. Cabeza 2002; Logan et al. 2002). Such pattern changes in older adults can include a decrease in neural activation in some brain regions but an increase in other regions relative to young adults. This pattern has been observed in a number of cognitive domains, from encoding pictures (Gutchess et al. 2005) to studies of episodic memory (Cabeza 2001). At least two hypotheses can be entertained concerning these age-related differences: the dedifferentiation hypothesis and the compensation hypothesis.

The dedifferentiation hypothesis holds that the more widespread activation seen in older adults is a consequence of cortical regions losing their dedicated contribution to a specialized function. Such a decline in the specialization of regional brain function with age results in additional brain areas being activated in the older adult in regions that are often engaged with a similar kind of task. As a consequence, one might see two cognitive tasks activating distinct, but anatomically related brain regions in young adults, whereas older adults show activation of both sets of regions for both tasks. The appearance of widespread activation when older adults are confronted with a cognitive task could thus reflect a general decline in neural efficiency, resulting in the loss of the differentiated function that is ordinarily observed when young adults engage in the same activity (Park et al. 2003). A key question here is whether the observed increase in areas of activity in older adults helps or hinders task performance. There are certainly cases where more widespread activation is thought to interfere with cognitive success (Cabeza 2001; Logan et al. 2002).

The compensation hypothesis, however, argues that the additional brain regions activated during task performance in older adults reflect focused recruitment in a specific anatomical distribution in response to the diminishing cortical resources that are unavailable as we age. Unilateral activation during cognitive-task performance by young adults, for example, may be supplemented by recruitment of homologous regions in the contralateral hemisphere in older adults (Cabeza et al. 2002). When performing tasks that are primarily sensory in nature, older adults show recruitment of the frontal cortex, which is not activated by younger adults (Cabeza et al. 2004). Because frontal brain regions are associated with executive functions like working memory but not sensory functions, this would be consistent with older adults employing higher-level activation to compensate for sensory decline.

It should be noted that although the two views are different, they are not mutually exclusive. For example, the aging brain may be prone to dissimilation, with increased use beneficial in some cases and detrimental in others.

3.3 A Combinational Model: The Scaffolding Theory of Aging and Cognition

With the overview of behavioral, structural, neuro-biological, and functional findings in mind, Park and Reuter-Lorenz (2009) have proposed the scaffolding theory of aging and cognition (STAC), an integrative theory arguing that the behavioral, structural, and functional data about aging can be understood within the framework of a compensatory scaffolding model (see Figure 1). The STAC posits that despite neurobiological challenges and functional deterioration, human behavior is maintained at a relatively high level with age, for the brain can build a protective scaffolding through "the recruitment of additional circuitry that shores up declining structures whose functioning has become noisy, inefficient, or both" (Park and Reuter-Lorenz 2009). Specifically, the STAC includes the basic principles as illustrated in Figure 1.

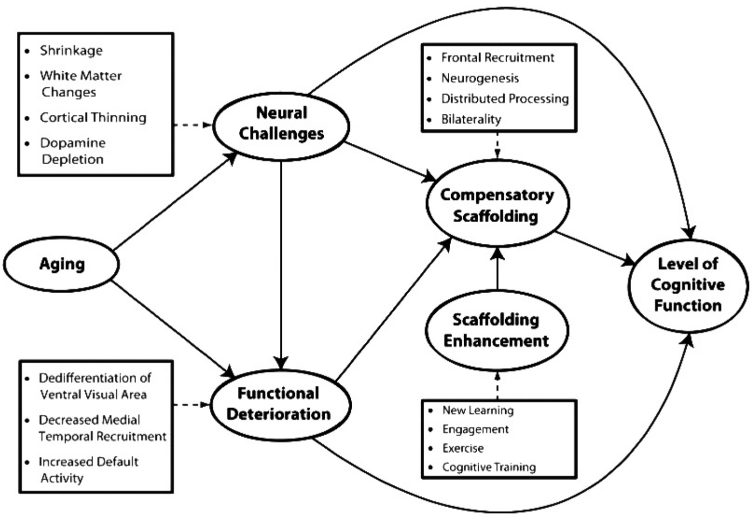

Figure 1: A conceptual model of the scaffolding theory of aging and cognition (STAC) (Park and Reuter-Lorenz 2009)

First, there are varying degrees of neural degradation with age, including "neural challenges" and "functional deterioration" (see Figure 1). "Neural challenges" refers to structural changes in the brain across a person's lifespan, including cortical thinning and regional atrophy, loss of white matter integrity, and dopamine depletion. Functional deterioration is an indicator of age-related decline in brain activity that has been well documented in the imaging literature, including dedifferentiation (decreased specificity) of ventral-visual and motor areas (Park et al. 2004; Voss et al. 2008; Bernard and Seidler 2012), decreased memory-related recruitment of medial temporal lobe regions (Cabeza et al. 2004; Gutchess et al. 2005), and dysregulation of the DM network (Lustig et al. 2003; Persson et al. 2007; for a review, see Park and Reuter-Lorenz 2009; Reuter-Lorenz and Park 2010).

Second, in response to the above negative indices, the brain engages in a series of beneficial processes which work as "compensatory scaffolding" operating to counteract the adverse effects of neural and functional degradation. To be specific, scaffolds entail the engagement of supplementary neural circuitry, including greater activation or additional recruitment of prefrontal brain regions (Gutchess et al. 2005; Davis et al. 2008), bilateral recruitment (Cabeza 2002; Reuter-Lorenz et al. 1999; Reuter-Lorenz et al. 2000; Tyler et al. 2010; Cappell et al. 2010; Schneider-Garces et al. 2010; for a review, see Cabeza and Dennis 2012), as well as neurogenesis, which may also be a potential source of positive plasticity for compensatory scaffolding (Fuchs and Flügge 2014; Lovden et al. 2013).

Finally, the model suggests that some explicit interventions such as new learning, exercise, and intellectual engagement, as well as more formal cognitive training, may play a positive role in enhancing neural scaffolding activity, as they provide the additional computational support required by an aging brain to preserve cognitive function in the face of localized or global neurofunctional decline.

Park and Reuter-Lorenz (2009) suggest that the scaffolding process is not a process that simply begins in older age. Rather, across the life span, the individual is confronted with cognitive challenges to which the brain must adapt. Thus, when a child or young adult is engaged in active learning, new neural circuitry is recruited and harnessed to support the acquisition and performance of the desired task (Petersen et al. 1998). In this model, what is unique about older adults is that scaffolding occurs not only under conditions of new learning, but may be invoked even for less novel or practiced behaviors because the existing neural circuitry for performing the task has degraded. These secondary networks may be less efficient than the primary circuitry, but nevertheless result in task performance that is better than could be achieved by using only the primary but degraded network. The proposed continuity of scaffolding across the life span corresponds with the parallel between the sequence of neural development in childhood and age-related neuro-anatomical decline, which follows a "last in, first out" progression: the regions that are later to myelinate developmentally are the first to decline in older age (Raz 2008; Kennedy and Raz 2009). Thus, the order of neural decline may recapitulate earlier developmental states, and thereby revisit scaffolding solutions that originally aided in the acquisition of cognitive abilities in early development. So, scaffolding is a lifelong process that is relied upon continually and increasingly in the later stages of life.

To summarize, the theoretical models develop along with findings in the relevant studies. These varied theories for the relation between aging and cognition are in fact correlated with each other. For example, the cognitive aging models imply the interaction between languages and other cognitive abilities, in consistency with the interactionism theory. And both the compensation and dedifferentiation hypotheses are often taken as a result of less efficient cognitive capabilities. Furthermore, the scaffolding theory is a combination of the previous speculations, illustrating simultaneously the possible reasons for as well as the solutions to brain change with age.

4 Implications and Prospects

The existing studies on age-related syntactic processing are varied in their investigation of sentence structures and languages, as well as in their methodologies, yet the answer for the age-related effect on syntactic processing is still not in consensus. It is possible that the effect of age may vary with syntactic complexities, where older adults' syntactic ability may be preserved in simple sentences but may deteriorate in complex sentences (Obler et al. 1991; Stine-Morrow et al. 2000; Yoo and Dickey 2017; Reifegerste and Felser 2017; Alatorre-Cruz et al. 2018). Of course, there are also findings contrary to this idea, such as those by Zhu et al. (2018) and Poulisse et al. (2019), who have found age-related decline in simple sentences, and Reifegerste et al. (2017) who have found older adults' reduced accuracy in comprehending both simple and more complex sentences.

An alternative explanation for the varied results is that older adults' syntactic processing involves many individual factors and the individual difference among these factors, such as education (Feier and Gerstman 1980), language background (Davis and Ball 1989), disease processes (Baum 1990), working memory (Just and Carpenter 1992; Kemptes and Kemper 1997), print exposure (Payne et al. 2014), and crystalized knowledge (Campbell et al. 2016), may affect age-related syntactic processing. Therefore, it is crucial that the researchers control these non-syntactic factors in investigating syntactic interpretation.

Despite the mixed results in most behavioral studies, fMRI studies find similar results on age-related changes in syntactic comprehension. That is, older adults can activate a core region for language syntax like the younger adults, and at the same time increase activities in other regions to complete overt tasks (Peelle et al. 2010; Davis et al. 2014; Campbell et al. 2016). The consensus of imaging studies on syntactic processing with age reflects the importance of methodology in investigation, and it is very possible that the current questions will be answered with more developed techniques.

However, it is notable that up to now it is the studies on English that predominate over the relevant studies on age-related syntactic processing, and only a few studies address other languages such as Spanish (Alatorre-Cruz et al. 2018), German (Reifegerste and Felser 2017; Reifegerste et al. 2017), and Chinese (Zhu et al. 2018), implying an obvious lack of language diversity in the relevant area.

Corresponding to the more and more varied studies, the relevant theoretical models also develop from psycholinguistic models (modular and interactive), based on behavioral studies, to neurocognitive models (compensation and dedifferentiation), based on neurocognitive investigations, and then to a comprehensive model (STAC) based on both of the previous two kinds of research. It seems that the STAC model resolves the previous conflict between the different models, but it in fact ignores the specificity of all cognitive abilities and tries to connect the whole cognition system together. Is this model available to all cognitive abilities such as language? How can this model reflect the specific property of language processing ability? And how much can the explicit interventions influence the decline in language ability? There are still many questions to be answered to verify the reliability of the model.

In a word, the question of whether there is an age-related decline in syntactic processing is still not fully answered. Based on the implications concluded above, we can recognize that there is still a lot to do if we want to detect the secret of syntactic processing accompanying aging. To be specific, future studies should pay attention to more different languages, more syntactic complexities, and individual differences with more advanced methods to explore the nature of the effect of age on syntactic processing and to verify or modify the existing models.

5 Conclusion

This study reviewed the relevant studies and theories of syntactic processing in older adults over the past 40 years and showed the development of this field in detail. Research on the syntactic processing of the elderly has gradually developed from employing offline tasks, which can only observe the results of subjects' interpretation, to using online tasks, which can observe people's neurocognitive changes, and from the speculation that syntactic processing is affected by other cognitive abilities to the in-depth and systematic research on the relationship between syntactic processing and other cognitive factors, especially working-memory capacity. At the same time, the relevant theories have developed from modular and interactive models and the compensation and the dedifferentiation hypothesis to a comprehensive model combining evidence from behavioral, neurocognitive, and individual difference studies which provides a systematic illustration for the change of language processing across age and emphasizes the role of explicit interventions in language preservation. Future research should involve more languages, enrich the research scope, and improve the research methods to resolve the existing debates and provide further and more significant suggestions to account for language development across the human lifespan.

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Bionotes

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