AN EXPERIMENTAL INVESTIGATION INTO OLDER ADULTS OF PRODUCTION/COMPREHENSION ASYMMETRIES AND DECLARATIVE/PROCEDURAL MEMORY CONTRIBUTIONS: A CHINESE CONTEXT

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An experimental investigation into older adults of production/comprehension asymmetries and declarative/procedural memory contributions: a Chinese context

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CERTIFICATE OF ORIGINALITY

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_______XIE Chenwei_______ (Name of student)

Abstract

Children tend to experience an asymmetry in production and comprehension as their language develops. However, it remains unclear whether older adults exhibit such production/comprehension asymmetry (PCA) in a retrogenic manner. The overarching target of the current study is to examine whether PCA exists in the syntactic and semantic abilities of older adults. As language ability is correlated with various cognitive abilities, we further probe whether PCA is associated with the declarative and procedural memory, since semantic and syntactic abilities are considered to be subserved by declarative and procedural memory, based on the declarative/procedural model.

The declearn task was used and the serial reaction time task was administered in order to measure declarative memory and procedural memory, respectively. It was found that both declarative memory and procedural memory deteriorated in older adults. Our results also demonstrate that the erasure of items in declarative memory follows the retrogenesis theory. As adults age, they tend to remember more real objects and forget more made-up objects; this pattern is the reverse of that in childhood.

Using production tasks and comprehension tasks, we systematically investigated the syntactic and semantic processing patterns in the Chinese population, especially in older Chinese people. The results indicated that although older adults were able to express relevant information with intact syntactic and semantic complexity, they required a greater amount of planning time to initiate sentence production than younger adults. It was determined that older adults had a significantly lower level of semantic comprehension compared to younger adults because of their relatively low accuracy rate, as well as the absence of the N400 effect. On the other hand, it was shown that

older adults were capable of reaching a similar accuracy rate as younger adults when judging syntactic correctness. Despite this, older adults failed to exhibit the anterior negative effect that could be observed in the neural potential of younger individuals. Thus, there are behavioral and neural differences in the receptive syntactic abilities of older adults.

According to our findings, the semantic performance of older adults fluctuated in terms of receptive modality and expressive modality, resulting in a semantic PCA similar to that of children. The findings are in accordance with the retrogenesis theory, which posits that the decline of language reverses the trajectory of its development. Additionally, we found that the asymmetry between semantic production and comprehension emerged after both behavioral and neural declines in semantic ability. It is also important to note that the asymmetry may be hidden at the behavioral level and only visible at the level of neural activity.

Furthermore, we found that declarative/procedural memory was associated with semantic/syntactic performance in adults of all ages. In addition, the original declarative/procedural model has been extended in the current study, as the two memory systems tend to be unequally linked to language abilities in the expressive modality and receptive modality. It is likely that the lifelong unequal associations contribute to PCA.

The findings of our study provide a comprehensive picture of age-related memory deficits and language attrition, as well as behavioral and neural mechanisms responsible for these declines. The results of our research on retrogenic production and comprehension asymmetries indicate that we have a responsibility to treat the elderly with the same care and attention offered to our children.

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List of abbreviations

AD: Alzheimer's disease

AN: anterior negativity

CDA: cognitive developmental approach

ChOA: Chinese older adults

CON: congruent sentence

DLD: developmental language disorder

DM: declarative memory

EEG: electroencephalograph

ERPs: event-related potentials

ELAN: early left anterior negativity

fMRI: functional magnetic resonance imaging

HEOG/VEOG: vertical/horizontal electro-oculogram

ICA: independent components analysis

IQR: interquartile range

ISI: interstimulus interval

LAN: left anterior negativity

LMTG: left middle temporal gyrus

LPC: late positive component

MCI: mild cognitive impairment

MMSE: mini-mental state examination

MoCA: Montreal cognitive assessment

NLP: natural language processing

PCA: production/comprehension asymmetry

PDH: procedural circuit deficit hypothesis

PM: procedural memory

RTs: reaction times

SEM: semantically incongruent sentence

SPS: syntactic positive shift

SRT: serial reaction time

SYN: syntactically incongruent sentence

WEIRD: Western, Educated, Industrialized, Rich, and Democratic

Chapter 1. Introduction

Aging cannot be avoided by any human being. As we become a sexagenarian, aging would more or less inflict physical deterioration, cognitive decline and language attrition on us and impose troublesome inconvenience on our daily life. However, inevitable aging does not mean all aspects of cognitive and language abilities suffer from equal decline, and what we can do is not vainly wait for its occurrence and passively endure its infliction. On the contrary, diverse trajectories have been observed in cognitive and language abilities throughout life-span changes (Tucker-Drob et al., 2022), and we can actively make use of some strategies to accommodate age-related changes and minimize the disadvantages of declining abilities (Stern, 2012). It has been reported that many adults over 65 years can still live independently and contribute to society, in spite of the increased prevalence of dementia in these years (Salthouse, 2010). The heterogeneity across intra-individual and inter-individual cognitive and language decline raises questions about why different people and different abilities show different susceptibilities and plasticity to senescence. The answers to these questions can improve our understanding of age-related cognitive and language decline, whereby older adults would ultimately be benefited, and thereby live in dignity and enjoy successful aging (Baltes & Baltes, 1993).

Language ability is undoubtedly important in daily life which would support our communication and thinking. However, in the sunset stage, it has been reported that language abilities are subject to various age-related changes (for a review, see Shafto & Tyler, 2014). Language-related features can be used to diagnose Alzheimer’s Disease (AD) (Ammar & Ayed, 2020; Horigome et al., 2022) and detect early signs of cognitive decline (Beltrami et al., 2018). Among these linguistic features, semantic processing and syntactic processing are two discoverable indicators associated with cognitive ability scores and degrees of cerebral atrophy based on a series of studies in nuns (Kemper, Greiner, et al., 2001; Riley et al., 2005; Snowdon et al., 2000; Snowdon et al., 1996).

The development and dissolution of language proceed in a somewhat predicable manner (Jakobson, 1941/1968; B. Reisberg et al., 1999). Previous studies have suggested that older adults are vulnerable to language attrition and the decline pathway, to some extent, resembles the reverse model of language development (Ahmed et al., 2017; Reisberg et al., 2002). Moreover, lexical processing, in spite of the uncertainty in sentence processing, seems to exhibit unequal or asymmetrical decline in terms of production tasks and comprehension tasks, for a review, see Thornton and Light (2006).

One underlying reason for various aspects of age-related language decline is that older adults suffer from different degrees of memory impairment (for a review, see Buckner, 2004); for instance, declarative memory deficits and procedural memory deficits could affect semantic processing and syntactic processing respectively (Ullman, 2008; Ullman et al., 1997). However, most of these studies have been based on the Western, Educated, Industrialized, Rich, and Democratic (WEIRD) population (Henrich, 2020; Henrich et al., 2010a; Henrich et al., 2010b). It is evident that the Chinese population is not WEIRD, and the Chinese language is strikingly different from that of the WEIRD population (Wang, 1973). Thus, in order to assist Chinese older adults (ChOA) to prevent age-related language attrition and memory decline, it is necessary and urgent to establish what changes ChOA undergo in terms of memory ability and language usage, and how memory ability and language usage interact with each other in ChOA.

In the current study, we aimed to investigate how various language and memory abilities changed and interacted with each other, and how older adults benefited from cognitive reserve strategies in the sunset years (Stern, 2009). In particular, we focused on syntactic processing and semantic processing, as these two abilities were "strong predicators" of low cognitive function and dementia in late life (Snowdon et al., 1996). We investigated whether expressive modality and receptive modality manifested balanced or asymmetrical performance for syntactic and semantic processing, as is the case for children during the language development process (B. Reisberg et al., 1999). On the other hand, cognition and language are intimately connected, in particular semantic and syntactic abilities and declarative and procedural memory systems (Ullman, 2004). As such, we further explored how age-related semantic and syntactic changes were related to declarative memory (DM) and procedural memory (PM).

1.1. Aging challenges in China

It is no secret that China's population is aging. According to the general definition of an aging society published by the United Nations in 1956[1], when a country or region's population aged 65 and above accounts for 7% of the total population, the country or region enters the aged stage. According to the National Bureau of Statistics of China[2], as shown in Figure 1, China had around 88 million older adults aged 65 and above in 2000, accounting for 7% of the total population, which means that China had already officially become an aged society at the beginning of this century. And this aging situation has become worse. The number of older adults aged 65 and above exceeded 200 million at the end of 2021, which was more than half the US population[3].

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[1] Department of Economic and Social Affairs, United Nations, *The Aging of Populations and Its Economic and Social Implications* (New York: United Nations, 1956), 7.
[2] For details about the newest information of Chinese population, see the official webpage of the National Bureau of Statistic of China at https://data.stats.gov.cn/easyquery.htm?cn=C01.
[3] The United States had an population of around 331 millions in 2021, according to the U.S. Census Bureau. For more details, see https://www.census.gov/newsroom/press-releases/2021/2021-population-estimates.html.

It had nearly tripled from 2000 and represented around 14.2% of the entire population.

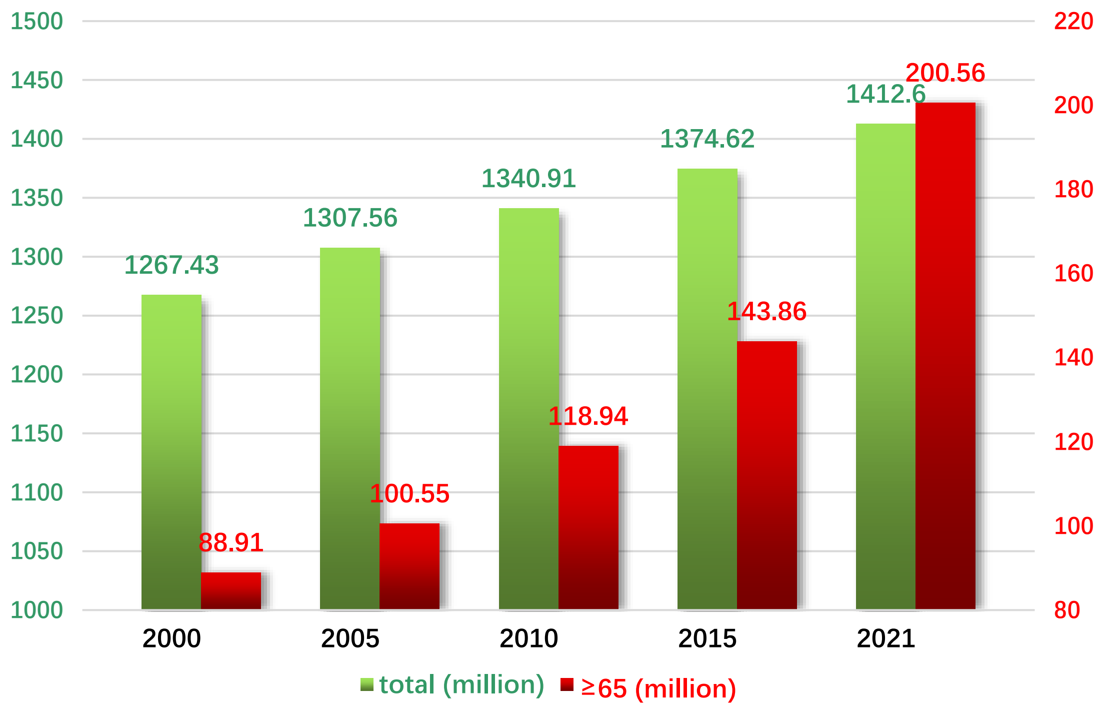

Figure 1. Chinese population changes from 2000 to 2021
Green bars refer to the entire Chinese population, indexed in the left vertical axis. Red bars refer to the number of Chinese older adults, indexed in the right vertical axis. Millions are the unit. The number of older adults increased almost three times during the last two decades which was a more drastic increase compared to increases in the total population.

Moreover, it is expected that China will face a more serious aging issue in the near future. Firstly, as shown in Figure 2, there are a large number of adults who are around 55 years old. It is expected that these people will become older adults within the next decade. Secondly, Chinese people are projected to surpass a life expectancy of 80 years on average by 2040 (81.9 years [78.6–84.2]) vs. USA (79.8 years [76.3–82.9]) (Foreman et al., 2018). This means older adults would inevitably constitute a part of the entire population for a longer period. A critical aspect of successful aging is regarded as being when average onset of infirmity increases less rapidly than the average life expectancy, which compresses morbidity into a shorter period (Baltes &

Baltes, 1993). It is important to find sufficient ways to delay the onset of chronic infirmity to achieve successful aging.

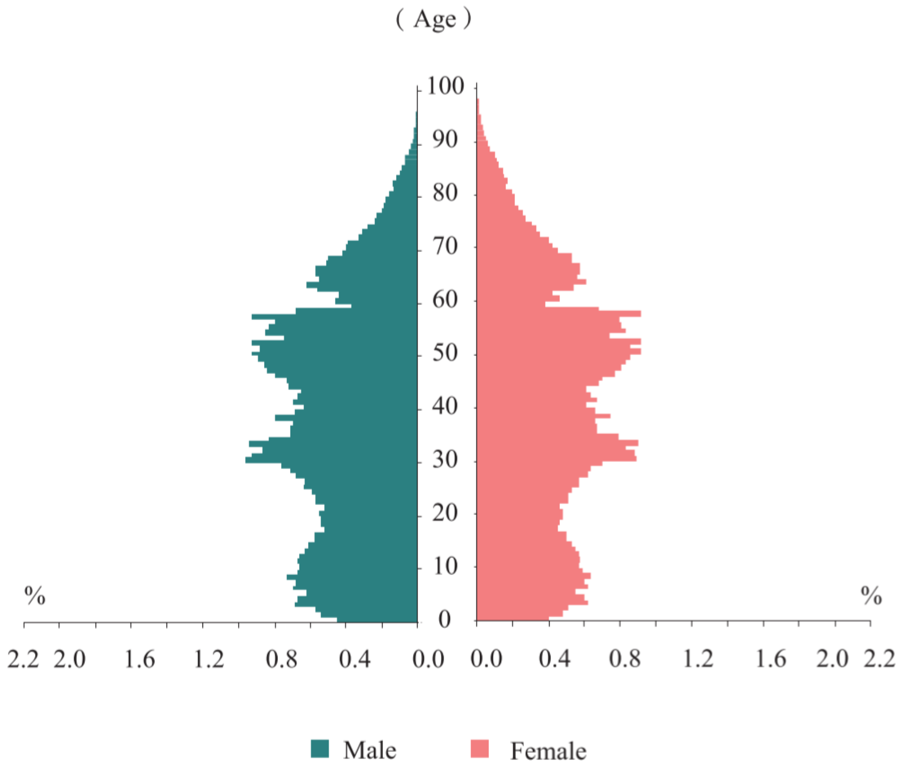

Figure 2. A pyramid from the Chinese population census in 2020
Data were taken from the *Major Figures on 2020 Population Census of China* (2021), in which adults aged from 45 to 60 occupied a large amount of the whole Chinese population. It is anticipated that these individuals will become older adults in the coming decades which will increase the severity and complexity of the aging challenge in China.

Furthermore, it has been determined that the prevalence of dementia among Chinese people is around 6%, which equates to approximately 25% of the total population suffering from dementia globally (Jia et al., 2020). The Chinese population accounts for the largest proportion of people with dementia compared to any other region in the world, and such a situation will become more severe soon as reported in a series of *Lancet* publications (Ferri et al., 2005; Nichols et al., 2022; Rodriguez et al., 2008). The total annual cost of dementia in China is predicted to reach US$ 114.2

billion in 2030 (J. F. Xu et al., 2017), resulting in heavy economic burdens for the whole society and older adults themselves as well as their families (Chan et al., 2013). Thus, it is urgent to explore effective solutions to address the aging challenge (Wang, 2019).

1.2. Production/comprehension asymmetries

In communication, speakers and listeners are the two sides of the information sending and receiving coin (Denes & Pinson, 1993), and production and comprehension involve two opposite pathways for processing inputs and outputs. Speakers produce sentences during which conceptual ideas are transferred into serial sounds, while listeners comprehend sentences during which linguistic representations are converted into meaningful information. It is easy to tell that production and comprehension proceed along opposite pathways of operating meanings and forms. In the production mechanism, the input is the meaning someone wishes to express and the output is the forms mapped from the meaning. In contrast, the input in the comprehension mechanism is the forms perceived from outside and the output is the meaning extracted from the forms. This opposite pathway may involve poor coordination between production and comprehension; for instance, it is a well-known phenomenon that children show asymmetries between production and comprehension in language acquisition (Hendriks & Koster, 2010).

Production/comprehension asymmetry (PCA) is quite common in the language acquisition stage (Clark & Hecht, 1983; Hendriks, 2014; Hendriks & Koster, 2010). For instance, 15-month-old infants can understand two-word combinations, such as “wash baby”, whereas they can only produce two-word utterances once they are 18 months old. And 16-month-old infants are able to understand 170-230 words but produce only 50 words (Kuhl & Damasio, 2013). This superior comprehension also exists in the developmental stage of early over-extensions of words. For example, Thomson and Chapman (1977) found that children aged from 1;9 (one year and nine months) to 2;3 overextended words like “doggie” to represent all types of four-legged animals in picture-naming tasks, but consistently selected only appropriate referents for the same words in picture-pointing tasks. Not only does comprehension precede production in lexicon acquisition, but it is also ubiquitous in the acquisition of morphological and syntactic forms, such as singular-plural distinction (Fraser et al., 1963; Nurss & Day, 1971). Therefore, it is not difficult to conclude that infants and children become competent in language comprehension before they are able to acquire similar competence in language production.

It is also possible that this asymmetry appears with comprehension falling behind production. As a case in point, English-speaking children exhibit unequal capacities in understanding and producing pronouns and reflexives. When comprehending a sentence including within reflexives like “Kitty says that Sarah should point to herself”, children between the ages of 6;0 and 6;6 showed an adult-like response and interpreted herself as Sarah; meanwhile when presented with sentences including within pronouns like “Kitty says that Sarah should point to her”, the same children did not consistently understand the pronoun “her” to be Kitty. This was different from adults’ responses that the nonlocal antecedent or the sentence-external referent was consistently considered as correct for the pronoun cases (Chien & Wexler, 1990). In contrast, Bloom et al. (1994) found in spontaneous speech, even 2- and 3-year-olds virtually showed adult-like patterns by saying, for example, “John hit me” and not “John hit myself”, and “I hit myself” and not “I hit me”. Thus, children must have mastered how to manipulate pronouns and reflexives on the production side but not on the comprehension side. This mismatch where comprehension is inferior to production was also discovered in the acquisition of word order at the sentence level

(Chapman Robin & Miller Jon, 1975).

Besides, cumulative evidence with neural image technologies has suggested that in addition to the shared brain region, production and comprehension activate different brain areas (Giglio et al., 2022; Menenti et al., 2011; Segaert et al., 2012); for instance, anterior temporal lesions were associated with production while posterior temporo-parietal lesions were associated with comprehension (Lukic et al., 2021), see also a review Price (2010). Due to the opposite pathways and different brain regions related to production and comprehension, it is plausible that these two modalities may show distinct vulnerability to age-related decline. It could also be the case that older adults, much like children, may exhibit retrogenic incoordination or asymmetries in their production and comprehension abilities, such that their expressive capacities are likely to be unequal to their receptive abilities. To clarify this question is the overarching aim of the current study.

1.3. Retrogenesis theory

Language is not invariable, on the contrary, it shows ontogenetic and phylogenetic variance. Furthermore, in contrast to being random, the change of language is guided by principles. In terms of the ontogenetic trajectory, language acquisition and dissolution follow the retrogenesis theory (Jakobson, 1941/1968; Barry Reisberg et al., 1999; Ribot, 1881/2012), or in other words, the first-in-last-out principle, which means the first one acquired in the language system is the last one dissolved from the system. In this situation, the earlier acquired ability in children is superior to the later acquired ability due to repeated practice. The ability to dissolve later in older adults is greater than the ability to dissolve earlier according to retrogenesis theory. Accordingly, retrogenesis theory suggests that the ability that is more stable in children should also be more stable in older adults. Alternatively, what occurs in children is likely to reoccur in older adults.

Roman Jakobson (1941/1968), based on his observations of language usage, proposed a forethought hypothesis that what is acquired last in language acquisition is lost first during the process of language dissolution, that is, “the dissolution of the linguistic sound system in aphasics provides an exact mirror-image of the phonological development in child language” (p. 60). This hypothesis is, to some extent, supported by extreme cases of expressive aphasia patients and receptive aphasia patients who suffer from brain damage in Broca’s area and Wernicke’s area respectively and have asymmetrically lost either production capacities or comprehension capacities (Price, 2000). The reversion idea is not confined to the linguistic discipline, however. Before Jakobson, Théodule-Armand Ribot (1881/2012), a French psychologist who pioneered psychology as a science, proposed Ribot's law of regression, that is, “it is a well-known fact in organic life that structures last formed are the first to degenerate… in the biological world, dissolution acts in a contrary direction to evolution… the new perishes before the old, the complex before the simple” (p. 127). After Jakobson, B. Reisberg et al. (1999), given the clinical, physiologic and pathological evidence, proposed the retrogenesis theory, that is, “the process by which degenerative mechanisms reverse the order of acquisition in normal development” (p. 28). In general, various declining features appearing in older adults are reminiscent of children.

There is mounting evidence that retrogenesis is rooted in neural and genetic processes, especially after the terminology was coined by Reisberg in 1999 (Alves et al., 2015; Ashford & Bayley, 2013; Braak & Braak, 1996; Brickman et al., 2012; Brun & Gustafson, 1976; Colantuoni et al., 2011; Cools & D'Esposito, 2011; Davis et al., 2009; Di Paola et al., 2010; Douaud et al., 2014; Fjell et al., 2014; Gao et al., 2011; Jacobs et al., 2011; Karama et al., 2014; Kavroulakis et al., 2021; Liana & Barry, 2009;

McGinnis et al., 2011; Medina et al., 2021; Meguro et al., 2020; Mura et al., 2010; Mustapha et al., 2021; O'Dwyer et al., 2011; Rathi et al., 2014; Raz, 2005; Raz et al., 2005; Raz & Rodrigue, 2006; Sang et al., 2021; Stricker et al., 2008; Tamnes et al., 2013; Thompson & Apostolova, 2007; Vik et al., 2015; Walker, 2011; Wasling et al., 2009; Williams, 1957/2001; Yeatman et al., 2014), for a recent review see Ahmed et al. (2017). For instance, in terms of the electrophysiologic changes, EEG activity patterns in AD recapitulate those of normal development inversely: as the patient ages, fast wave activity (alpha) gradually decreases and slow wave activity (theta and delta) increases; however, in normal development, slow wave activity is replaced by fast wave activity with increasing age. (Cioni et al., 1992; Liana & Barry, 2009; Prichep et al., 1994). Besides, in terms of the neuropathological changes in the cerebral cortex, Braak and Braak (1996) found “regressive changes of the cortex frequently repeat the process of maturation in reverse order”(p.200), as children show the outward progression of myelination which is from the neocortical core fields into the associated higher-order processing areas, whereas the progression of intraneuronal neurofibrillary changes of the AD is from the entorhinal regions via neocortical higher-order processing areas and belt areas, and finally into the core fields. Thus, myelination and destruction proceed in opposite directions, as also seen in white matter fiber degeneration, gray matter alterations, cortical and subcortical volume deduction, and neocortical-related functions decline during normal cognitive aging (Brickman et al., 2012; Douaud et al., 2014; Rathi et al., 2014; Rubial-Álvarez et al., 2013; Tamnes et al., 2013).

Moreover, the attempt to relate development and aging on a genetic level has also attracted attention. The concept of antagonistic pleiotropy is a representative example. The pleiotropic genes produce different effects in different somatic environments. In more detail, pleiotropic genes promote fitness and reproduction for development, but also reduce vigor and guarantee senescence by the same mechanism (Walker, 2011; Williams, 1957/2001). However, it was only recently discovered that retrogenesis was explicitly implicated in gene expression. During fetal development, there is a wave of gene expression changes that are reversed in the early postnatal period. Most importantly, this pattern of reversals reoccurs half a century later in life in the form of neurodegeneration and aging (Colantuoni et al., 2011). Thus, what occurs during the development stage repeats during the aging stage in the human genome, underpinning the genetic control of retrogenesis.

On the other hand, it should be noted that retrogenesis is one major type of age-related change and there are alternative variations. For instance, in the neural aspect, neuronal disruption is associated with Wallerian degeneration (opposed to retrogenesis), which is characterized by retrograde structural changes such as axonal dissolution, followed by contraction and fragmentation of myelin, and finally breakdown and removal of myelin (Alves et al., 2015; Beaulieu et al., 1996). In addition, retrogenesis contributes substantially to regional differences in development and aging in terms of cortical changes, although a simple last-in-first-out hypothesis of life-span changes is not sufficient to account for all spatial variation (Douaud et al., 2014; Westlye et al., 2010). Lastly, in terms of language ability, although few studies have attempted to refute the “regression hypothesis” with observations of older adults’ syntactic ability in language production (Lust et al., 2015), their results were likely to reflect preference in terms of language usage rather than language competence due to the limitations of their imitation tasks(Lust et al., 1996). Thus, with the preponderance of retrogenesis, it is likely that older adults also display the PCA that is observed in children.

1.4. Language abilities and declarative/procedural memory

Language ability is not an isolated system, rather it is closely related to multiple cognitive abilities. Just like Wang (1982) proposed, based upon mosaic theory, "language is regarded as a kind of interface among a variety of more basic abilities" (p. 17). At the beginning of human evolution, language emerged by reusing preexisting functions. As Jacob (1977) proposed, the evolution process functions in much the same way as a "tinker", who "works on what already exists, either transforming a system to give it new functions or combining several systems to produce a more elaborate one" (p. 1164). For instance, at the molecular level, natural selection loses its constraints on gene function when a gene exists in multiple copies within a cell or a gamete. It is then possible for mutations to accumulate freely and eventually alter protein structures, which are likely to lead to the development of novel functions. Namely, the new function is generated from the existing molecular structures.

The "tinker" idea also resonated with the principle of "exaptation" which was coined by Gould (1991). He pointed out the differences between historical origin and current utility, and differentiated "exaptation" from the hegemony of "adaption" during the ultra-Darwinian period. According to his opinion, the exaptation referred to "useful structures not evolved for their current function, but coopted from other contexts" (p. 46). For instance, as an initial evolution of the adaptation for thermoregulation, the proto-wing was then coopted for a flying apparatus. This can also be applied to reading ability which is a relatively recent cultural acquisition, based on the "neuronal recycling" hypothesis (Dehaene, 2005). The neuronal recycling hypothesis proposes that "the human capacity for cultural learning relies on a process of preempting or recycling preexisting brain circuitry" (p. 134). For instance, reading evolves from the precursor which opts for object recognition, as these two systems resemble each other and the flexibility of the precursor is sufficient to allow it to be reconverted. To be specific, such flexibility allows the evolutionary precursor to connect visual recognition processes with new mental syntheses, such as phonological representations which is a key factor for visual word recognition, and eventually developing mature reading abilities.

Therefore, it is likely that language system reuses preexisting neurobiological bases and preemptive cognitive abilities, for instance, DM and PM (Ullman, 2014). Lexical memory and aspects of grammar reutilize DM and PM respectively (Ullman, 2001b), as these two systems share similar features. Mental lexicon involves handling arbitrary associations between forms and meanings, which is corresponding to the function of DM. On the other hand, the PM is expected to subserve the processing of sequences and rules, which is required for most mental grammar content. Such reuse happens not only in phylogenetic history but also across different ontogenetic stages. During the development of first language, children build the connections to recruit DM and PM to acquire semantic knowledge and syntactic knowledge (Ullman, 2001b; Ullman, 2014).

Thanks to cortical plasticity, language abilities and memory abilities do not always correspond in a one-to-one fashion. For instance, Procedural circuit Deficit Hypothesis (PDH) posits that children with developmental language disorder (DLD) suffer from abnormalities of the brain networks which support the PM system. On the other hand, the DM systems which remain relatively normal play a compensatory role for procedural circuit deficits (Ullman et al., 2020; Ullman & Pierpont, 2005). In addition to the cooperative aspect, there is also a competitive aspect in the plasticity of the two memory systems. Xie et al. (2019) recruited participants to complete PM tasks at the same time as memorizing destructive words. They found that it was possible for DM to interfere with PM if the tasks had no semantic association with the destructive words, while the interference effect disappeared when there was a semantic association.

Moreover, when both semantic association and sequence matching were encoded in the destructive words, the interference effect could be reversed into an enhancement effect. There are diverse possibilities for the two memory systems broadening and/or narrowing their functions.

There is evidence that different cognitive abilities are subject to different changes over the course of a lifetime (Park & Reuter-Lorenz, 2009). DM appears to improve during childhood, plateau in adolescence and early adulthood, and then decline thereafter. PM seems to be robust early in childhood and tends to decline around the time of adolescence (Finn et al., 2016; Ullman, 2020). Though the declining rates of both memory systems are not clear, it is plausible that older adults may demonstrate different levels of declarative and procedural memory performance. In addition, it is likely that the strength of the connections between declarative and procedural memory abilities and semantic and syntactic abilities differs between individuals. In the current study, we aim to clarify age-related changes in declarative and procedural memory and their associations with language abilities.

1.5. Research questions and hypothesis

The overarching aim of the present study is to investigate if there is a retrogenic PCA in ChOA and, if so, how the asymmetry relates to DM and PM. To achieve this goal, the semantic and syntactic processing mechanism of the Chinese Ba construction was explicitly investigated in both younger adults and older adults, and a systematic comparison was made of expressive and receptive abilities. Moreover, DM and PM were carefully measured in order to examine how these two memory systems were related to PCA. To be more specific, we aimed to answer the following three questions.

Firstly, we focused on investigating the detailed changes in the semantic/syntactic abilities of ChOA as a result of aging, including both behavioral and neuronal changes. In particular, we attempted to clarify the impact of aging on semantic and syntactic abilities, both in the expressive and receptive modalities. Secondly, we aimed to investigate if there are production and comprehension asymmetries in ChOA similar to that frequently reported in language developmental stages. Thirdly, we intended to probe the associations between declarative/procedural memory and semantic/syntactic capacity in ChOA. In other words, we attempted to examine whether declarative and procedural memory systems interact differently with language abilities in the expressive and receptive modalities for older adults.

In alignment with previous studies, we expected that older adults would tend to, on the one hand, exhibit age-related decline in semantic abilities in both the expressive and receptive modalities and, on the other hand, display relatively well-preserved syntactic abilities in both the expressive and receptive modalities. In terms of PCA, based on the retrogenesis theory and the reported asymmetry in children, we hypothesized that older adults were likely to demonstrate PCA in terms of either syntactic ability or semantic ability. Finally, we presumed that, according to the declarative/procedural model, on the one hand, younger and older adults would probably exhibit associations between declarative/procedural memory systems and semantic/syntactic abilities in both the expressive and receptive modalities; on the other hand, we posited that the PCA in older adults was likely to be related with unequal correlations with declarative/procedural memory systems.

To be more specific, we hypothesized that older adults may have difficulty accessing DM and PM systems to support semantic and syntactic processing. This is possible as certain cognitive abilities, such as implicit learning, may be constrained by higher cognitive mechanisms (Smalle et al., 2022). Therefore, the connections between declarative/procedural memory and semantic/syntactic processing might not be equally robust due to the effects of aging. The association between declarative/procedural memory and syntactic/semantic processing at the production level might not be apparent at the comprehension level, and vice versa. Moreover, the presence or absence of this association at the production level and comprehension level may eventually impact on performance in terms of production and comprehension, and cause asymmetry such that the capacity for generating a sentence and the capacity for comprehending a sentence are not equal.

1.6. Outline of the dissertation

The first chapter presents background information regarding retrogenic PCA and how it relates to memory abilities. Additionally, it explains the significance of the current study and details the research questions and hypotheses. The second chapter identifies the research gap by reviewing previous work on PCA, semantic and syntactic processing, and declarative and procedural memory. In the third chapter, we present the tasks used to measure DM and PM, as well as receptive and expressive semantic abilities and receptive and expressive syntactic abilities. Also described in Chapter 3 is the basic information of participants and the arrangement of all the experimental tasks over the course of two consecutive days.

Chapter 4 provides a detailed analysis of the results of the DM and PM for both groups. DM and PM are examined in this chapter to determine if there is an age-related decline. The chapter continues with a discussion of whether the decline in DM and PM was consistent with retrogenesis theory.

The results of the constrained production tasks are presented in Chapter 5. The participants were asked to construct a sentence using the provided words. The reaction times (RTs) and semantic complexity of a suitable verb condition indicated expressive semantic ability. On the other hand, the RTs and syntactic complexity of an unsuitable verb condition revealed expressive syntactic ability. Production performance was found to differ with age.

In Chapter 6 and Chapter 7, the results of comprehension tests were discussed. The receptive syntactic and semantic abilities were assessed using syntactic and semantic correctness judgment tasks, respectively. A simultaneous recording of electroencephalograph (EEG) signals was undertaken. A decline in both receptive syntactic and semantic abilities was observed in older adults, but the decline was not paralleled at the behavioral and neural levels.

A general discussion of all the results is provided in Chapter 8. The retrogenic decline in DM was further elaborated on. The semantic PCA was explicitly described, including its developmental pathway and the underlying mechanism. PCA was explained by the extended declarative/procedural model, which links declarative/procedural memory to semantic/syntactic abilities asymmetrically in expressive and receptive modalities.

Chapter 2. Literature review

2.1. Theories related to production/comprehension asymmetries

Production and comprehension are two opposite processing mechanisms (Hendriks & Koster, 2010). When producing speech, the input of meaning is mapped onto the output of the corresponding form, while the input of form is decoded into the output of appropriate meaning when comprehending a sentence. Meaning and form proceed in opposite directions for production and comprehension. The directional sensitivity of language processing might be one reason why children exhibit production and comprehension asymmetries (Hendriks & Koster, 2010). In addition, children still possess immature cognitive abilities, which can result in instabilities and uncertainties in language use. Thus it is plausible that children exhibit poor coordination in production and comprehension as a result of cognitive limitations. A prime example is how children acquire reference set computation in processing sentences containing a pronoun (Reinhart, 2004). Reinhart has argued that the reference set computation is an operation applied in the interface between grammar and working memory, and it allows the hearer to construct comparisons between two deviations and their corresponding interpretations of a sentence. As children do not fully develop working memory, they may be unable to complete the comparisons and fail to comprehend the sentence. However, it is unnecessary for them to utilize the reference set computation to produce a sentence, as they generally tend to express only one deviation and interpretation of a sentence. In the end, due to working memory limitations, there is a developmental delay in comprehension rather than in production.

A similar theory was proposed to explain production and comprehension asymmetries in older adults, namely the resource theory, for a review, see Burke and Shafto (2011). According to the resource theory, the mental resources that we can utilize are fixed. As older adults tend to consume more mental resources in the perceiving stage due to their degenerative sensory organs, the remaining mental resources that can be applied to language processing are reduced and become insufficient. Consequently, older adults show a decline in language comprehension. In contrast, this problem does not exist on the production side as there is no need for older adults to perceive any inputs before producing a sentence. However, the resource theory is uncertain and has been subject to skepticism due to the vagueness of the definition of resources. It is unclear which cognitive abilities can be included among the resources that facilitate input perception. Also, it is unclear why the same quantities of resources are not saved for later output generation when initiating language production since older adults suffer from age-related decline in phonation and articulation (Arias-Vergara et al., 2017). Therefore, there are some drawbacks inherent in the resource theory.

Another hypothesis is the transmission deficit model, which was proposed by Burke and colleagues (Burke, 2002; Burke & Shafto, 2004; MacKay & Burke, 1990). This assumes that there are multiple layers of nodes between input and output. Comprehension involves bottom-up processing during which the output starts from orthographic or phonological nodes; it is then transmitted in parallel to the lexical node and activates the upwards semantic system. In contrast, production is a top-down process, with activations spreading from a lexical node to several orthographic or phonological nodes. An individual word represents a lexical node and it has a certain number of orthographic and phonological nodes depending on how many letters or phonemes it contains. Therefore, comprehension allows for converging activation from multiple orthographic and phonological nodes to a single lexical node while production depends on activation from a sole lexical node to each of its orthographic and phonological nodes. With increasing age, the strength of the connections within the network weakens, resulting in a slower transition speed and less activation being transferred. As a result, older adults' comprehension performance may remain relatively unaffected, since the lexical node receives converging activation from multiple nodes. In contrast to comprehension, production performance is more vulnerable to aging since one lexical node is responsible for multiple orthographic and phonological activations.

It has been demonstrated across a variety of tasks that there are asymmetries between comprehension and production for single words, with older individuals showing production deficits despite the absence of comparable comprehension deficits, for a review, see Thornton and Light (2006). The transmission deficit model has been posited as a possible explanation for these phenomena. For instance, White and colleagues (2012) investigated how aging influences the perception and production of homophones. They asked younger and older adults to write down sentences they heard and to determine whether the sentences they read contained any word that made them ungrammatical. The same sentences were used as stimuli in two tasks, one example being, “There are only a couple of feet before I cross the line and *beat* my opponent.” and “Jamie thought it would be neat to serve chicken with *beet* glaze at her dinner party.”; these contained a dominant homophone and a subordinate homophone respectively. Older adults made more errors in spelling dominant homophones but, on the other hand, exhibited better detection of homophone errors than young adults. The PCA for homophone processing was consistent with the transmission deficit model.

However, it is important to note that the transmission deficit theory is information-specific and focuses on word production deficits. As Burke (2002) argued, “we would not expect older adults’ transmission deficits to affect language production at a higher level such as the production of semantically coherent discourse” (p. 17). This argument could also be extended to sentence production and comprehension, since additional semantic and syntactic processing is required to handle external context.

In conclusion, to our knowledge, the existing theories and hypotheses are not appropriate for explaining or predicting PCA in older adults with regard to sentence processing. A major reason for this is that, unlike single lexical processing, sentence processing involves simultaneous semantic and syntactic processing, making the situation much more complex. In order to disentangle this issue, the following sections review the changes in semantic and syntactic processing that result from aging, and discuss how these changes relate to memory functions.

2.2. Age-related differences in semantic/syntactic processing

Semantic processing is implicated in constructing meaning in production and extracting meaning in comprehension. Converging evidence has demonstrated that older adults suffer from a semantic decline in production performance, and this situation is even worse in dementia patients (Bates et al., 1995; Conner et al., 2011; Dave et al., 2018; Faroqi-Shah et al., 2020; Kavé & Levy, 2003; Kemper, Thompson, et al., 2001; Kempler et al., 1987); for a review, see Mortensen et al. (2006). For instance, Kemper et al. (2003) asked younger adults and older adults to complete a constrained production task in which participants were required to compose a sentence based on words provided; they found that older adults produced simpler and less complex sentences than younger adults. However, it is noted that some studies, for example, Burke and Shafto (2004) proposed that semantic capacity is also preserved in older adults when producing sentences. On the other hand, comprehension studies using EEG technology have suggested that older adults exhibit different patterns from younger adults in terms of the amplitude, latency, and scalp distribution of the N400 congruity effect when reading semantically incorrect sentences (Federmeier & Kutas, 2005; Federmeier et al., 2010; Federmeier et al., 2002; Federmeier et al., 2003; Kutas & Iragui, 1998; Wlotko et al., 2010; Xu et al., 2020; N. N. Xu et al., 2017; Zhu et al., 2018; Zhu et al., 2019). For example, Kutas and Iragui (1998) found that older adults showed a reliable decrease in amplitude and a reliable increase in peak latency on the N400 congruity effect, which indicated that older adults' semantic processing declined in terms of receptive modality. We are aware of a few studies that have reported that older adults preserve their semantic processing in comprehension tasks. For instance, Federmeier et al. (2002) found that older adults, but only those with "higher verbal fluency and larger vocabularies" can "offset certain age-related changes", and show the younger response pattern in semantic comprehension tasks. Though this group of adults cannot be considered normal older adults, it does provide prospective insight into how older adults can prevent age-related semantic decline by improving their cognitive ability, for example, their DM and PM, which will be discussed in the next section.

Syntactic processing refers to combining various constituents into linear sequences in production and parsing a sentence into syntactic constituents in comprehension. Previous studies have reported that older adults show a syntactic decline in production performance, especially those with dementia (Bates et al., 1995; Kemper et al., 2003; Kemper, Thompson, et al., 2001). For instance, Kemper and Sumner (2001) asked both younger adults and older adults to describe an influential person or interesting experience, and found that compared with younger adults, older adults tended to use syntactically simple sentences, which suggested that older adults experienced an age-related syntactic decline in production. However, some studies also suggested that older adults are not impaired in syntactic processing in production tasks (Davidson et al., 2003). These inconsistent results were also found in comprehension tasks in which subjects were required to read syntactically incorrect sentences while EEG signals were recorded. Some studies reported that older adults showed reduced amplitude and prolonged latency on the P600 congruity effect indicating an age-related syntactic decline in receptive modality (Alatorre-Cruz et al., 2018; Zhu et al., 2018), while other studies found that older adults showed a similar P600 congruity pattern with younger adults suggesting that their syntactic capacity is intact when comprehending sentences (Kemmer et al., 2004).

The overview of previous studies has demonstrated that, except in the area of semantic processing in comprehension, other aspects all produced inconsistent results in older adults. That is to say, older adults have demonstrated both preserved and degraded abilities in semantic processing, which is used in production, as well as in syntactic processing, and is used in both production and comprehension. One possible reason for the contradictory performance in older adults is that different studies recruited different participants, and the individual differences would more or less lead to these controversial results. Therefore, in the current study, we adopted a within-subject experimental design. We controlled for the homogeneity of subjects and recruited older adults to complete all the production and comprehension tasks, in order to reduce, as far as possible, the deviation between production and comprehension caused by different participants.

Some special patterns in Chinese are feasible for investigating semantic processing and syntactic processing, for instance, the Ba construction, Bei construction, Existential construction, and so on. In the present study, we focused on one type only, namely the Ba construction. We selected the Ba construction as an observational window for the following three reasons: firstly, the Ba construction is a special kind of syntactic pattern which involves in a fixed word order and this is different from the canonical Subject-Verb-Object order in the Chinese language (Huang & Shi, 2016). The object in Ba construction is placed before the verb rather than in its canonical post-verb position; for instance, “管家/把/房间/整理/了 (housekeeper/Ba/room/tidy/aspect marker; The housekeeper tidied up the room)”. Consequently, Chinese native speakers would absolutely regard a sentence like “*管家/把/整理/房间/了 (housekeeper/Ba/tidy/room /aspect marker)” as a syntactic anomaly. One possible reason why the word order is reorganized is to alter the information structure and highlight the disposal meaning of the verb which is directly imposed on the nouns (Xie, 2018). And this is also the second reason why we chose the Ba construction, as the semantic feature of the verb should explicitly match the preceding noun. For instance, if the verb “拔(pull)” in the sentence “园丁/把/杂草/拔/了(gardener/Ba/weeds/pull/aspect marker; The gardener pulled up the weeds)” is replaced by “宰(kill)”, it obviously leads to a semantic anomaly for Chinese people. Finally, as the Ba construction spotlights the meaning of disposal, only verbs containing a disposal meaning can fit in the construction. Therefore, sentences like “*学生/把/老师/喜欢/了(student/Ba/teacher/like/aspect marker)” which involves a stative verb, are definitely grammatically incorrect. All these three advantages of the Chinese Ba construction make it a potential tool for discovering how older adults execute their semantic processing and syntactic processing in production tasks and comprehension tasks.

In the current study, we focused on semantic processing and syntactic processing which are two important factors in connecting meaningful units and parsing sentences. Moreover, these two capacities are closely associated with DM and PM, as elaborated in the next section.

2.3. Declarative/procedural model

Memory is a complex system that is made up of multiple subcategories. DM and PM are two major components of the memory system (Cohen & Squire, 1980; Squire, 2004; Tulving, 1985; Ullman, 2001c; Ullman et al., 1997). The DM system refers to rapid learning, representation, and the use of arbitrarily-related information, including the active or conscious recall of previous experiences and conscious retrieval of factual knowledge about the world (Kuhl & Damasio, 2013; Squire, 2004; Tulving, 1972; Ullman, 2001a, 2004). In the encoding stage, DM can be acquired rapidly, and even one single exposure is enough to generate storage in the DM system. Moreover, DM is encoded not only explicitly, but also at least in part, implicitly. For instance, most of the time, the memory of eating a green apple yesterday is stored implicitly and unconsciously.

DM systems primarily depend on the hippocampus and nearby regions in the temporal lobes. These structures not only support the encoding and consolidation of new information but also facilitate the retrieval of stored information (Lum et al., 2012; Ullman, 2001a, 2004). Moreover, the prefrontal cortex is also engaged in encoding DM. And it shows hemispheric specialization that encoding verbal words and non-verbal pictures enhance neural activation in the left prefrontal cortex and right prefrontal cortex respectively. It also indicates that DM learning interacts with executive control processes subserved by the prefrontal cortex (Kuhl & Damasio, 2013). After repeated consolidation, the new engram eventually transfers to long-term potentiation and is principally stored in the neocortex instead of relying on the medial temporal lobe structures. This is why amnesia patients, like H.M. whose medial temporal lobe was surgically removed, can still remember their childhood experiences but can’t form new DM (Milner et al., 1998). Furthermore, the acquired knowledge is distributed in the discrete cortical region based on its features (Martin & Chao, 2001). For instance, one may restore the sound of his/her grandmother in the auditory cortex and restore the image of his/her grandmother in the visual cortex[4] (Poo, 2020).

On the other hand, the PM system supports the learning and implementation of perceptual-motor and cognitive skills and habits, such as driving a car and playing skilled games (Ullman, 2001a, 2004; Ullman et al., 2020). In particular, learning rules and sequences requires the support of the PM systems. Unlike the rapid acquisition of DM, PM is gradually acquired via cumulative exposure to stimuli and responses, which also proceeds implicitly. After mastering the rule, it is applied quickly and implicitly with the response elicited by the original stimuli automatically. The system is subserved by the cerebellum, the basal ganglia and their associated circuitry, especially the basal ganglia. Learning hinged on the basal ganglia involves developing predictions about associations between stimuli and then assessing these predictions on the basis of the feedback. Moreover, different stages of procedural learning are subserved by distinct regions of the basal ganglia. The earlier phases of prediction-feedback learning of associations rely on the anterior striatum, primarily the anterior caudate and putamen which may underlie aspects of motivation, as well as working memory and executive. In contrast, the later phases involve the processing of automized association dependent on posterior parts of the striatal circuits which may support aspects of motor and/or visual learning (Ullman et al., 2020).

DM and PM change in different trajectories across the lifespan (Hedden & Gabrieli, 2004). The PM barely exhibits age-related decline, even in patients with mild AD (Hirono et al., 1997). In contrast, DM, particularly in terms of new encoding memories of episodes or facts, declines evidently in later years. A piece of robust evidence is that the preliminary phases of AD are marked by shortfalls in DM(Buckner,

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[4] This example was cited directly from a public lecture of Poo(2020). More evidence with language materials, such as that action verbs with different body part (e.g., kick, pick and lick) would activate different brain regions, also support this idea (Hauk et al.,2004； Pulvermüller et al.,2001).

2004; Lai & Lin, 2013). Besides, regional changes in the brain in terms of volume are not uniform pertaining to the DM system and PM system. Striatal volume declines by about 3% per decade between 20 and 80 years of age (Gunning-Dixon et al., 1998), whereas the hippocampus and the para-hippocampal gyrus show a 2–3% per decade decline in volume (Raz, Gunning-Dixon, et al., 2004), and this might extend to a 1% annual decline after the age of 70 (Clifford R. Jack et al., 1998), which would likely result in deterioration of the neural foundation of DM. It is reasonable to conjecture that behavior patterns including language usage which are guided by the DM system and PM system could also change in different ways in older adults. Nevertheless, the relationship between changes in various language domains and changes in DM and PM remains unclear, since these two memory systems are also likely to interact as outlined below.

The declarative/procedural model proposes that the brain systems that subserve DM and PM also play analogous roles in language usage (Ullman, 2001a, 2004, 2008, 2013, 2016). DM systems serve the mental lexicon of memorization relating to word-specific knowledge, whereas PM systems assist the mental grammar of the rule-governed complex representations combined from subordinate items. The mental lexicon consists of simple words which are arbitrary pairings of sound and meaning (e.g. cat), bound morphemes that are smaller than words (e.g. the -ed or -er suffixes, as in worked or worker), and idiomatic phrases that are larger than words (e.g. kick the bucket). DM is crucial for semantic processing, since the first step in semantic processing is to construct meaning or extract meaning from the mental lexicon. Moreover, mental grammar supports sequential and hierarchical combinations across linguistic domains, including phonology, morphology, and syntax. Automatically applying mental grammar is important in syntactic processing.

It is noted that the PM involved in the declarative/procedural model refers only to one type of implicit, non-DM system (Ullman, 2001a, 2004); this is generally measured by the visuospatial serial reaction time (SRT) task during which subjects are required to press buttons corresponding to where spots appear on a monitor. The position of the spot changes with a regular or irregular sequence (Clark et al., 2014; Hedenius, Persson, et al., 2013; Janacsek et al., 2020; Koch et al., 2020; Lum et al., 2014; Lum et al., 2019; Lum et al., 2013; Takács et al., 2018; Takács et al., 2017; Vakil et al., 2021). Subjects who are guided by PM systems will perform much better than subjects who are not guided by PM systems. On the other hand, DM is typically assessed using declearn tasks and the story recall task (Conti-Ramsden et al., 2015; Hedenius, Ullman, et al., 2013; Kavé & Sapir-Yogev, 2020; Lukács et al., 2017; Lum et al., 2012; Lum et al., 2015; Tulving, 1972).

Various memory systems operate not only independently but also cooperatively to support behaviors, which also exist in DM and PM. For example, a memory of being bitten by a vicious dog in childhood would be stored in the DM system and you cannot forget the event itself and its details. On the other hand, it could also be stored in PM and give you a phobia of dogs, in which case the event is not just a memory but unconsciously and automatically changes your personality and reaction when facing a dog (Squire, 2004). DM system and PM system operate collaboratively and competitively, and comprise a dynamically interacting network to optimize their functions (Squire, 2004; Ullman, 2001a, 2004). Our brain as a whole subserves all our related cognitive and physical activities, and some specific regions also support various domains of activities (Ullman, 2008).

In language processing, complex English structures, such as “walked” can be an example to illustrate this parallelism. In PM, “walked” could be computed into the composition of the original word “walk” and English regular past tense “-ed”, which can be stored based on its rule-based grammatic foundation. However, it could also be acquired and stored as a chunk in DM. This is the so-called compensatory role of DM to PM (Ullman et al., 2020; Ullman & Pierpont, 2005), which is quite common in DLD children (Conti-Ramsden et al., 2015; Hedenius, Persson, et al., 2013; Hedenius, Ullman, et al., 2013; Lukács et al., 2017; Lum et al., 2014; Lum et al., 2012; Ullman & Pullman, 2015). For instance, Lum et al. (2012) found that compared to typically-developing children, DLD children performed poorly in the visuospatial SRT task but not in the word pairs and stories recall tasks, which means DLD children were impaired at PM but not DM. Besides, they also found that both lexical abilities and grammatical abilities were correlated with DM in DLD children, suggesting a compensatory role of DM to PM. Older adults also suffer from an impairment, but probably only in DM not in PM. However, it remains uncharted whether older adults take advantage of this compensatory mechanism of memory to support language usage, due to scarce investigation in the aging population (Rieckmann & Bäckman, 2009), not least ChOA.

In the current study, the Chinese Ba construction will be deliberately designed to investigate how declarative/procedural memory systems interact and subserve language usage. The Ba construction is optimal for exploring this issue for the following two reasons. Firstly, previous studies have found that semantic violations in the Ba construction would elicit a prominent N400 effect (Wang et al., 2013; Ye et al., 2006; Yu & Zhang, 2008; Zhu et al., 2018). For instance, Ye et al. (2006) found that when Chinese readers comprehended sentences that included a semantic violation in the Ba construction, such as “*伐木工开采森林, 把松树裁了(*Exploiting the forest, the timberjack cut pine trees.)”, an N400 component that pinpointed the semantically incorrect usage of “裁 (cut)” could be discovered in the event-related potentials results, compared to reading a semantically correct sentence, such as "设计师制作新衣，把布料裁了(To make new dresses, the stylist cut the cloth.)". It is reasonable that N400 effects would be triggered for the incorrect sentence, since none of the meanings of "裁(cut)" that could be retrieved match the preceding context. DM systems support the retrieval of lexical items. It is plausible that readers with higher DM ability would comprehend sentences easily and identify the correctness much faster. In a similar manner, older adults who possess intact DM are more likely to be able to distinguish sentences than those who possess impaired DM and failed to compensate with PM. Besides, there might be an extreme circumstance when older adults are spared from the deficit in DM, but still demonstrate impairment in their ability to comprehend sentences, as their DM cannot support their semantic processing, or to put it in another way, the connection between DM and semantic processing has been broken or cannot be accessed. Their DM competence is intact, but their DM performance is impaired. There is an asymmetry between competence and performance. It is not the DM itself, but the supporting functions linking to language comprehension suffer from age-related decline, which eventually leads to poor performance in semantic comprehension.

Besides, the Ba construction also requires a strict word order which makes it a feasible tool for exploring how older adults process syntactic rules and sequences and how it is guided by PM. In the Ba construction, the nominal phrase must appear after the Ba marker and before the verb, which is different from its typical post-verbal object position (Huang & Shi, 2016). Thus, sentences like "*把/砍/松树/了(Ba-marker/cut/pine/aspect marker.)" are obviously incorrect, as the verb "砍 (cut)" is preceding the noun "松树 (pine)" which violates the required word order for the Ba construction. Chinese is an isolating language and does not possess systematic suffixes to express various syntactic meanings. Therefore, it is difficult or even impossible to design the kind of stimuli implicating morphological violations that appear frequently in previous studies investigating how English or other inflectional language native speakers process syntactically correct or incorrect sentences. Moreover, the stimuli used in previous studies to explore syntactic processing in Chinese may not represent pure syntactic violations. For instance, Ye et al. (2006) directly deleted the critical word from sentences, such as "*伐木工开采森林，把砍了(*Exploiting the forest, the timberjack cut.)". Zhang et al. (2010) directly replaced the critical verb with a noun, such as "*李薇把新鲜的鸭梨慢慢地*刀子*了两个 (*Wei Li *knife* two fresh pears slowly). These examples definitely cause syntactic anomalies, but also cause severe semantic anomalies. Thus, word order violations in the Ba construction would be a potential window to scrutinize the syntactic processing of Chinese. Hagoort et al. (1993) found that word order violations in Dutch, such as "*De echtgenoot schrikt van de *emotionele nogal reactive* van zijn vrouw (The husband [is startled] by the *emotional rather response* of his wife.)" which is a violation of phrase structure constraints that nouns should be preceded by transpositions of adverbs and adjectives, would elicit a syntactic positive shift (SPS) component compared to syntactically correct sentences. Therefore, it is plausible that older adults with or without PM deficit would exhibit different performances in processing sentences like "*把/砍/松树/了 (*Ba-marker/cut/pine/aspect marker.)" which involves a word order violation, as PM systems are specifically important for sequence operations. Older adults with intact PM are predicted to perform better in dealing with this kind of incorrect Ba construction. Still, they could also behave poorly if their connection between the PM and receptive syntactic processing has deteriorated.

2.4. Summary

Previous studies have suggested that during language development, children were reported to display production and comprehension asymmetries at both the lexical level and sentence level (Fraser et al., 1963; Gershkoff-Stowe & Hahn, 2013; Hendriks & Koster, 2010; McClellan et al., 1986; Nurss & Day, 1971). Based on the retrogenesis theory (B. Reisberg et al., 1999), PCA is likely to appear in older adults. This was confirmed by the unequal performance in producing and comprehending lexical items (Ullman et al., 2022; White et al., 2012).

However, it is still unknown whether PCA exists in sentence processing for older adults. One possible reason is that sentence processing involves both semantic processing and syntactic processing which were reported to be subject to a decline in some research (Bates et al., 1995; Faroqi-Shah et al., 2020; Kavé & Levy, 2003), and to be intact in other research (Duñabeitia, Marín, Avilés, et al., 2009; Kempler et al., 1987; Zhuang et al., 2016). The inconsistent results about age-related changes in semantic processing and syntactic processing have led to uncertainty about the existence of PCA in older adults. Therefore, the current study aims to clarify age-related changes in semantic processing and syntactic processing and further examine PCA in older adults.

Moreover, existing theories and hypotheses cannot predict and explain PCA in older adults due to their inherent limitations. In the present study, we seek to rectify this issue by using the declarative/procedural model which has been proposed as an explanation for language processing (Ullman et al., 2020; Ullman & Pierpont, 2005; Ullman & Pullman, 2015).

Chapter 3. Methodology

The current study followed the within-subject design in which all subjects were exposed to all language tasks and memory tasks. One advantage of this repeated measures design was that the same set of subjects was required to complete all the production tasks and comprehension tasks with a particular language pattern (Ba construction), which could lead to consistent results and ultimately disclose retrogenic PCA. Moreover, all the memory ability measurements and language ability measurements were applied to all the subjects. This could result in an explicit and systematic comparison between memory ability and language ability, and eventually, throw light on the underlying mechanisms of age-related memory decline and language attrition.

3.1. Subjects

In total, 28 Chinese younger adults (mean age = 24.1 ± 2.6, range = 19-30; 14 males) and 29 ChOA (mean age = 68.3 ± 2.6, range = 65-76; 13 males) [5] were recruited for the current study. Younger adults were students at The Hong Kong Polytechnic University. Older adults were recruited through the Shenzhen Association of Senior Scientists and Technicians or through the dissemination of information about the study. All the subjects were Chinese native speakers and used Mandarin in daily life. There was no history of motor or neurological disorders among the subjects, all of whom had normal or corrected-to-normal vision. The experiments were approved by The Hong

[5] Two older subjects were excluded from data analysis in the following part, as they were diagnosed with mild cognitive impairment (MCI) when examining their scores of the Beijing version of the Montreal Cognitive Assessment (MoCA-BJ). These two subjects were remained for future further study to make a comparison between healthy older adults and patients with MCI to depict the pathological trajectories of production and comprehension asymmetries as well as the declarative and procedural memory decline. In the end, the rest of older subjects (mean age = 68.0 ± 2.7, range = 65-76; 11 males) were all cognitively healthy ChOA which keeps subjects in a same cohort and rule out potential unwanted factors. The mean MoCA score of the rest older adults was 26.85 ± 1.75, ranging from 22 to 29. We lowered the cut-off score of MoCA-BJ to 22, as this point could show optimal sensitivity and specificity for Chinese population. For more details about the recommended cut-off score of MoCA-BJ, see Yu,J.,Li,J.,Huang,X.(2012).

Kong Polytechnic University's Human Subject Ethics Subcommittee (Reference Number: HSEARS20210303002). Prior informed written consent was obtained from each participant. An honorarium was paid to each participant.

3.2. Declarative memory ability measurement

DM was tested with the declearn task which was developed by the Brain and Language Lab at Georgetown University. It is suggested that this efficiently measures the DM which is incidentally encoded, and excludes the influence of working memory (Lum et al., 2012). There are three stages to the tasks. The first stage is the incidental encoding phase during which subjects are presented with pictures; they are required to identify whether the presented item is a real object. The stimuli consist of pictures of real objects and made-up objects. After a 10-minute delay and a 24-hour delay, there is an initial recognition phase and a delayed retention phase respectively. Subjects are required to complete similar tasks in the latter two phases during which they need to recognize whether they have seen the items in the previous encoding phase. The accuracy rate in all sessions was recorded. Subjects would obtain a higher accuracy rate in the initial recognition phase and the delayed retention phase if they had better declarative memory ability.

3.3. Procedural memory ability measurement

The SRT task has been frequently used to measure the PM in various subjects (Janacsek et al., 2020), including infants (Koch et al., 2020), children with DLD (Lum et al., 2014), children with Tourette syndrome or Attention Deficit Hyperactivity Disorder (Takács et al., 2018; Takács et al., 2017), dyslexia patients (Lum et al., 2013), and Parkinson's disease patients (Clark et al., 2014). In the current study, we applied this method to assess participants' procedural memory capacity. It appears that participants employ procedural learning for perceptual-motor sequences in the task.

After repeated exposure to a predefined sequence, participants are able implicitly to learn the sequence via their PM. The acquired sequence allows them to press buttons that follow the predefined sequence much faster than in the initial state, and causes them to slow down abruptly when the pattern of the sequence is violated. There are two phases and both phases include random blocks and sequential blocks. The better the procedural memory ability, the larger the extent that the pressing speed rebounds from sequential blocks to random blocks.

3.4. Expressive language ability measurement

The constrained production task was used to assess expressive language ability (Kemper et al., 2003). To complete this task, participants were required to formulate sentences using words that were provided. The Ba was included in all stimuli of the given words. Due to the need to use the Ba in the given words, participants were forced to construct sentences using the Ba construction. For the purpose of evaluating expressive semantic ability, the semantic association between given words was controlled. Furthermore, the syntactic features of verbs were manipulated in order to assess participants' expressive syntactic abilities. As mentioned in Section 2.2, some types of verbs cannot be used in the Ba construction. Therefore, verbs that are suitable (e.g., action verbs) or unsuitable (e.g., state verbs) for the Ba construction were used in the stimuli.

Our decision not to use a standard language test was primarily due to the fact that most of the existing tests are oriented to a WEIRD population, and Chinese translation versions have many problems. Further, almost no tests were specific to one particular language pattern to test both expressive and receptive abilities simultaneously. This is of significance for the current study as we aimed to investigate whether there are retrogenic production and comprehension asymmetries in one particular language pattern.

3.5. Receptive language ability measurement

The syntactic correctness judgement task was used to measure receptive syntactic ability, and the semantic correctness judgement task was used to measure receptive semantic ability. Sentences within the Ba construction were used as the experimental stimuli for both judgement tasks in order to examine retrogenic PCA. At the same time, EEG signals were recorded to monitor neural activity. Standard language tests also did not provide corresponding neural results, representing another reason not to choose them. It is noted that the measure of receptive language ability in the current study was specific to the ability to detect anomalies in sentences. The ability to detect syntactic and semantic incongruences in sentences requires corresponding syntactic and semantic capacities. In this case, the correctness judgement task was appropriate to measure language comprehension abilities.

3.6. Procedures

Younger participants took part in the test at the Hong Kong Polytechnic University. Older adults took part in the test at the Shenzhen Institute of Advanced Technology. Both experiments took place in a quiet and light laboratory.

Participants were required to complete all the tasks within two consecutive days. During the day-one session, participants were instructed to complete the incidental encoding phase and initial recognition phase of the declearn tasks, the first phase of the SRT task, as well as the syntactic correctness judgement task. Participants were asked to return to the laboratory after around 24 hours to perform the day-two session which included the delayed retention phase of the declearn task, the second phase of the SRT task, the constrained production task, and the semantic correctness judgement task. There were several other cognitive ability assessments inserted in both sessions and each session lasted for around two and a half hours. The arrangement of tasks on the two days was not disclosed to participants, except for a story recall task which was intended to distract participants from the declearn task and the SRT task.

Chapter 4. Age-related declarative/procedural memory differences

4.1. Introduction

DM and PM are two important capacities that independently and cooperatively subserve “mental lexicon” and “mental grammar” (Ullman, 2001a, 2004). In DM, learning increases during childhood and plateaus in adolescence and early adulthood, following which it declines. In contrast, it appears to be the case that PM learning is already robust in childhood, and begins to decline around adolescence (Finn et al., 2016; Lum et al., 2010; Ullman, 2020).

The order of breakdown of cognitive abilities in older adults is considered to be the reverse of the developmental order of children, according to the retrogenesis theory (B. Reisberg et al., 1999; Reisberg et al., 2002). Jakobson (1941/1968), based on his observations on the phonological features of language users, initially proposed the concept of retrogenesis, such that “aphasic losses reproduce in inverse order the sequence of acquisition in child language” (p. 78). B. Reisberg et al. (1999), through reviewing data from clinical, electrophysiologic, neurophysiologic, neuroimaging, and neuropathologic sources, developed the “mirror-image” idea of acquisition and aging, and coined the terminology “retrogenesis”. Retrogenesis was defined as “the process by which degenerative mechanisms reverse the order of acquisition in normal development” (Reisberg et al., 2002).

One of the first pieces of empirical evidence for this was provided by De Ajuriaguerra and Tissot (1975), who used an empirical approach to study retrogenesis for the first time. De Ajuriaguerra and Tissot (1975) found that modifier redundancy, such as redundant adjectives, existed in the language of dementia patients. The demented tended to say “a drawing pencil”, “a tea cup” and “a wild duck” rather than “a pencil”, “a cup” and “a duck” respectively. This kind of disorganization of the semantic field was also observed in children’s pre-concept usage; for instance, “the wind that drives the clouds is the *white wind* (*arnein blanc*)” and “the wind that makes the trees tremble is *the blue wind* (*amein bleu*)”. Not only did the semantic disturbances but also the syntactic disturbances in dementia patients mirror children’s language acquisition. For instance, both those with dementia and children accepted and could say “*it is raining for I am going to leave” which contained syntactic mistakes at the operational level, because neither of them preserved or developed a clear understanding of the relations of cause and effect to correct the mistakes in logic. Recent research, from picture naming tasks (De Bleser & Kauschke, 2003; Kim et al., 2011) and semantic feature questionnaires (Simoes Loureiro & Lefebvre, 2016) as well as drawing tasks (Pozueta et al., 2020), also found that there was a tendency for AD patients to lose semantic knowledge acquired later in life, but to retain that acquired earlier in life.

The retrogenesis phenomenon was also observed in the cognitive, neurologic, and neuropathologic aspects. Ouvrier et al. (1993) asked children to complete the Mini-Mental State Examination (MMSE) which was a screening test to measure cognitive impairment for dementia, and found a positive correlation between MMSE score and mental age in children. Similarly, when asking AD patients to perform the traditional Piagetian measures, their MMSE scores were significantly related to Piagetian Test scores. Matteson et al. (1996) compared the specific cognitive abilities in each Piagetian developmental level and each Alzheimer’s stage and summarized the results in a cognitive developmental approach (CDA) in which "loss of cognitive abilities follows a reverse order of the acquisition of those abilities”. Neurologic and neuropathological data suggest that on the micro-scale, cortical regressive changes in myelination often follow a reverse progression of maturation (Braak & Braak, 1996); on the other hand, on the macro-scale, the distribution of cerebral degeneration in AD reverses the ontogenetic process (Brun & Gustafson, 1976). Even though retrogenic processes become evident from converging evidence, this question tends to be conceptually and empirically under-identified in memory systems.

In this chapter, we mainly investigated whether there is an age-related decline in DM and/or PM. In line with previous research (Ullman, 2020), we hypothesized that older adults would exhibit degeneration in DM and/or PM. Moreover, we probed whether the decline followed retrogenic processes, namely, whether older adults demonstrated a reverse pattern to the development of children for two memory systems, especially DM. Based on the retrogenesis theory and previous studies among children (Hedenius, Ullman, et al., 2013; Lukács et al., 2017), we predicted that older adults would perform better when remembering items that had been restored in the memory system, such as real objects, compared to items that were unfamiliar, such as made-up objects. It was expected that DM would disintegrate earlier than PM, as DM matures at a later stage compared to PM (Finn et al., 2016; Lum et al., 2010; Ullman, 2020).

4.2. Methods

4.2.1. Subjects

Data from all subjects, namely 28, Chinese younger adults (mean age = 24.1 ± 2.6, range = 19-30; 14 males) and 27 healthy ChOA (mean age = 68.0 ± 2.7, range = 65-76; 11 males) were included for memory ability analysis in this section.

4.2.2. Procedures

4.2.2.1. The declearn task

DM was tested using the declearn task which includes three stages. The first stage is the incidental encoding stage during which subjects are presented with pictures, and they are required to identify whether the presented item is a real object. The stimuli consist of pictures of real objects and made-up objects. After a 10-minute delay and a

24-hour delay, there is an initial recognition phase and a delayed retention phase respectively. Subjects are required to complete similar tasks in the latter two phases during which they are asked to recognize whether they have seen the items in the previous encoding phase. All three phases require participants to make a two-choice decision. The accuracy rate and reaction time were recorded for all the sessions. Only the accuracy rate was included in the later analysis, as it was reported that reaction time did not differ significantly between the healthy and unhealthy groups and a speed-accuracy tradeoff was not observed for either the recognition or delayed retention phase (Hedenius, Ullman, et al., 2013; Lukács et al., 2017). More detailed concerns will be explained in the following parts.

The picture stimuli are all black-and-white line drawings of made-up objects and real objects. Each phase consists of 64 picture stimuli including 32 real objects and 32 made-up objects. The real objects are divided into two categories based on whether they can be manipulated or not. In the encoding phase and the recognition phase, half of the real objects can be manipulated and the other half cannot be manipulated. In the retention phase, 17 real objects can be manipulated and the remaining 15 real objects cannot be manipulated. In the recognition phase, there are 32 picture stimuli from the previous encoding phase and 32 foil pictures that were not presented in the previous phase. The retention phase consists of the other 32 picture stimuli which had been presented in the encoding phase and 32 other foil pictures. All the stimuli are ordered in a pseudo-randomized sequence, with no more than 3 consecutive real or made-up objects.

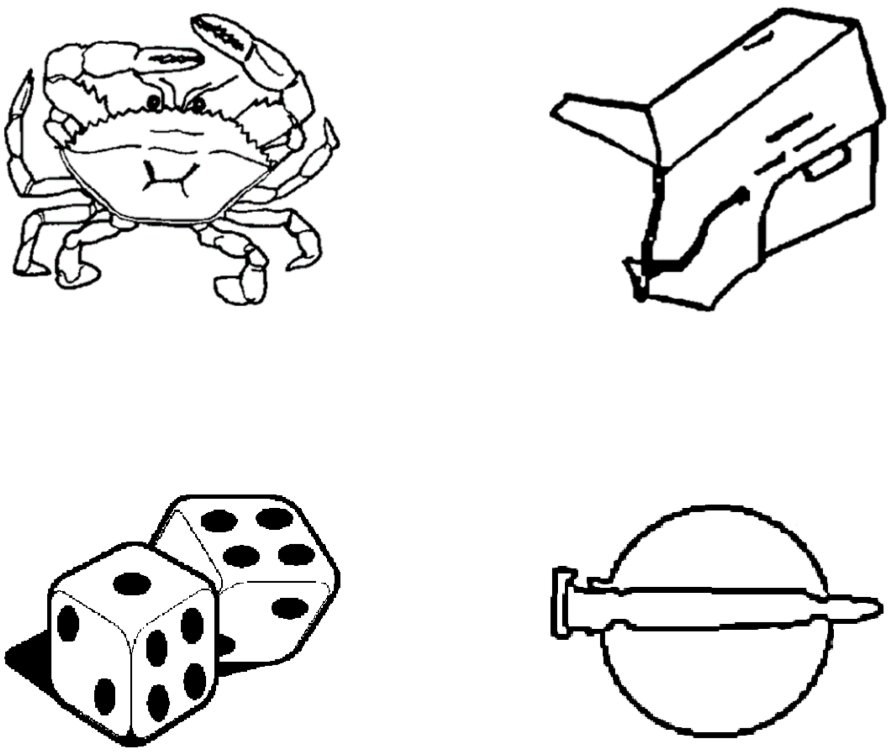


Figure 3. Examples of stimuli from the declearn tasks
Items in the pictures on the left-hand side are two real objects: the upper one can be manipulated and the lower one does not have this feature. Those on the right-hand side are made-up objects.

The stimuli were presented on a liquid-crystal display via a Surface Book 2 PC laptop running Windows 10, using E-Prime version 3.0 (Psychology Software Tools). 1920 x 1080 pixels were used in the display. A 640 x 480-pixel image was presented in response to the objects. The participants were seated approximately 100 centimeters away from the screen. Testing took place in a quiet and light laboratory. Participants were instructed to respond with their index finger and middle finger of the dominant hand by pressing the designated buttons on a multifunctional response and stimulus device (E-prime Chronos). The Chronos was placed on a desk in front of the participants.

Stimuli were presented with the following presentation and timing parameters in all three phases. In the beginning, a fixation cross appeared at the center of the screen for 1000 milliseconds (ms) which reminded participants to focus on the screen and prepare for the stimulus which was about to be displayed. The fixation cross was then replaced by the picture stimulus which stayed on the screen for 500 ms. If participants responded within 500 ms, the picture stimulus was removed until the 500 ms finished, and it was replaced by a fixation cross for the next item. If participants didn't respond, the picture stimulus was followed by a waiting interface which remained for up to 4500 ms. As soon as participants pressed any buttons, the waiting interface was removed and followed by the fixation cross signaling the next item. A reminder of "real" and "made-up" appeared on the lower left and lower right corners of the screen throughout the encoding phase indicating the mapping of the Chronos buttons. During the recognition and retention phases, the reminder was changed to "yes" and "no" options.

In the encoding phase, participants were instructed to identify whether the object on the screen was a real one or a made-up one. They needed to use the index finger and middle finger of their dominant hand to press the two leftmost buttons on the Chronos box to indicate their response. The position of the right and left buttons was consistent with the position of the reminder for "yes" and "no" on the bottom of the screen. There were two practice blocks. In the first practice block, there was no time limit for pressing buttons and participants were able to familiarize themselves with how to identify the object picture. In the second practice block, participants were required to make a decision as correctly and quickly as they could after the stimulus disappeared from the screen. It was also allowed if participants, especially older adults, accidentally press the button before the stimulus disappeared from the screen as it indicated the participants' intended response. Even though participants' answers were recorded before the stimuli disappeared from the screen, we instructed them to press the buttons after the stimulus disappeared rather than when they saw the stimulus. This is because we found that some pilot study participants, especially older adults, sometimes rushed to press the buttons even before the stimulus appeared on the screen (which means no response was recorded) and then waited for the next trial, even though they had been instructed to press the button again at the beginning of the task. As the task involved a delayed force choice, the reaction time data were excluded in the later analysis, which was applied to the data of the recognition and retention phase as well. Participants were not informed there were recognition and retention phases afterwards but were asked to focus on identifying whether or not the item in the picture was real.

In the recognition phase, participants were required to recognize whether the picture had been presented in the encoding phase which took place around 10 minutes before. If they thought it was presented before (present trial), participants needed to press the YES button. If they thought it was not presented before (absent trial), the participant needed to press the NO button. Two practice blocks preceded the test blocks. In the first practice block, there was no time limit for pressing the buttons which allowed participants to familiarize themselves with how to press the buttons and recognize the picture. In the second practice block, participants were required to make a decision as correctly and quickly as they could after the stimulus disappeared from the screen. Pressing buttons before the stimulus disappeared was also allowed. Participants were able to be familiar with the procedures of the task in the second practice block.

The retention phase was conducted on the following day after around 24 hours. Participants were not informed there was a retention phase until they began to complete the third phase. All the instructions and procedures for the retention phase were similar to those for the recognition phase, except the picture stimuli were replaced with another set. The accuracy rate was recorded for the recognition phase.

Recognition memory accuracy was assessed using d’ (d-prime), which is a method that considers response bias. D-prime is equal to the Z value of the hit rate minus that of the false alarm rate (d’ = z (hit rate) – z (false alarm rate)). The hit rate refers to the proportion of present items to which the subject responded "yes", whereas the false alarm rate refers to the proportion of absent items to which the subject answered "yes". The d-prime was calculated via the psycho 2.2.3 package in R (Makowski, 2018) in which algorithms were formed based on Pallier (2002), and the adjustment for extreme values was made following the recommendations of Hautus (1995). Generally speaking, the higher the d-prime score, the better the ability of the subject to distinguish between old and new items.

4.2.2.2. The serial reaction time task

In the current study, we applied the SRT task to assess participants’ procedural memory capacity. As participants are exposed to a predetermined sequence repeatedly, they can learn it implicitly through their PM. This task involves the procedural learning of perceptual-motor sequences. After the preset sequence is acquired, they can press the buttons that follow the predefined pattern much more quickly than in the initial state, and this causes them to slow down abruptly when the pattern is violated.

The SRT task was executed by E-Prime version 3.0 (Psychology Software Tools). During the task, the participants were required to press the button of the E-prime Chronos which corresponded to the position where the visual stimulus (a yellow smiley face) appeared on the screen. The smiley face appeared in one of four empty squares which were presented horizontally on the screen. The leftmost and rightmost squares corresponded to button 1 and button 4 respectively, and the other two corresponded to button 2 and button 3 on the Chronos. Participants were instructed to place their index and middle fingers of both hands on the four buttons and respond only with these four fingers. Participants were informed that processing speed was being tested in this task and they needed to press the correct buttons as quickly as possible. RTs and error rates were analyzed.

The presentation of the sequence was divided into two types based on their presenting order. The first type was sequential (S), following a ten-item patterned order which is 1-3-4-2-3-1-4-2-1-4 for its locations. The second type was random (R), following a pseudorandom and balanced order, namely, there was no pattern for its order. Participants were not informed that they were being exposed to these two types of presentations until the end of the tasks.

Two tasks were conducted on two consecutive days. On the first day, participants undertook the learning task for which six blocks followed the structure: random-sequence-sequence-sequence-sequence-random (RSSSSR). The presentation order of stimuli in the middle four blocks was sequential, while that of the first and final blocks was random. Each block contained 60 trails. In both random blocks and sequence blocks, the appearance of the smiley face in each square was shared an equal number of times with an equal probability of transitions. The interstimulus interval (ISI) between trials was 100 ms. There was no time limit for button pressing and the next trial was not presented unless participants provided a correct response or 20 incorrect responses. There were two practice blocks preceding the test block. During the first practice block, no time limit was imposed and so the participants had the opportunity to become familiar with the button pressing. The purpose of the second practice block was to familiarize participants with pressing the corresponding button following stimulus onset. The second practice block would be repeated if participants made too many mistakes.

After around 24 hours, participants returned to the laboratory to undertake the second task which was the retention task. Participants were not aware that there was a retention task until they came to the laboratory on the second day. There were three blocks in the retention task which followed the structure: random-sequence-random (RSR). No practice block was added before the three test blocks. All the parameters of the retention task were the same as for the learning task. After the third block had been completed, an explicit recall task followed to assess participants' explicit knowledge of the sequence. Participants were first asked whether they had noticed a pattern in the sequence and they were asked about any pattern that they could remember. Then they were given 20 seconds to press buttons to upload the sequence that they thought matched the pattern. Finally, participants were asked to produce a sequence that was different from the one they had produced in the previous stage. Another 20 seconds were provided for participants to press buttons to upload this different sequence.

Both the accuracy and RTs of participants were recorded. The RTs were converted into z-scores by referencing the median and standard deviation across all correct trials for each participant, in order to control for within-subject variations in motor speed. This method of normalizing data ensured that the shortest RT for each participant was approximately the same, as were the longest RTs for each participant. As an example, if one participant's longest RT was 6000 milliseconds (ms) and another's was only 1000 ms, the values for both participants might become the same 6 after z-normalizing, as 6000 ms and 1000 ms are both 5 standard deviations (SD) above the median of these two participants respectively. The same approach has previously been used in an attempt to examine differences between typically-developing children and children with DLD when attempting SRT tasks (Lum et al., 2012). In addition, we addressed the possibility of attention lapses in this task, as the task was monotonous and lasted for quite a long time (around 10 minutes), with 60 trials per block. As a result of this concern, we deleted data points for participants whose RTs were 3 SD or more above their mean RT. Participants in the older group deleted an average of 19.89 ± 16.51 data points, while participants in the younger group deleted an average of 20.36 ± 11.44 data points. There was no statistically significant difference between the two groups in terms of the removed data points [$t(53) = -0.123$, $p = 0.903$, Cohen's $d = -0.033$]. Thus, the removal of outliers did not have a significant differential impact on one group over the other.

4.2.3. Statistical analysis

Regarding the statistical analysis for DM performance, we followed the procedures of Hedenius, Ullman, et al. (2013) where firstly a 2 (group: young vs older adults) x 2 (day: day one recognition phase after 10 minutes vs day two retention phase after 24 hours) ANOVA with d-prime scores as the dependent variable was performed. This two-way ANOVA was to test the first hypothesis about whether there are significant differences in declarative memory performance between younger and older adults on two phrases. Afterwards, 2 (condition: real vs made-up objects) x 2 (group: younger vs older adults) ANOVAs for each of the two phases (day-one recognition phase and day-two retention phase) were performed to examine whether the two groups differed in terms of potential effects of object condition.

The statistical analysis of PM performance was based on the procedures of Lum et al. (2012). We first inspected the accuracy of both younger and older adults and examined whether there were differences in button pressing between these two groups. Then we probed the RTs with 2 (condition: sequence vs random) x 2 (group: younger vs older adults) ANOVAs for each of the two-day sessions to investigate whether the two groups differed in terms of the time taken to press a button which was the primary dependent measure of sequence learning with the SRT task.

Statistics were calculated using R 4.1.2 (Team, 2021), the analysis of variance (ANOVA) functionality of afex 1.1.1 (Henrik Singmann et al., 2022) and followed by post-hoc tests using package emmeans 1.7.1.1 (Lenth, 2021). A Greenhouse-Geisser adjustment for significance was applied to cases that failed to comply with the assumption of sphericity. Post hoc pairwise comparisons were carried out if significant effects were found. *P* values were Tukey-adjusted for multiple post hoc comparisons. All the settings were also applied in the analysis in the following chapters.

4.3. Results

4.3.1. Declarative memory results

Declarative memory performance was indicated by the d-prime scores. Figure 4 shows the overall differences in mean d-prime scores for both the younger adults and older adults for the first and second phases on two consecutive days. Table 1 shows the 2 (Group) x 2 (Day) ANOVA results for d-prime scores.

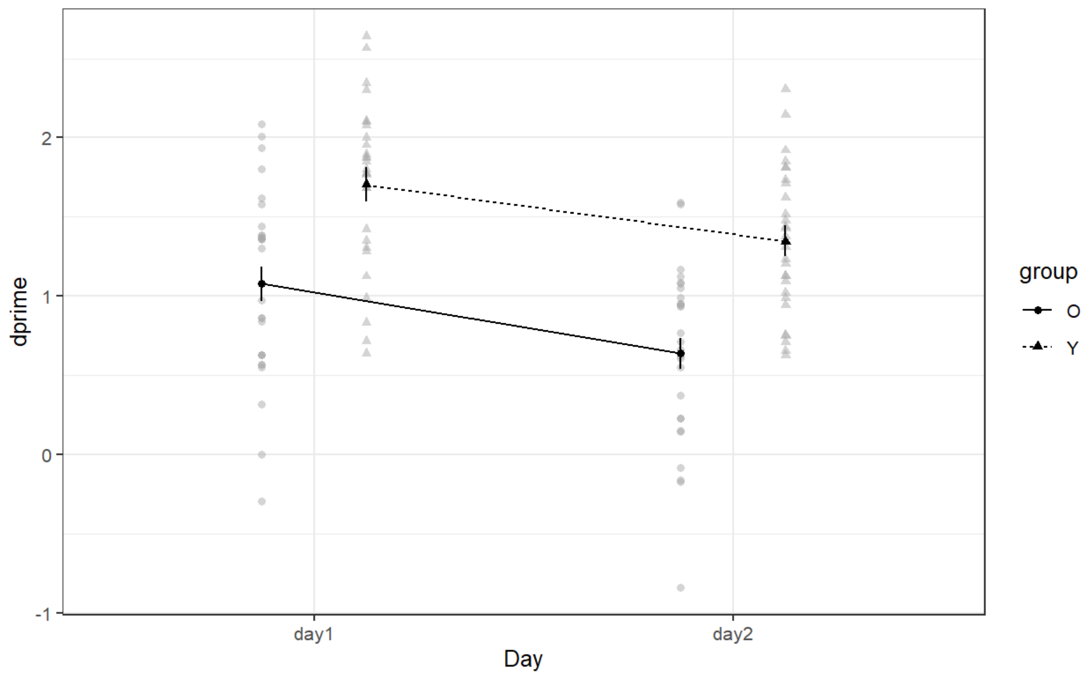


Figure 4. Mean d-prime scores for declearn tasks reported by Group and Day
Larger d-prime scores indicate better declarative memory ability and 0 is equal to chance. Both groups demonstrated better performance on the day-one phase than on the day-two phase, and younger adults performed better than older adults in both phases.

As shown in Figure 4, both younger adults and older adults demonstrated similar patterns for mean d-prime scores for declarative memory performance that decreased from the day-one test to the day-two test. Younger adults performed better than older adults in both phases. Besides, compared to younger adults, older adults showed slightly larger amounts of decline from the recognition phase to the retention phase.

Table 1. ANOVA results for d-prime of DM performance

Predictor	df_{Num}	df_{Den}	SS_{Num}	SS_{Den}	F	p	η^2_g
(Intercept)	1	53	156.22	20.49	404.18	.000	.83
group	1	53	12.24	20.49	31.66	.000	.28
day	1	53	4.38	10.46	22.19	.000	.12
group x day	1	53	0.05	10.46	0.24	.629	.00

Note[6]: The results of the two-way mixed ANOVA indicated that there was a significant main effect of group on d-prime scores, with younger adults (mean = 1.53) showing

[6] *dfNum* indicates degrees of freedom numerator. *dfDen* indicates degrees of freedom denominator. Epsilon indicates Greenhouse-Geisser multiplier for degrees of freedom, *p*-values and degrees of freedom in the table incorporate this correction. *SSNum* indicates sum of squares numerator. *SSDen* indicates sum of squares denominator. η2g indicates generalized eta-squared. These parameters were also appliable for the other ANOVA results in the following tables.

average higher scores than older adults (mean = 0.86). In addition, there was also a significant main effect of day, with both younger and older participants showing better average d-prime scores for the day-one recognition phase (mean = 1.38) than the day-two retention phase (mean = 1.00). In contrast, there was no significant interaction between group and day.

A two-way ANOVA was conducted to compare the main effects of group (younger or older adults) and day (day-one recognition or day-two retention phases), as well as their interaction effects on the d-prime scores for DM performance, as shown in Table 1. All the main effects were statistically significant at the .05 significance level. The main effect of group yielded an F ratio of $F(1, 53) = 31.66$, $p < .0001$, indicating that the mean d-prime score was significantly greater for younger adults (M = 1.53, SD = 0.95) than for older adults (M = 0.86, SD = 0.88). The main effect of day yielded an F ratio of $F(1, 53) = 22.19$, $p < .0001$, indicating that the mean d-prime score was significantly larger for the day-one recognition phase (M = 1.40, SD = 1.04) than for the day-two retention phase (M = 1.00, SD = 0.85). The interaction effect was non-significant, $F(1, 53) = 0.24$, $p = .63$.

Next, we conducted 2 (object-condition: real vs made-up) x 2 (group: younger vs older adults) ANOVAs for both the recognition and retention phases to examine if there were differences in the effects of object conditions between the two groups.

Figure 5 and Table 2 indicate the declarative memory performance for the two groups for the day-one recognition phase.

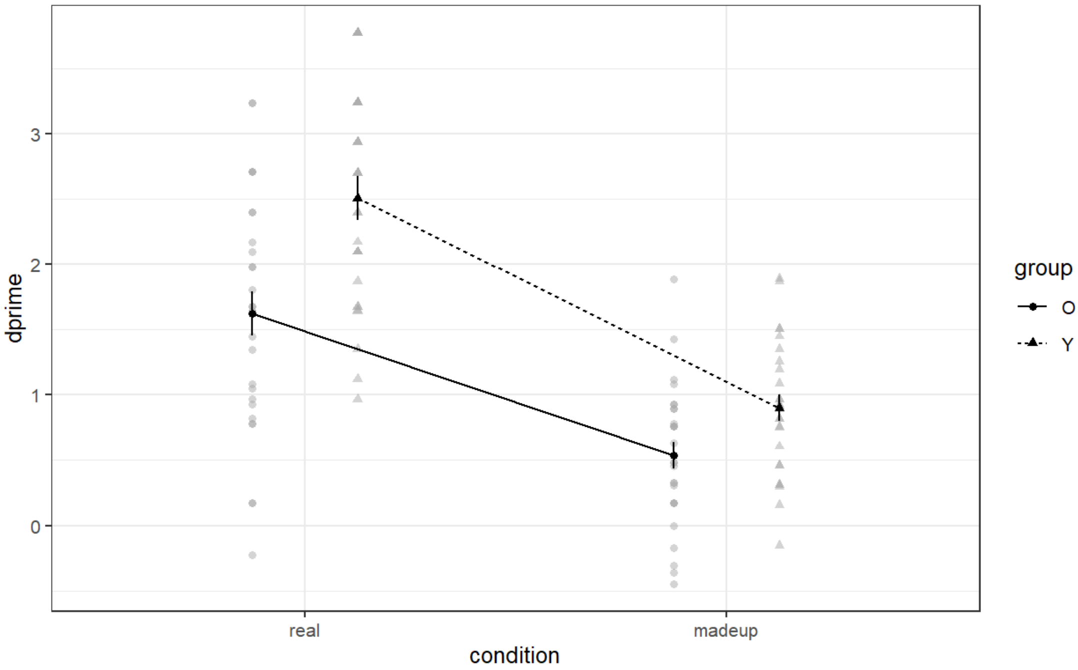


Figure 5. Mean d-prime scores for declearn tasks reported by Group and Condition for the day-one recognition phase

Larger d-prime scores mean better declarative memory ability and 0 is equal to chance. Both groups demonstrated better performance for the real objects than the made-up objects, and the d-prime scores for made-up objects for both groups were much higher than the chance level. However, younger adults and older adults differed in recognizing real objects while demonstrating similar performance in recognizing made-up objects.

As shown in Figure 5, a comparison of the real and made-up objects indicated that both groups performed better for the real objects. It is noted that the older adults had significantly higher d-prime scores than the chance level when learning made-up objects on day one [t(53) = 8.51, *p* < .0001], indicating that they could harness DM to learn the made-up items. There was, however, a significant difference between the performance of younger adults and older adults when recognizing real objects, despite the similar performance when recognizing made-up objects.

Table 2. ANOVA results for d-prime for DM performance on day-one recognition phase

Predictor	df_{Num}	df_{Den}	SS_{Num}	SS_{Den}	F	p	η^2_g
(Intercept)	1	53	212.92	33.96	332.35	.000	.79
group	1	53	10.78	33.96	16.82	.000	.16
condition	1	53	49.86	21.59	122.41	.000	.47
group x	1	53	1.87	21.59	4.60	.037	.03

condition

Note: The results of the two-way mixed ANOVA showed that there was a significant interaction between group and condition, indicating that the group effect was greater for the real objects than for the made-up objects.

A two-way ANOVA was conducted to compare the main effects of group (younger or older adults) and condition (real or made-up object), as well as their interaction effects for the d-prime scores for day-one DM performance, as shown in Table 2. All the effects were statistically significant at the .05 significance level. There was a significant interaction between group and condition with an F ratio of $F(1, 53) = 4.60$, $p = .037$. Following up on this interaction, post hoc analyses revealed that, younger adults ($M = 2.51$, $SD = 0.84$) and older adults ($M = 1.62$, $SD = 0.92$) had significantly different performances in terms of recognizing real objects (t.ratio = -3.74, $p = 0.003$), but similar accuracy when recognizing made-up objects (younger adults: $M = 0.90$, $SD = 0.50$; older adults: $M = 0.54$, $SD = 0.55$; t.ratio =-2.58, $p = 0.059$), suggesting that older adults had equivalent DM ability for memorizing made-up objects within a 10-minute delay when compared to younger adults.

Figure 6 and Table 3 indicate the declarative memory performance of the two groups for the day-two retention phase.

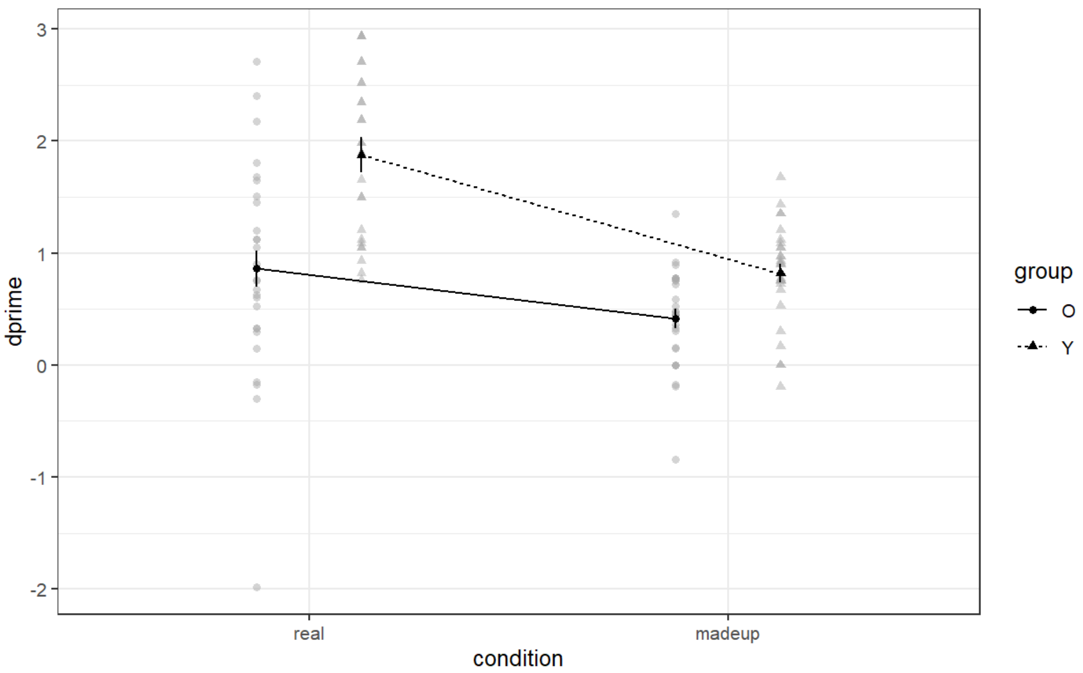


Figure 6. Mean d-prime scores for declearn tasks reported by Group and Condition for the day-two retention phase

Larger d-prime scores mean better declarative memory ability and 0 is equal to chance. Both groups demonstrated better performance for the real objects than the made-up objects, and younger adults performed better than older adults for both types of objects. It is noted that even older adults exhibited much larger d-prime scores for made-up objects.

There was an obvious difference between the performance of each group for the real objects and the made-up objects in terms of accuracy. Furthermore, neither type of object was as effectively recognized by the younger adults as it was by the older adults, which was different from the day-one recognition phase during which older adults demonstrated comparable accuracy in recognizing made-up objects. In other words, younger adults and older adults had similar levels of declarative memory for recalling made-up objects after a 10-minute delay. However, this equivalence did not persist after a 24-hour delay in spite of the fact that older adults' d-prime scores for made-up objects were still significantly above the chance level [$t(53) = 6.06$, $p < .0001$], suggesting that they can still make use of declarative memory to support the retrieval of made-up objects after 24 hours.

Table 3. ANOVA results for d-prime for DM performance on day-two retention phase

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g
(Intercept)	1.00	53.00		496.55	64.93	405.30	.000	.85
group	1.00	53.00		36.35	64.93	29.67	.000	.29
condition	1.81	95.88	0.45	43.07	25.67	88.95	.000	.32
group x condition	1.81	95.88	0.45	2.76	25.67	5.69	.006	.03

Note: The results of the two-way mixed ANOVA indicated that there was a significant main effect of group on d-prime scores, with younger adults (mean = 1.35) showing average higher scores than older adults (mean = 0.64). In addition, there was also a significant main effect for condition, such that average d-prime scores were significantly high for real objects (mean = 1.38) than for made-up objects (mean = 0.62). There was also a significant interaction between group and condition.

Table 3 summarizes the results of a two-way analysis of variance which was conducted in order to compare the main effects of group (younger or older adults) and condition (real or made-up object) and their interaction effects for day-two DM performance. All the effects were statistically significant at the .05 significance level. There was a significant interaction between group and condition with an F ratio of $F(1, 95.88) = 5.69$, $p = .006$. Post hoc analyses revealed that, younger adults (M = 1.88, SD = 0.69) and older adults (M = 0.86, SD = 0.96) had significantly different performances in terms of real objects (t.ratio = -4.51, $p = 0.0002$), and made-up objects (younger adults: M = 0.81, SD = 0.45; older adults: M = 0.42, SD = 0.44; t.ratio =-8.14, $p < .0001$), suggesting that the declarative memory ability of older adults to recall made-up objects dramatically declined after a 24-hour delay, though it was sustained within a 10-minute delay.

4.3.2. Procedural memory results

In this study, we examined procedural memory through the analysis of sequence learning in the SRT task. First, we evaluated the accuracy of both groups. A maximum level of correct responses was reached by both the younger group (M = 96.8%, SD = 2.5%) and the older group (M = 97.4%, SD = 3.0%) in terms of the average proportion of correct responses. Based on an independent samples t-test, no significant differences were found between the groups in terms of accuracy [t(53) = 0.76, *p* = 0.45, Cohen's d = 0.205]. It can be seen from the results that older adults completed the SRT task as accurately as their younger counterparts.

In the following section, RTs were examined, which were our principal dependent measure. We first displayed the averaged normalized RTs for correct response by block for each group. Figure 7 illustrates the results for the day-one session. Then we examined the change in RTs between block 4 (sequential order) and block R2 (random order) on day one as well as block 5 (sequential order) and block R4 (random order) on day two, separately, for both groups, to investigate if there was significant sequence learning for both or either group on each.

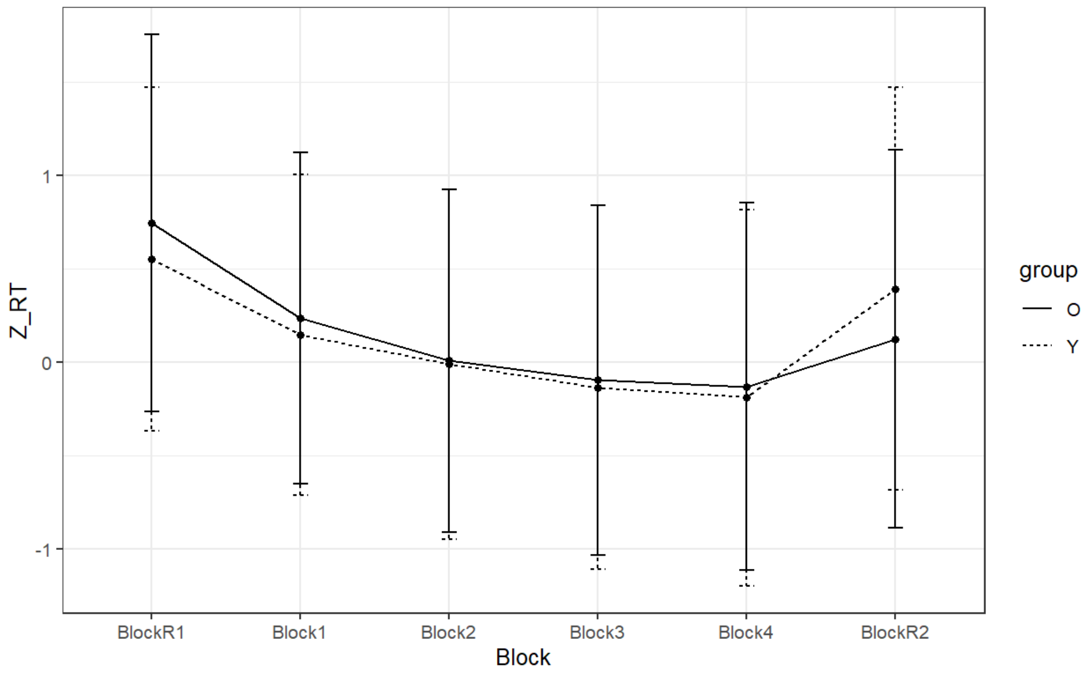


Figure 7. Day-one mean normalized RTs of SRT tasks reported by Block and Group
The x-axis represents different blocks where R1 and R2 are random orders and the others are sequential orders. The y-axis represents normalized reaction time. The reaction times of both groups decreased from block R1 to block 4 and then bounced at block R2, which indicated participants acquired the predefined pattern. Additionally, younger adults bounced back more than older adults.

As shown in Figure 7, participants in both groups demonstrated a decrease in reaction times from block R1 to block 4, followed by a bounce at block R2. This indicated they acquired the predefined pattern during experiencing the sequential blocks, as their pressing speed abruptly slowed down when the order denied the pattern at block R2. Furthermore, the bounce-back rate of younger adults was higher than that of older adults.

Table 4. ANOVA results for normalized RTs for PM performance on day-one session

Predictor	df_{Num}	df_{Den}	SS_{Num}	SS_{Den}	F	p	η^2_g
(Intercept)	1	53	0.38	5.65	3.57	.064	.05
group	1	53	0.05	5.65	0.42	.518	.01
condition	1	53	2.22	1.99	59.27	.000	.23
group x condition	1	53	0.21	1.99	5.70	.021	.03

Note: The results of the two-way mixed ANOVA showed that there was a significant main effect for the condition, such that average normalized RTs were significantly high for the last random block (mean = 0.085) than for the last sequential block (mean = -0.203). There was also a significant interaction between group and condition.

A two-way ANOVA was conducted to compare the main effects of group (younger or older adults) and condition (random or sequential order), as well as their interaction effects on the normalized RTs for day-one PM performance, as shown in Table 4. There was a significant interaction between group and condition with an F ratio of F(1, 53) = 5.70, p = .02. Following up on this interaction, post hoc analyses revealed that younger adults had significant differences in normalized RTs between the last sequence block (M = -0.23, SD = 1.02) and the last random block (M = 0.15, SD = 1.08) (t.ratio = 7.20, p < .0001), and older adults also exhibited significant differences in normalized RTs between the two blocks (sequence block: M = -0.18, SD = 0.98; random block: M = 0.03, SD = 1.01; t.ratio = 3.72, p = 0.003), suggesting that both younger adults and older adults exhibited sequence learning from the day-one session. In addition, the RT difference between the random block and sequence block for the younger adults group was 0.58 (SD = 0.33), whereas it was 0.30 (SD = 0.30) for older adults. A Welch two-sample t-test showed that the RT difference between younger adults and older adults was statistically significant, $t(52.9) = -3.38$, $p = 0.001$, Cohen's $d = -0.91$, indicating that although older adults can still make use of procedural memory on the day-one session, its efficacy declined precipitously.

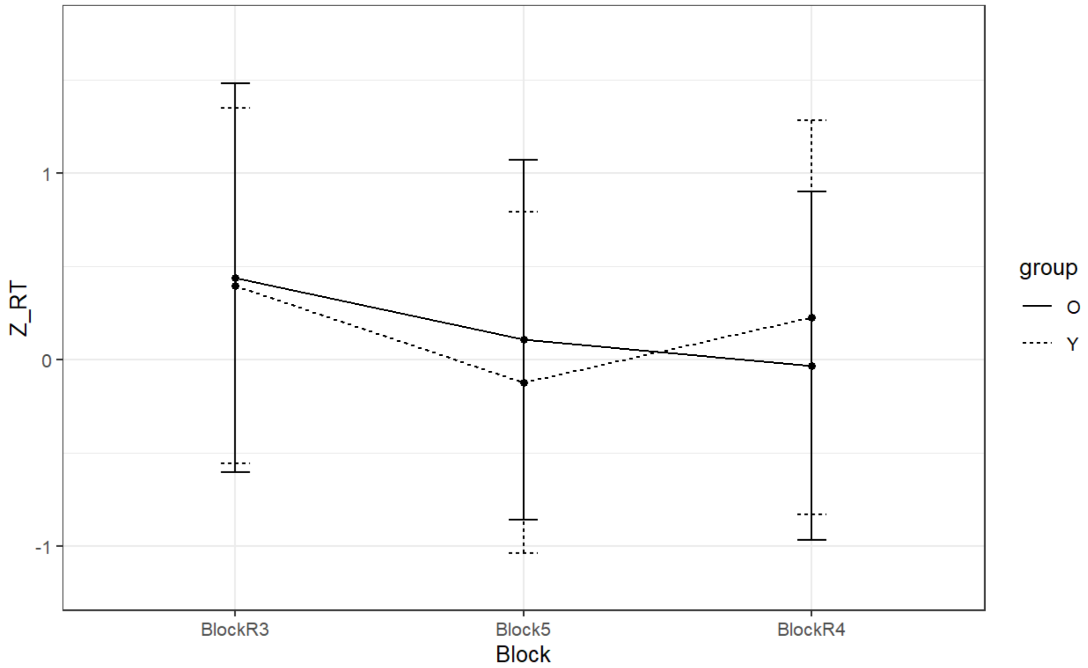


Figure 8. Day-two mean normalized RTs for SRT tasks reported by Block and Group
The x-axis represents different blocks where R3 and R4 are random orders and block 5 is a sequential order. The y-axis represents normalized reaction time. The reaction times for younger adults decreased from block R1 to block 5 and then bounced at block R4, while that of older adults decreased gradually from block R3 to block R4. This indicated younger adults but not older adults had retained the acquired sequential pattern on the day-two session.

As shown in Figure 8, throughout the blocks, younger adults had a decrease in reaction time from block R1 to block 5 and then bounced off at block R4, while older adults had a gradual decrease in reaction time from block R3 to block R4. This suggests that on the day-two session, older adults had forgotten the acquired sequential pattern that they had learned on the day-one session as there was no residual effect on button pressing.

Table 5. ANOVA results for normalized RTs for PM performance on day-two session

Predictor	df_{Num}	df_{Den}	SS_{Num}	SS_{Den}	F	p	η^2_g
(Intercept)	1	53	0.23	1.77	7.03	.011	.05
group	1	53	0.01	1.77	0.21	.648	.00
condition	1	53	0.30	2.42	6.68	.013	.07
group x condition	1	53	1.61	2.42	35.31	.000	.28

Note. The results of the two-way mixed ANOVA indicated that there was a significant interaction between group and condition, showing that the condition effect was greater in the younger than in the older adults.

A two-way ANOVA was conducted to compare the main effects of group (younger or older adults) and condition (random or sequential order), as well as their interaction effects on the normalized RTs for day-two PM performance, as shown in Table 5. There was a significant interaction between group and condition with an F ratio of $F(1, 53) = 35.31$, $p < .0001$. Following up on this interaction, post hoc analyses revealed that younger adults showed significant differences in normalized RTs between the last sequence block (M = -0.12, SD = 0.92) and the last random block (M = 0.23, SD = 1.06) (t.ratio = -6.09, $p < .0001$), while older adults failed to exhibit significant differences in normalized RTs between the two blocks (sequence block: M = 0.11, SD = 0.97; random block: M = -0.03, SD = 0.94; t.ratio = 2.35, $p = 0.10$), suggesting that older adults were not able to make use of procedural memory to recall the predefined pattern that was acquired at the day-one session.

4.4. Discussion

Our goal was to investigate, on the one hand, declarative learning with an incidental picture learning task, the declearn task, and on the other hand, procedural learning with an implicit probabilistic sequence learning task, the SRT task, in both younger and older adults. To our knowledge, this is the first study to examine these two fundamental learning systems across both younger and older adults in a Chinese context, let alone the retrogenic role in the DM system.

Results revealed that compared to younger adults, older adults performed poorly in both declarative and procedural memory tasks, particularly for the day-two session. The DM decline in older adults is likely due to the age-related reduction in the volume of the medial temporal lobe and the hippocampus, considering its well-established vital role in DM (Nyberg & Pudas, 2019; Ullman, 2001c). Converging evidence on different samples suggests age-related atrophy of the temporal lobe and hippocampus, and the shrinkage rate tended to be 2–3% per decade in the hippocampal gyrus (Allen et al., 2005; Cowell et al., 1994; C. R. Jack et al., 1998; Raz et al., 2005; Raz, Rodrigue, et al., 2004). Besides, older adults with DM deficits were reported to exhibit disruptive alterations in neural activations and networks on both task-relevant and resting-state functional hippocampal connectivity (Pudas et al., 2013; Salami et al., 2014).

A similar reason for the inferior procedural memory learning of older adults is likely to be the atrophy of some areas of the brain, such as the basal ganglia and cerebellum, which play an important role in sequencing learning (Squire, 2004; Ullman et al., 2020). Striatal volume declines by about 3% per decade at a span between 20 and 80 years of age (Gunning-Dixon et al., 1998). There was a 2% per decade shrinkage of the vermian lobules and the cerebellar hemispheres between the ages of 20 and 80, despite spatially varying atrophy patterns within the cerebellum (Han et al., 2020; Raz et al., 2001). However, as with younger adults, older adults seemed to be able to recruit a similar neural network of brain regions, including cerebellum and basal ganglia, when engaging in implicit sequence learning (Daselaar et al., 2003). This might be why older adults still are capable of acquiring the sequence within 10 minutes in spite of the lower learning rate.

In terms of retrogenesis, the results revealed that, firstly, older adults exhibited better recognition performance on real objects compared to made-up objects in the declearn task. Real objects were those that had been acquired earlier and were familiar to subjects, while made-up objects were first presented and later encoded into subjects' knowledge. Children demonstrated better performance in recognizing real objects than in recognizing made-up objects (Hedenius, Ullman, et al., 2013; Lukács et al., 2017). Older adults' DM performance for real objects and made-up objects was exactly the mirror pattern of that of children, as shown in Figure 9. Real objects were already stored in the DM system and their "consolidation process" in the brain should thus be much more robust compared to the first introduction of made-up objects (Kim et al., 2011). Real objects, consequently, obtain richer semantic associations, resulting in faster activation and less neural activity (Kounios et al., 2009; Pexman et al., 2007; Pexman et al., 2003; Pexman et al., 2002). It is reported that a significant positive correlation was reported between the age of acquisition values and gray matter density values in several regions of the brain, including the right para-hippocampal (Venneri et al., 2008), which plays an instrumental role in supporting the DM (Tulving & Markowitsch, 1998). According to these hypotheses and our findings, earlier acquired objects that have been firmly ingrained in DM may be more resistant to the effects of aging. The latter acquired objects may, however, be stored superficially in DM, and may therefore be relatively susceptible to fading away from memory.

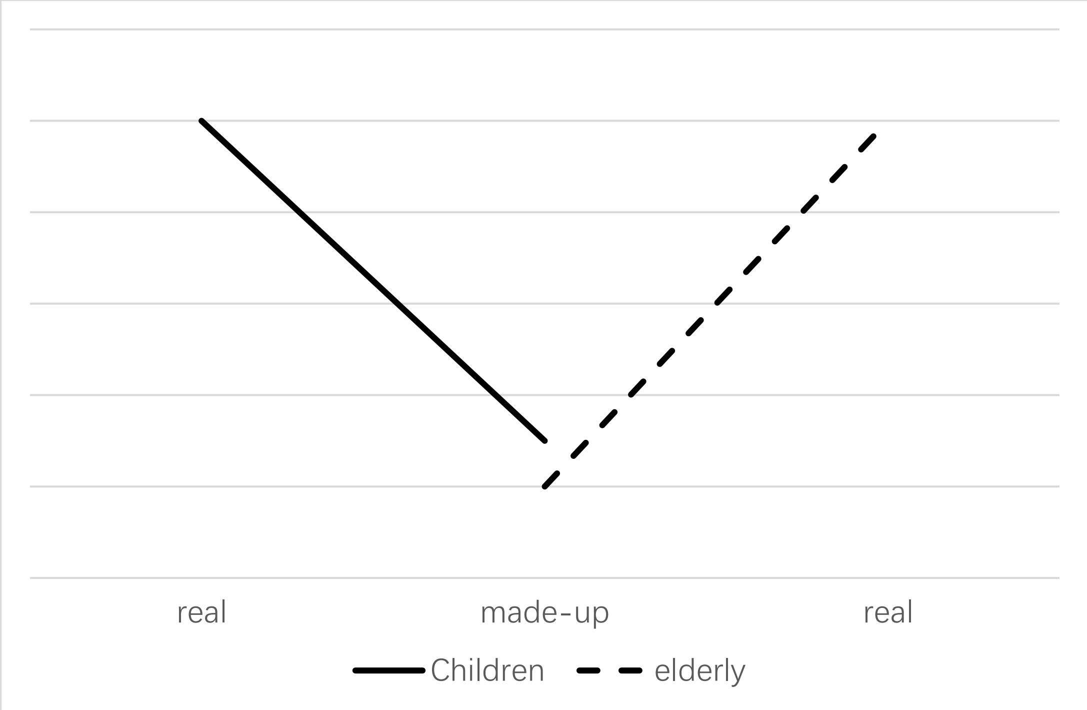


Figure 9. The schematic diagram of retrogenic DM decline for real and made-up objects

The x-axis represents different types of objects. The y-axis represents normalized performance where a higher value indicates better performance. For easy comparison and illustration, the exact values of the y-axis were skipped in the figure. Children show better DM performance in recognizing real objects and it is preserved better in older adults, while they scored worse for recognition of made-up objects and the impairment was more severe in older adults. This is consistent with the retrogenesis theory that degenerative mechanisms reserve the order of acquisition in normal development.

Secondly, when comparing younger adults' recognition performance on real objects and made-up objects, older adults exhibited significantly worse results on real objects but compatible results on made-up objects in the day-one phase, although these differences disappeared in the day-two phase. In other words, older adults' memory decayed faster for real objects than for made-up objects, which was a contradiction of the retrogenic theory, since real objects are acquired earlier and expected to disintegrate later from DM.

One potential reason might be that older adults accumulate crystalized knowledge across their lifespan (Tucker-Drob et al., 2022), which in turn facilitated them in recoding and connecting the made-up objects with the pre-existing knowledge (Umanath & Marsh, 2014). This then might have compensated for the decline in the DM of older adults and allowed them to produce comparable results when recognizing made-up objects. Alternatively, it may be the case that the inferior performance of real objects was the result of impaired inhibitory ability for intrusion related to the real objects (Fong et al., 2021; Hasher et al., 1991; Hasher & Zacks, 1988; Lustig et al., 2007). There may be considerable situational and contextual connections between real objects and other entities as they were learned a long time ago (Steyvers & Tenenbaum, 2005), and these closely connected entities were likely to intrude and corrupt older adults' recognition due to their reduced ability to down-regulate irrelevant information. A third possible explanation for the relatively preserved performance for made-up objects and relatively declined performance for real objects in older adults is likely due to the different trajectories of age-related changes of brain regions. A third factor that may explain the relatively preserved performance for made-up objects and relatively diminished performance for real objects in older adults is the different trajectories of age-related changes in brain regions that contribute to various DM. A real object involves associations with prior knowledge which are mainly retrieved through the recollection of the hippocampus (Anderson et al., 2008; Barense et al., 2011; Montaldi & Mayes, 2010; Reifegerste et al., 2020), whereas a made-up object is encoded as an isolated item and principally retrieved through the familiarity of the perirhinal cortex (Bowles et al., 2007; Parker et al., 2002; Reifegerste et al., 2020; Wang et al., 2014), also for a review about recollection-and familiarity-based recognition memory[7] see

[7] We followed the classification in Reifegerste et al. (2020), though it should be noted that a few studies have suggested that it is not appropriate to distinguish between recollection and familiarity (Wixted & Squire, 2010). And intriguingly, this general dual-process memory itself seems to follow the retrogenesis theory. According to Ghetti and Lee (2013), familiarity appears to stabilize by the middle of childhood, while recollection tends to continue to improve through adolescence. When combined with our results, it is not difficult to conclude that familiarity is the first-in-last-out ability. There is a possibility that the development and decline of the hippocampus

Eichenbaum et al. (2007) and Diana et al. (2007). In the course of aging, the hippocampal volume declines precipitously (Allen et al., 2005; Jack et al., 2015; Koen & Yonelinas, 2014; Pelletier et al., 2013; Raz et al., 2010; Šimić et al., 1997; Yang et al., 2013), but the perirhinal cortex volume declines less reliably (Daselaar et al., 2006; Insausti et al., 1998; Koen & Yonelinas, 2014; Raz, Rodrigue, et al., 2004; Rodrigue & Raz, 2004). It is consistent with the steep decline in real objects and the shallow decline in made-up objects, as also reported in previous studies in MCI patients and AD patients, for a review see Schoemaker et al. (2014) and Koen and Yonelinas (2014). Lastly, this contradiction may reflect the difference between forgetting and breakdown. Retrogenesis theory explains the breakdown of knowledge stored in the DM system (Pozueta et al., 2020; B. Reisberg et al., 1999). In contrast, there is a possibility that the retrogenesis theory cannot explain the forgetting of an item. Hence, made-up objects and real objects do not follow the first-in-last-out principle when it comes to forgetting in the current study. Further research needs to be conducted to explore this issue.

On the other hand, DM retrogenesis should also be considered with a caveat, which is the inherent difficulty of the two types of stimuli. According to the results of this study, as well as previous studies (Hedenius, Ullman, et al., 2013; Lukács et al., 2017), children, older adults, and even younger adults performed better at recognizing real objects than made-up objects. This is probably due to the fact that real objects that are consistent with previously acquired knowledge are more memorable than made-up objects that are inconsistent with previously acquired knowledge. Prior knowledge provides mnemonic properties that facilitate the encoding, storage, and retrieval of real

and perirhinal cortex is at least partially responsible for this retrogenic phenomenon. The hippocampus expands until early in adolescence, but volumetric development in the perirhinal cortex terminates by age 4 (Hu et a., 2013). On the other hand, volume declines precipitously in the hippocampal region, but less reliably in the perirhinal cortex (see main text). The hippocampus is the first-developed and last-declined region, compare to the perirhinal cortex.

objects (Badham et al., 2016). Additionally, there is a difference in difficulty based on whether or not the object is able to be named. Real objects can all be easily named using existing labels (Reifegerste et al., 2020). With the assistance of verbal labels, a deeper process of real objects can be promoted, resulting in more effective encoding and greater success during the later recognition phase.

Thirdly, although older adults exhibited a significant decline in DM, they were able to recognize what they had learned 24 hours previously as their performance was significantly higher than the chance level during the day-two phase. In contrast, no evidence reflected that older adults preserved sequence learning after 24 hours, although younger adults did not show improvement from offline consolidation either, which is consistent with the results of Nemeth et al. (2010). In other words, with a 24-hour delay, older adults could still take advantage of DM but failed to make use of PM. This is divergent from the expectations of retrogenesis theory that DM matures earlier and breaks down later while PM matures later and breaks down earlier. A possible reason for this exception is that it reflects the separability between DM and PM (Ullman, 2001b), and separated capacities seem to be constrained in terms of comparing their acquisition and dissolution order. Similarly, there has been some evidence of dementia patients losing their naming abilities while maintaining the ability to produce grammatical sentences (Schwartz et al., 1979), even though word meanings are acquired before the ability to produce sentences is developed. A cautious approach should be applied when comparing linguistic components across the lexical and sentential levels. As Caramazza et al. (1994) pointed out, there are important “similarities” and “mutual constraints” between acquisition and breakdown, and the importance is to probe the “principles that govern the general functioning of the two systems”, rather than managing to calibrate all aspects of the two systems. The results of our study have provided direct evidence in support of retrogenesis theory and indicated some limitations when attempting to consider acquisition and breakdown in parallel.

It is necessary to note that the declearn task and SRT task were originally used to measure DM and PM abilities. Nonetheless, under overall retrogenesis theory, we serendipitously observed retrogenic decline in DM. Although many factors were controlled for in the measurement of both memory abilities, factors that were likely to affect the comparison between these two memory systems might be neglected at the beginning. Therefore, more caution would be needed before generalizing the findings and the results need to be validated with more sophisticated studies.

Chapter 5. Age-related constrained language production differences

5.1. Introduction

Language production is important in daily communication, especially the semantic and syntactic abilities which manipulate expressed messages. Syntactic and semantic abilities are normally indicated by syntactic complexity or grammatical complexity, and semantic complexity or propositional content respectively. Longitudinal studies have found that grammatical complexity and propositional content were subject to age-related decline for healthy older adults and patients with dementia (Kemper, Greiner, et al., 2001; Kemper, Thompson, et al., 2001). However, cross-sectional research reported that even dementia patients were able to express required information if they were given enough time (Ahmed, de Jager, et al., 2013), and they were relatively able to make use of syntactic cues in a writing task thanks to the "overlearned and automatic nature of syntactic ability" (Kempler et al., 1987). Therefore, it is still necessary to investigate expressive semantic and syntactic abilities in older adults carefully.

Recent studies have focused on multiple semantic and syntactic indicators and regarded them as sensitive biomarkers for the detection of MCI and dementia (Ahmed, Haigh, et al., 2013; Wang et al., 2019). There were two major indicators among them: syntactic complexity and semantic complexity. For instance, a study based on the structured and unstructured connected speech of Chinese older adults found that there was a decreasing linear tendency in semantic complexity and syntactic complexity. More advanced research has made use of the machine learning model to extract features from syntactic complexity and semantic complexity and ultimately identify subjects with and without dementia (Horigome et al., 2022; Orimaye et al., 2017). Such exploitation of semantic and syntactic features may have future applications. Nonetheless, it is important to note that all the data used to extract syntactic and semantic complexity were from spontaneous language production tasks. Although it is a promising approach to obtaining natural language data, it is difficult to elicit certain target language patterns, for example, the Ba construction which is used in most of the experimental sentences in the current study.

In order to make a comparison with comprehension performance, we adopted constrained production tasks to elicit language production (Kemper et al., 2003). The RTs, as well as the syntactic and semantic complexity, were the major indexes to represent expressive language abilities. In line with previous studies, we predicted that older adults would exhibit worse performance than younger adults.

5.2. Methods

5.2.1. Subjects

Data from all subjects, namely 28 Chinese younger adults (mean age = 24.1 ± 2.6, range = 19-30; 14 males) and 27 healthy ChOA (mean age = 68.0 ± 2.7, range = 65-76; 11 males) were included for expressive syntactic and semantic ability analysis in this section.

5.2.2. Stimuli

All the experimental stimuli were divided into three conditions based on the syntactic feature of the given verb, and three levels based on the number of given words, as shown in Table 6. In terms of the condition, except for the filler one, the given verbs of both experimental conditions belonged to two categories, namely, suitable verbs and unsuitable verbs. Suitable verbs referred to verbs that could be put into the Ba construction directly, while unsuitable verbs referred to those that could not be put directly into the verb position in the Ba construction. Regarding the level, as the number of given words increased, the difficulty increased. The given word combination in two experimental conditions included the following constraints. The two-word combination level contained a verb and the Ba. The three-word combination level contained a verb, an animate noun and the Ba. The four-word combination level contained a verb, an animated noun, an inanimate noun and the Ba.

Table 6. Representative experimental stimuli in constrained production tasks

level	Condition		
	Suitable verb	Unsuitable verb	Filler
Two-word combination	把 收拾 Ba tidy	喜欢 把 like Ba	失去 律师 lose lawyer
Three-word combination	医生 清理 把 doctor clean Ba	将军 把 听见 general Ba hear	企业家 毛巾 逃跑 entrepreneur tower escape
Four-word combination	走廊 把 警察 打破 corridor Ba police break	把 啤酒 游客 值得 Ba beer visitor worth	建立 餐厅 运动员 面具 establish canteen athlete mask

Note: The term suitable verb refers to a verb that can be put into the Ba construction directly, for instance, "张三把桌子收拾了/ Zhangsan tidied up the table". In contrast, the term unsuitable verb refers to those that cannot be put into the Ba construction directly; for instance, it is not grammatically correct to say a sentence like "*张三把苹果喜欢了/ Zhangsan liked the apple".

We first selected potential words (frequency: Mean = 58.74 per million, SD = 136.54 per million) from the database of Cai and Brysbaert (2010), and combined the potential words as a possible stimulus. Then a total of 22 students from The Hong Kong Polytechnic University who were not participants in the constrained production task were recruited to assess the familiarity of all the stimuli, as well as the semantic association of paired given words in one stimulus. A total of 54 candidate stimuli were rated, and 36 stimuli were ultimately selected for use as experimental stimuli. Here are the rating results for the experimental sentences. The familiarity of words was significantly higher than the chance level (M = 6.71, SD = 0.23) [$t(83) = 108.39$, $p < .0001$] (1 = very unfamiliar; 7 = highly familiar). The semantic association between the paired words was significantly lower than the chance level (M = 2.35, SD = 0.67) [$t(35) = -5.78$, $p < .0001$] (1 = very unrelated; 5 = highly related).

The semantic association between words within a stimulus was controlled to the infinitesimal level in order to measure the semantic ability of subjects. The suitable verb condition represented semantic difficulty, while the unsuitable verb condition represented additional syntactic difficulty as it compelled participants to undertake more syntactic manipulation to produce a grammatically correct sentence. Therefore, expressive semantic ability was assessed via the RTs and the semantic complexity of the suitable verb condition, while expressive syntactic ability was assessed via the RTs and the syntactic complexity of the unsuitable verb condition.

5.2.3. Procedures

The experiments were conducted in Mandarin. The stimuli were presented on an LCD screen via a Surface Book 2 PC laptop running Windows 10, using E-Prime version 3.0 (Psychology Software Tools). All Chinese sinograms were presented using the Simsun font and were 100 in size. All sinograms were printed in white color and put on a black background. In this task, subjects were required to produce a sentence with words that were provided. Subjects were not prohibited from masterly adopting circumlocutory strategies to produce several sentences in order to incorporate the given words as these given words were not semantically correlated with each other within one sentence for some subjects. In this case, the average syntactic complexity and semantic complexity were calculated to ensure the results were comparable. The following was the instruction that was given:

“Hello! Welcome to our experiment! This experiment requires you to make a sentence(s) based on the provided words. First, several given words will appear on the screen. You need to make a sentence(s) by using the given words. When you finish thinking about the sentence(s) you want to say, please press any button on the response box to initiate recording. Then the recording interface appears. Meanwhile, please speak out your sentences loudly. If you think the sentence you are speaking is wrong, you can reiterate it. When you feel you have finished the sentence you want to say, please press any button on the response box to end the recording interface. Then it goes to the next sentence-making task. We will record the time you think about the sentence and the time you speak out the sentence. Please think about your sentences and speak your sentences with the given words quickly and accurately. If you are ready, press any button on the reaction box to start the exercise."

The RTs and language production were recorded. The RTs indicated the length that participants took to produce a sentence with the given words. The language productions were recorded as audio files for transcription and further analysis.

5.2.4. Coding of constrained production tasks

First of all, subjects' speech responses were transcribed via the Python package speech recognition 3.8 (Zhang, 2017), and then all obtained transcripts were manually examined and revised. All inaccurate sentences were excluded from the semantic and syntactic analysis which followed. Sentences with repetition were corrected in order to put them into the semantic and syntactic analysis model which followed. In addition, fillers and meaningless syllables were deleted, while commas and periods were properly added so that the semantic features and syntactic features could be analyzed in the procedures which followed. For example, "乘务员在一个旅客的行李中查到了子弹嗯整班列车、导致了整班列车的延误" was adjusted to the accurate sentence "乘务员在一个旅客的行李中查到了子弹，导致了整班列车的延误。".

The decomposition from transcribed sentences into words, as well as the measurement of syntactic and semantic complexity, were performed via Python package HanLP 2.1 (He & Choi, 2021), which was specific to Chinese natural language processing (NLP) and had already been efficiently applied in production environments. The theoretical foundation of syntactic and semantic analysis was derived from dependency structures and transformation rules (Robinson, 1970). The labeling standard of semantic analysis in HanLP 2.1 adopted the guideline of the SemEval-2016 (Che et al., 2016). The number of semantic roles and semantic relations labelled in the semantic dependency graph of a sentence was counted and taken as its level of semantic complexity. The labeling standard of syntactic analysis in HanLP 2.1 was based on the Penn Chinese Treebank (Xue et al., 2000). The number of layers of the parse tree of a sentence was counted and taken as its level of syntactic complexity.

5.2.5. Statistical analysis

An omnibus ANOVA for RTs and syntactic complexity was performed on the data from the unsuitable verb condition, while another omnibus ANOVA for RT and semantic complexity was performed on the data from the suitable verb condition. Each omnibus ANOVA included one between-subject factor (group: young or old adults) and one within-subject factor (level: two, three, or four given words).

5.3. Results

5.3.1. Unsuitable verb condition results

5.3.1.1. Reaction time for constrained production time tasks

The reaction time reflected how long participants took to produce a sentence with the given words. As the unsuitable verb condition involved additional syntactic manipulation, it indicated the syntactic ability of participants. Shorter reaction times were associated with better expressive syntactic ability.

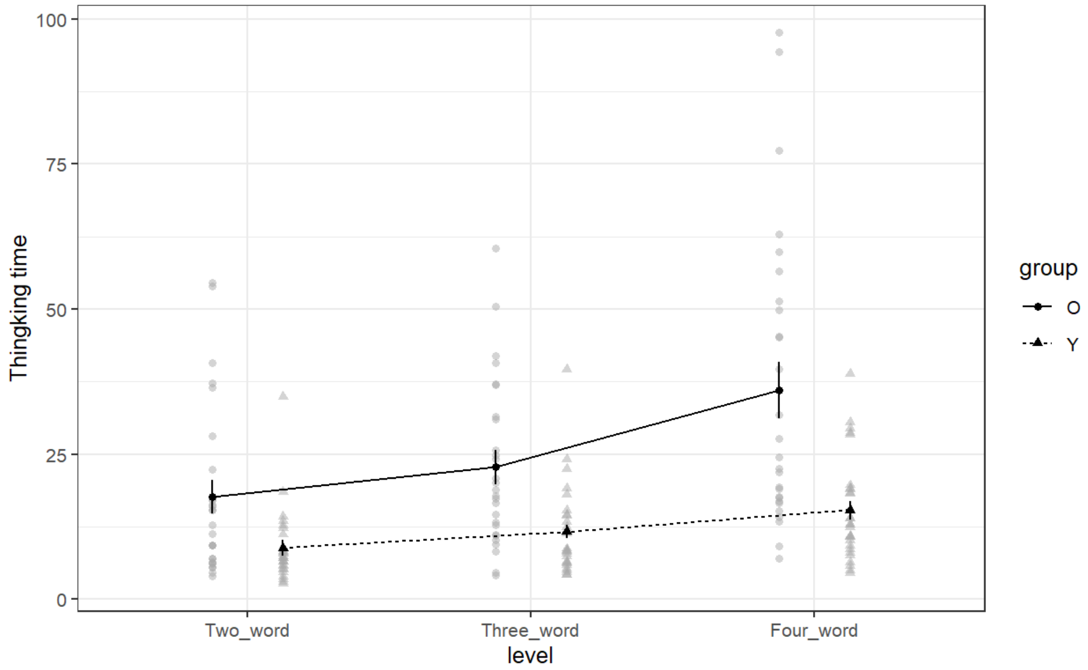


Figure 10. Mean RTs for unsuitable verb condition reported by Level and Group
Shorter thinking time meant better expressive syntactic ability. Both groups demonstrated better performance with fewer given words, and younger adults performed better than older adults at all levels.

As shown in Figure 10, both younger adults and older adults demonstrated similar patterns in terms of the mean thinking time or reaction time and this increased from two given words to four given words. Younger adults performed better than older adults at all levels. Moreover, compared to younger adults, older adults showed larger increments from three given words to four given words.

Table 7. ANOVA results for RTs for unsuitable verb condition in constrained production tasks

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g
(Intercept)	1.00	53.00		57722.43	27383.72	111.72	.000	.64
group	1.00	53.00		7600.53	27383.72	14.71	.000	.19
level	1.35	71.67	0.68	4488.77	5190.39	45.84	.000	.12
group x level	1.35	71.67	0.68	1095.54	5190.39	11.19	.000	.03

Note: The results of the two-way mixed ANOVA showed that there was a significant interaction between group and level, indicating that the group effect differed across the three levels.

A two-way ANOVA was conducted to compare the main effects of group (younger or older adults) and level (two, three, or four given words), as well as their interaction effects on the RTs for the unsuitable verb condition in constrained production tasks, as shown in Table 7. All the effects were statistically significant at the .05 significance level. There was a significant interaction between group and level with an F ratio of $F(1, 71.67) = 11.19$, $p < .0001$. Following up on this interaction, post hoc analyses revealed that, firstly older adults exhibited significantly different RTs between two given words (M = 16.81, SD = 17.83) and three given words (M = 23.60, SD = 21.72) (t.ratio = -4.92, $p < .0001$), and between three given words and four given words (M = 36.42, SD = 32.19) (t.ratio = -6.01, $p < .0001$); secondly, younger adults exhibited significantly different RTs between two given words (M = 9.01, SD = 7.96) and four given words (M = 15.31, SD = 11.36) (t.ratio = -3.02, $p = 0.043$); thirdly, the RT differences between two groups significantly differed between three given words (younger adults: M = 11.64, SD = 10.75; older adults: M = 23.60, SD = 21.72; t.ratio = 3.63, $p = 0.008$) and four given words (younger adults: M = 15.31, SD = 11.36; older adults: M = 36.42, SD = 32.19; t.ratio = 4.07, $p = 0.002$). The results suggest that older adults performed worse when producing a sentence in which the given verbs were not suitable for the Ba construction, especially when the given words and difficulty increased, and their RTs were sensitive to the number of given words. It was also found that older adults' RTs were sensitive to the number of words provided, whereas younger adults' RTs increased only at four given words.

5.3.1.2. Expressive syntactic complexity

The syntactic complexity reflected how many layers of grammatical hierarchy were apparent in each sentence produced by participants. It directly reflected the syntactic ability of participants, especially for the unsuitable verb condition.

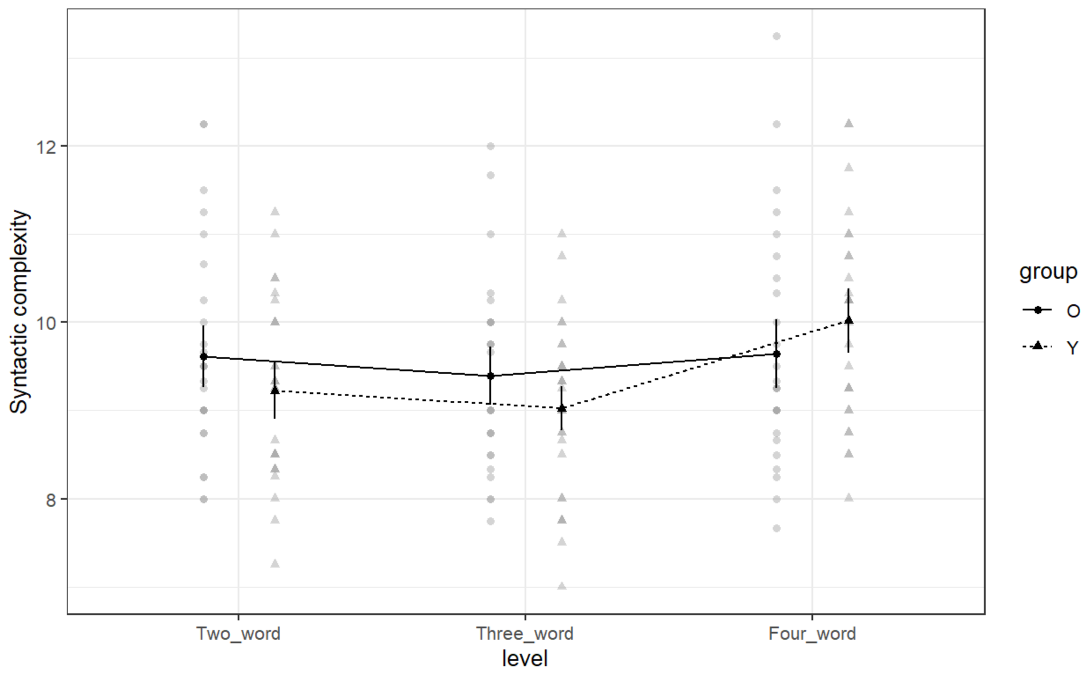


Figure 11. Mean syntactic complexity of sentences produced for the unsuitable verb condition reported by Level and Group
Both groups produced sentences with the lowest syntactic complexity with three given words. When four words were given, the syntactic complexity increased more dramatically for younger adults than for older adults.

As shown in Figure 11, both groups produced sentences with equally lower syntactic complexity when the given words were increased from two to three. However, a significant increase in syntactic complexity occurred for younger adults when the given words increased to four as compared to older adults. It should be noted that the lowest syntactic complexity of sentences produced for the three given words was probably due to the relatively integrated association among the given words, as the verb as well as the agent or patient were already provided in this level.

Table 8. ANOVA results for syntactic complexity of sentences produced for unsuitable verb condition

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g
(Intercept)	1.00	53.00		14847.32	123.84	6354.41	.000	.99
group	1.00	53.00		0.70	123.84	0.30	.588	.00
level	1.84	97.62	0.92	10.96	78.18	7.43	.001	.05
group x level	1.84	97.62	0.92	5.34	78.18	3.62	.034	.03

Note: The results of the two-way mixed ANOVA showed that there was a significant interaction between group and level, indicating that the group effect differed among the three levels.

A two-way ANOVA was conducted to compare the main effects of group (younger or older adults) and level (two, three, or four given words), as well as their interaction effects on the syntactic complexity of sentences that participants produced for the unsuitable verb condition for the constrained production tasks, as shown in Table 8. There was a significant interaction between group and level with an F ratio of $F(1, 97.62) = 3.62$, $p = .034$. Following up on this interaction, post hoc analyses revealed that only younger adults exhibited significantly different syntactic complexity for the produced sentences between two given words (M = 9.24, SD = 1.80) and four given words (M = 10.02, SD = 2.00) (t.ratio = -3.10, $p = 0.034$), and between three given words (M = 9.04, SD = 1.72) and four given words (t.ratio = -4.35, $p = 0.0008$), suggesting that the number of given words affected the syntactic complexity of the sentences produced by younger adults but not older adults. In other words, although older adults can still produce sentences with intact syntactic complexity, they failed to vary the corresponding syntactic structures based on the number of given words. Alternatively, it is probably due to the compensation of longer RTs for older adults.

5.3.2. Suitable verb condition results

5.3.2.1. Reaction time for constrained production time tasks

The reaction time for the suitable verb condition reflected the semantic ability of participants. Shorter reaction times were associated with better expressive semantic ability.

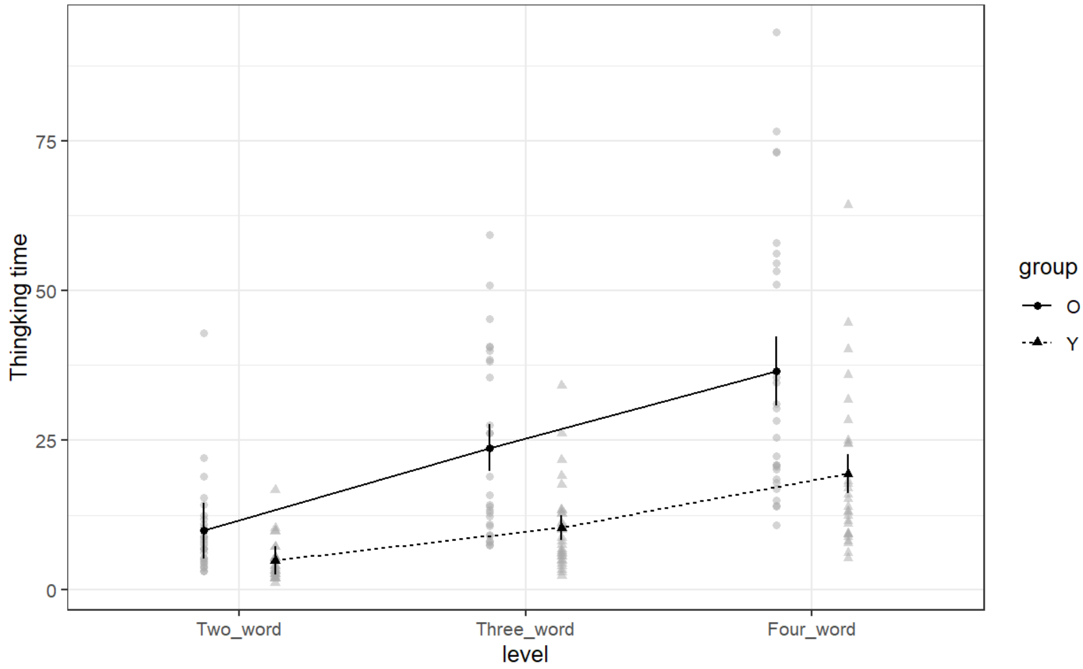


Figure 12. Mean RTs for suitable verb condition reported by Level and Group
Shorter thinking time meant better expressive semantic ability. Both groups demonstrated better performance with fewer given words, and younger adults performed better than older adults at all levels.

As shown in Figure 12, both younger adults and older adults demonstrated similar patterns for average thinking time which increased from the level of two given words to four given words. Younger adults performed better than older adults at all levels.

Table 9. ANOVA results for RTs for suitable verb condition in constrained production tasks

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g
(Intercept)	1.00	53.00		50157.17	18578.73	143.08	.000	.64
group	1.00	53.00		5788.43	18578.73	16.51	.000	.17
level	1.62	85.71	0.81	11651.34	10190.24	60.60	.000	.29
group x level	1.62	85.71	0.81	1069.42	10190.24	5.56	.009	.04

Note: The results of the two-way mixed ANOVA showed that there was a significant interaction between group and level, indicating that the group effect differed among the three levels.

A two-way ANOVA was conducted to compare the main effects of group (younger or older adults) and level (two, three, or four given words), as well as their interaction effects on the RTs for the suitable verb condition in constrained production tasks, as shown in Table 9. All the effects were statistically significant at the .05 significance level. There was a significant interaction between group and level with an F ratio of $F(1, 85.71) = 5.56$, $p = .009$. Following up on this interaction, post hoc analyses revealed that, firstly, older adults exhibited significantly different RTs between two given words (M = 9.94, SD = 9.54) and three given words (M = 23.95, SD = 24.42) (t.ratio = -7.08, $p < .0001$), and between three given words and four given words (M = 36.33, SD = 30.59) (t.ratio = -4.59, $p = .0004$); secondly, younger adults exhibited significantly different RTs for produced sentences between two given words (M = 4.92, SD = 4.49) and four given words (M = 19.47, SD = 20.74) (t.ratio = -4.72, $p = 0.0002$) and between three given words (M = 10.69, SD = 10.25) and four given words (t.ratio = -3.27, $p = 0.02$); thirdly, the RT differences between the two groups differed significantly between two given words (younger adults: M = 4.92, SD = 4.49; older adults: M = 9.94, SD = 9.54; t.ratio = 2.98, $p = 0.047$), between three given words (younger adults: M = 10.69, SD = 10.25; older adults: M = 23.95, SD = 24.42; t.ratio = 4.08, $p = 0.002$) and four given words (younger adults: M = 19.47, SD = 20.74; older adults: M = 36.33, SD = 30.59; t.ratio = 3.38, $p = 0.017$). All these results demonstrated that older adults performed worse in producing a sentence in which the given verbs were suitable for the Ba construction. Moreover, older adults' RTs were sensitive to the number of given words while younger adults demonstrated a significant increase in their RTs only for four given words.

5.3.2.2. Expressive semantic complexity

The semantic complexity reflected how many semantic roles were generated within a sentence produced by participants. This indicated directly the semantic ability of participants, especially for the suitable verb condition. Larger semantic complexity was associated with better expressive semantic ability.

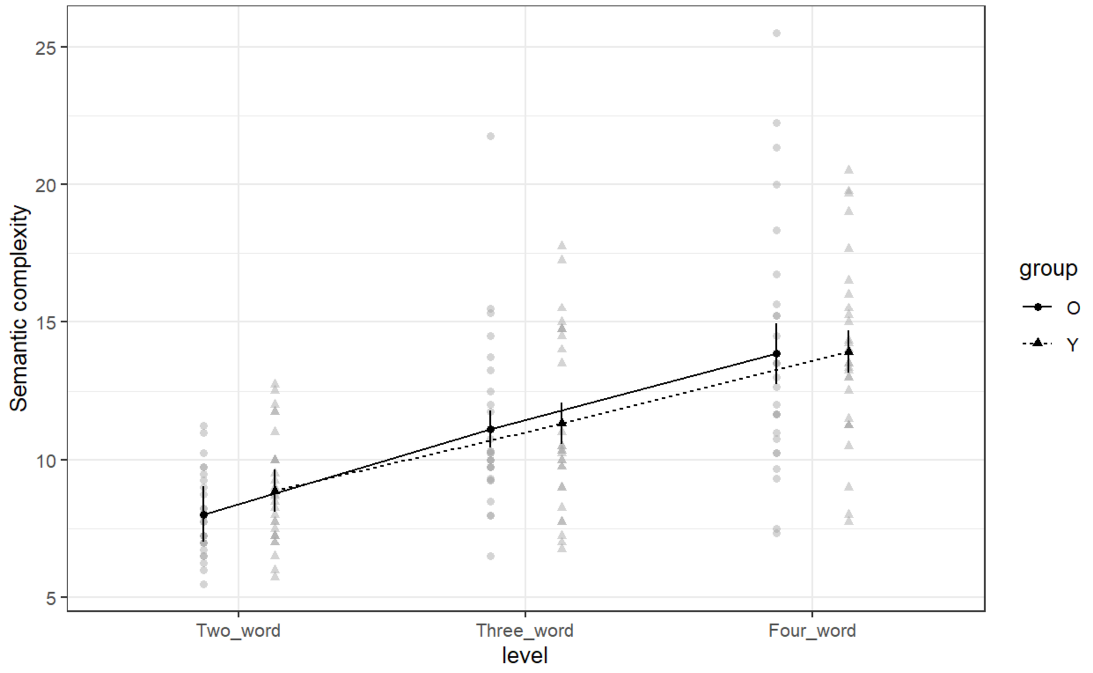


Figure 13. Mean semantic complexity of sentences produced for the suitable verb condition reported by Level and Group
Both groups produced sentences with the lowest semantic complexity with two given words, and the largest semantic complexity with four given words. Younger adults produced sentences with slightly greater semantic complexity compared to older adults.

As shown in Figure 13, both younger adults and older adults demonstrated similar patterns for semantic complexity that increased from the level of two given words to four given words. Additionally, younger adults performed slightly better than older adults at all levels.

Table 10. ANOVA results for semantic complexity of sentences produced for the suitable verb condition

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g
(Intercept)	1.00	53.00		20650.23	1016.82	1076.36	.000	.93
group	1.00	53.00		5.77	1016.82	0.30	.586	.00
level	1.82	96.59	0.91	812.86	505.74	85.18	.000	.35
group x level	1.82	96.59	0.91	4.84	505.74	0.51	.587	.00

Note: The results of the two-way mixed ANOVA showed that there was a significant main effect of level, with both younger and older participants showing the simplest semantic complexity for the level of two given words (mean = 8.51) followed by three given words (mean = 11.25) and showing the slowest speed for four given words (mean = 13.94). In contrast, there was no significant main effect of group and no significant interaction between group and level.

A two-way ANOVA was conducted to compare the main effects of group (younger or older adults) and level (two, three, or four given words), as well as their interaction effects on the semantic complexity of sentences that participants produced for the suitable verb condition for the constrained production tasks, as shown in Table 10. The main effect of group was nonsignificant, $F(1, 53) = 0.30$, $p = .59$. The main effect of level yielded an F ratio of $F(1, 96.59) = 85.18$, $p < .0001$. A Tukey post-hoc test revealed that the semantic complexity was significantly simpler for three given words ($M = 11.25$, $SD = 4.43$) than for four given words ($M = 13.94$, $SD = 5.06$) (t.ratio = -6.70, $p < .0001$), and significantly more complicated than for two given words ($M = 8.51$, $SD = 2.70$)) (t.ratio = -7.52, $p < .0001$). The interaction effect was non-significant, $F(1, 96.59) = 0.51$, $p = .59$. All the results indicated that the two groups produced sentences with similar semantic complexity.

5.4. Discussion

The goal of the current study was to examine whether there was an age-related difference in expressive semantic and syntactic processing when participants were asked to produce a sentence with a Ba construction. In addition, this chapter provides data on production to support an investigation of production and comprehension asymmetries explored in later chapters. Different combinations of given words were provided in order to elicit the target Ba construction. The given words were divided into two conditions based on the syntactic features of the verb. The unsuitable verb condition, for which the verb could not be put directly into the Ba construction, was used to measure expressive syntactic performance, while the suitable verb condition, for which the verb could be put directly into the Ba construction, was used to measure expressive semantic performance. RTs as well as syntactic and semantic complexity served as the measure indicators (Kemper et al., 2003).

Older adults took longer to produce a sentence, which was consistent with previous studies (Kemper et al., 2003; Spieler & Griffin, 2001). One possible reason is that older adults experience a general slowing of processing speed and this causes them to spend more time preparing a sentence (Salthouse, 1996). Alternatively, it may reflect the trade-off between ultimate output and processing speed (Caplan et al., 2011; Jones et al., 2019); that is, older adults sacrificed response speed to ensure that the produced sentences were fine-grained and comparable to younger adults' production in terms of the syntactic and semantic complexity.

It is noted that the differences in RTs between younger adults and older adults became much larger when the number of given words increased, especially for the unsuitable verb condition. Moreover, even an increase of one given word resulted in a significant increase in average RT in older adults, while younger adults did not exhibit this increase, particularly for the unsuitable verb condition. The more obvious increases observed for the unsuitable verb condition were probably related to the additional syntactic difficulty. It seemed that older adults were sensitive to the task difficulty, as the number of given words dictated how difficult it was for them to produce a sentence (Beese et al., 2019). A similar phenomenon was observed in the divided attention task and the motor learning task, for which age differences were exaggerated when tasks were more complicated (McDowd & Craik, 1988; Onushko et al., 2014). When doing tasks that are moderately demanding, older adults could still perform comparably to younger adults, as they may be able to make use of cognitive reserve (Stern, 2002) and compensatory strategies. One possible strategy is to recruit additional brain activation to maximize their behavioral performance (Zhang et al., 2018), as proposed by the compensation-related utilization of neural circuits hypothesis (CRUNCH) (Reuter-Lorenz & Cappell, 2008). Alternatively, the different performance between easy and difficult conditions is likely due to distinctive levels of failure to suppress the default mode network. It appears that older adults may have difficulty modulating the default mode network in response to task demands (Persson et al., 2007). For cognitively demanding tasks, age differences in suppression of the default mode may be most apparent, but these differences may not be evident at lower levels of task demand. Due to the failure of deactivation in the default mode network, older adults performed poorly at the four-word level, compared to younger adults.

Unlike for the RTs, there was no significant difference between younger and older adults regarding the syntactic complexity and semantic complexity of the sentences produced. It was not a surprise that older adults displayed similar syntactic complexity in terms of their language production, as the syntactic ability seemed to be resistant to aging effects and it has been observed that it tends to be preserved in patients with AD (Davidson et al., 2003; Hardy et al., 2020; Kempler et al., 1987). Besides, older adults displayed comparable semantic complexity, indicating similar semantic processing across ages (Beese et al., 2019). This was probably due to the fact that there was no time pressure for the task. Even dementia patients were able to express required semantic information with enough time (Ahmed, de Jager, et al., 2013). With unlimited planning time, it was unsurprising that healthy older adults, in the current study, were capable of producing sentences with sophisticated semantic complexity comparable to that of their younger counterparts.

Another interesting phenomenon which needs to be pointed out here is that the Ba, which is an auxiliary word, was sometimes used as a bound morpheme in the unsuitable condition. For instance, one older adult produced a sentence “我们一定要

把握住开始的时间和结束的时间。/We must grasp the time of the beginning and the time of the end.” in which Ba was one of the morphemes of the word “把握/grasp”. By doing this, the participant was able to avoid the syntactic difficulty of combining the Ba and the unsuitable verb “开始/begin”. Such usages of Ba confirmed that participants recruited DM to integrate the Ba into a chunk in order to eschew the syntactic burden.

Chapter 6. Production/comprehension asymmetries in syntactic processing

6.1. Introduction

Various types of sentences have been used to investigate syntactic processing with event-related potential (ERP) signals recorded at the same time, for a review, see Kuperberg (2007) and Steinhauer and Drury (2012). The first frequently used type was morphosyntactic agreement violations in which the critical word contained a morphological affix which was syntactically mismatched with the context (Allen et al., 2003; Newman et al., 2007), for instance, a past tense verb in a future tense sentence (e.g., The man will *worked on the platform), or a present tense verb in a past tense sentence (e.g., Yesterday I *grind up coffee). This morphosyntactic violation paradigm elicited many different ERP effects, ranging from no effects to LAN, AN, right anterior positives, N400 as well as P600 effects, leading to somewhat equivocal interpretations and conclusions, for a review, see Leminen et al. (2018).

The other major type was phrase structure violations which referred to both the word category violation and the word order violation in previous research. There were three main ways to create the word category violation. The first one was by replacing the suitable part of speech with an unsuitable one. For instance, Hagoort et al. (2003) mixed up the noun and verb in the corresponding phrase in Dutch (e.g., “De houthakker ontweek de ijdele schroef/* schroeft op dinsdag. (The lumberjack dodged the vain propeller/* propelled on Tuesday.)), and found it elicited AN and P600 effects. However, different effects were evoked by the misuse of the head in a noun phrase or verb phrase in other languages; for instance, Federmeier et al. (2000) reported N400 and P600 effects in English (e.g., John wanted to eat/*bear.), while Zhang et al. (2010) discovered LAN and P600 effects in Mandarin (e.g., Wei Li/ ba (PREP)/ fresh/ pears/

slowly/ *knife/ le (PERF)/ two. (Wei Li peeled/*knife two fresh pears slowly.)). As a result, this type of syntactic violation is deemed, to some extent, to be related to various neural effects.

In addition to the replacement of an appropriate part of speech, eliding an indispensable component or thrusting a mismatch component into a phrase were the other two methods for causing phrase structure violation. Function words were frequently manipulated in this case. For instance, Ainsworth-Darnell et al. (1998) deleted the preposition (*to*) for the prepositional phrase indirect object in the non-alternating datives structure (e.g., Jill entrusted the recipe *friends before she suddenly disappeared.) and found a P600 effect was elicited. As the preposition attached to the non-alternating datives is “a purely syntactic preposition” in the sentence (Ainsworth-Darnell et al., 1998), it is unlikely to cause a change of meaning, which means it has an ideal pattern for phrase structure violation. However, this kind of structure is not common in Chinese and can lead to unwanted semantic involvement. For instance, one study designed a syntactically incorrect sentence by deleting the noun in the Ba construction (e.g., *Shejishi zhizuo xinyi, ba cai-le. (*To make new dresses, the stylist cut.)) (Ye et al., 2006). The problem with the provided sentence stems from incorrect syntactic analysis, but it also makes semantic analysis problematic. The same problems also exist in the garden path sentence which is another type of sentence used to examine syntactic ability and which is reported to elicit a P600 effect (Osterhout & Holcomb, 1992). When reading garden path sentences, semantic analysis is involved in reanalyzing the preferred syntactic structure and disambiguating the sentence.

The last major type is word order violation which avoids meaning distortion of the whole sentence and thus is unlikely to cause semantic problems. For instance, Neville et al. (1991) designed syntactically anomalous sentences with a word order violation on noun phrases and prepositions (e.g., *The man admired Don's *of* sketch the landscape.), and found a left-lateralized anterior negativity (LAN). Although similar results were reduplicated in a later study among English native speakers (Newman et al., 2007), a syntactic positive shift (SPS) was elicited by word order violations in Dutch (Hagoort et al., 1993). Therefore, there were variations in the ERP effects for syntactic processing based on different languages.

In the current study, we adopted word order violation in the Ba construction to formulate experimental stimuli. This is because word order violation, on the one hand, ignores the involvement of an affix which is generally absent in Chinese; on the other hand, it also avoids unnecessary semantic problems. We assumed that word order violation in the Chinese Ba construction would elicit AN effects and/or SPS effects for younger adults. We adopted the AN effect, rather than the LAN effect, because these negativities are not restricted to the left hemisphere (Morgan-Short et al., 2012). Regarding aging effects, we presumed that these AN effects and/or SPS effects would be reduced in older adults.

6.2. Methods

6.2.1. Subjects

Data from 23 Chinese younger adults (mean age = 24.4 ± 2.7, range = 19-30; 13 males) and 19 healthy ChOA (mean age = 68.1 ± 2.6, range = 65-76; 9 males) were included for receptive syntactic ability analysis in this section. To ensure that the sample size was matched for the following analysis on both semantic and syntactic production and comprehension asymmetries, two younger adults were excluded. These two participants were rejected as their reject rates for the semantic correctness judgement task were too high. For more details, see Section 7.2.4.1. As a result, 40 subjects remained for the analysis on PCA.

6.2.2. Stimuli

There were four types of sentences in all conditions, as shown in Table 11. Each condition contained 60 stimuli. In total there were 240 sentences. The experimental sentences were those containing Ba constructions, and filler sentences followed with the canonical subject-verb-object word order. We used a variety of filler sentences containing *-le*, *-guo*, *-de*, and *-ne* for the final word in order to avoid overuse of *-le* as the complete aspect marker in the experimental sentences. Additionally, a function word, such as SHI in the example sentence, was inserted between the subject and the predicate in the filler sentence in order to match the number of words in the experimental sentence.

Table 11. Example sentences used in the syntactic comprehension tasks

Condition	Stimuli
Congruent sentence (CON)	管家/把/房间/**整理**/了。 guanjia/ba/fangjian/zhengli/le steward/BA/room/tidy/particle The steward has tidied the room.
Syntactically incongruent sentence (SYN)	*管家/把/整理/**房间**/了。 *guanjia/ba/zhengli/fangjian/le. steward/BA/tidy room/particle *The steward the room has tidied.
Congruent filler	股东/是/知道/实情/的。 gudong/shi/zhidao/shiqing/guo. shareholder/SHI/know/truth/particle The shareholder knew the truth.
Incongruent filler	股东/是/实情/知道/的。 gudong/shi/shiqing/zhidao/de. shareholder /SHI/ truth /know/particle *The shareholder the truth knew.

Note: The critical word was positioned on the penultimate word in all sentences and highlighted using a bold font in the table. In each example sentence, the first line is the stimulus in Mandarin for which a slash was inserted to mark the boundary between words. The second line is the corresponding pinyin. The third line is the English translation for each word. The fourth line is the meaning of the whole sentence. The incongruent sentence is labelled with an asterisk.

The verbs and nouns in Ba constructions were formulated into the syntactic anomalies in the experimental sentences. The penultimate word in the sentence served as the critical word for all experimental conditions. The critical verbs (M = 24.25 per million, SD = 40.27 per million) and nouns (M = 26.43 per million, SD = 28.87 per million) shared similar word frequency [t(118) = -0.34, p = 0.73], based on the database produced by Cai and Brysbaert (2010).

Moreover, 22 college students from The Hong Kong Polytechnic University who did not participate in the ERP experiment rated the familiarity, part of speech, and semantic compatibility of the critical nouns and verbs, as well as the correctness of the whole sentence. A total of 160 candidate sentences were rated and 120 sentences were ultimately selected as the experimental stimuli. The following were the rating results for the experimental sentences. The critical nouns (M = 6.69, SD = 0.25) and verbs (M = 6.64, SD = 0.21) had similar familiarity [t(118) = 1.20, p = .23] (1 = very unfamiliar; 7 = highly familiar). The critical nouns (M = 4.64, SD = 0.28) tended to be rated as nouns, and the critical verbs (M = 1.46, SD = 0.43) tended to be rated as nouns [t(118) = 62.71, p < .0001] (1 = very like a noun; 5 = very like a verb). The semantic compatibility between the paired critical nouns and verbs was significantly higher than the chance level (M = 4.67, SD = 0.23) [t(59) = 57.03, p < .0001] (1 = very incompatible; 5 = highly compatible). There was a significant difference in terms of the correctness between congruent sentences (M = 4.73, SD = 0.24) and incongruent sentences (M = 0.32, SD = 0.26) [t(118) = 100.81, p < .0001] (1 = very correct; 5 = highly incorrect).

6.2.3. Procedures

The experiments were conducted in Mandarin. The stimuli were presented on an LCD screen via a Surface Book 2 PC laptop running Windows 10, using E-Prime version 3.0 (Psychology Software Tools). All Chinese sinograms were presented in the Simsun font on the screen at a size of 100. All the sinograms appeared in white with a black background. The presenting procedure is demonstrated in Figure 4. In each semantic comprehension trial, a cross fixation was centered on the screen for 1000 milliseconds after a random period of 500, 1000, or 1500 milliseconds of a black blank screen. In the timeline of the example trial, it was 1000 milliseconds long. When the fixation disappeared, the first word was immediately presented in the center of the screen and it was left in place for 500 milliseconds. It was then followed by a 100-millisecond inter stimulus interval (ISI) with a blank screen before the next word appeared on the screen. When the final word disappeared from the screen at 4900 milliseconds, a response interface was presented to remind the subject to press the left or right button which corresponded to the “correct” or “incorrect” reply respectively. The response interface remained on the screen until a reply was provided, or lasted for a maximum period of 3000 milliseconds if subjects didn’t reply.

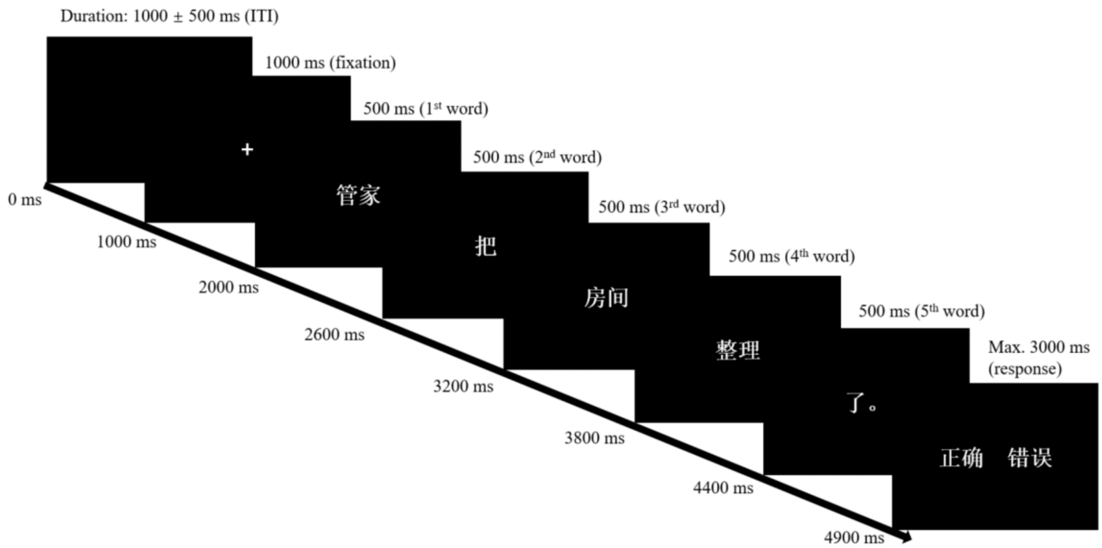


Figure 14. Sample sequence of syntactic comprehension trials
During each trial, a fixation appeared for a duration of 1000 milliseconds following a random ISI of 500, 1000, or 1500 milliseconds that was accompanied by a black blank screen. The ISI in the timeline of the example trial was 1000 milliseconds long. Following the disappearance of the fixation, the first word appeared immediately on the screen and was displayed for 500 milliseconds. This was followed by 100 milliseconds of a blank screen before the next word appeared. At 4900 milliseconds after the final word disappeared from the screen, a response interface was presented to prompt the subject to press the left or right button that corresponded to the "correct" or "incorrect" response. The response interface remained on the screen until a reply was given, or for

a maximum of 3000 milliseconds if subjects failed to respond.

During the experiment, each participant sat about 100 cm away from an LCD monitor that displayed the experimental stimuli in a quiet and dark room. An ActiveTwo 32-channel EEG system (BioSemi B.V., Amsterdam, The Netherlands) with Ag/AgCl active electrodes was used to obtain the EEG data. The electrodes were placed at the following positions: Fp1, Fp2, AF3, AF4, Fz, F3, F4, F7, F8, FC1, FC2, FC5, FC6, Cz, C3, C4, T7, T8, CP1, CP2, CP5, CP6, Pz, P3, P4, P7, P8, PO3, PO4, Oz, O1, and O2 (Acharya et al., 2016), as shown in Figure 15.

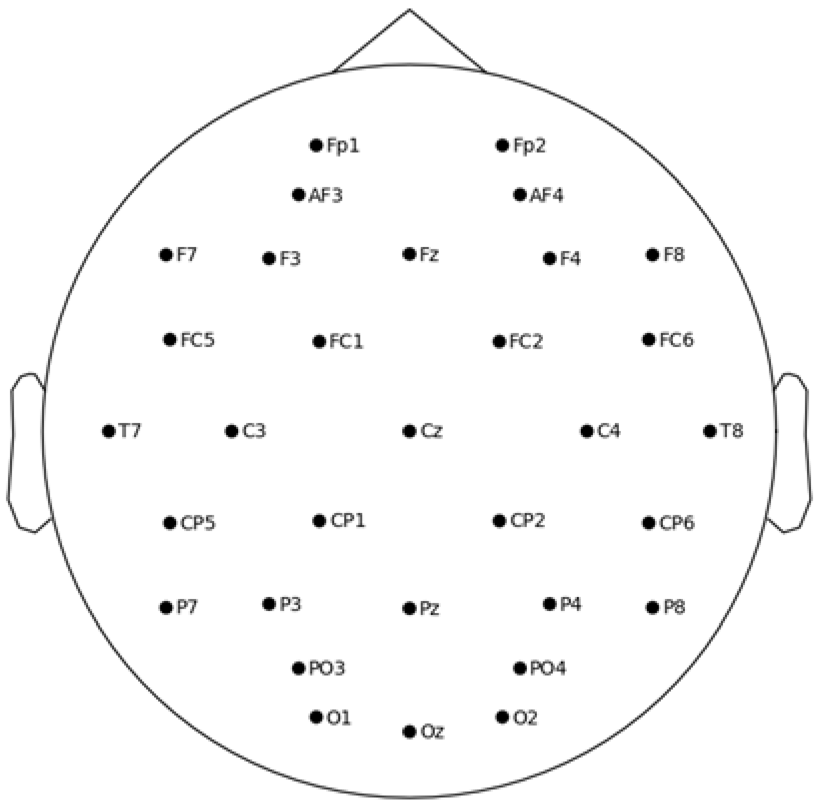


Figure 15. Schematic diagram showing the array of 32 scalp electrodes from which ERPs were recorded
The template montage figure was generated by MNE-Python 1.1 (Gramfort et al., 2013). In the current study, we focused on nine electrodes (or channels) of interest, which were F3, Fz, F4, C3, Cz, C4, P3, Pz, and P4.

We employed two additional electrodes to support a feedback loop to drive the average electrical potential as closely as possible to the amplifier reference voltage (BioSemi, 2017). These electrodes were placed on either side of the vertex at positions C1 and C2, respectively. A 0.1 Hz to 40 Hz digital bandpass filter was applied to the EEG data which were sampled at a rate of 1024 Hz. Vertical/horizontal electro-oculograms (HEOG/ VEOG) were collected with four electrodes which were stuck near the two outer canthi, and above /below the left eye respectively. There was no artifact correction applied to tackle eye blinks and eye movements during the period of data collection. To allow offline re-referencing in the subsequent data processing, two additional electrodes were placed on both mastoids.

6.2.4. Data analysis

6.2.4.1. EEG data analysis

The preprocessing of EEG data was performed according to the standard analysis pipelines provided by MNE-Python (Gramfort et al., 2013; Gramfort et al., 2014). The raw EEG data were firstly downsampled to 256 Hz and then re-referenced to the average mastoid. The power line frequency was set as 50 Hz as the EEG data were collected in mainland China and Hong Kong. After that, a filter between 0.1 and 30 Hz was applied to the data. Stimulus-locked epochs were obtained from 100 ms pre-stimulus to 1000 ms post-stimulus. The pre-stimulus 100 ms was used for the baseline correction. The independent components analysis (ICA) was used for artifact repair with the Picard algorithm provided by the MNE-Python built-in modules. For the following artifact rejection, only trials with correct responses were considered. Epochs with voltage fluctuation of over 200 μV or below 1μV in any of the scalp electrodes were excluded. Additionally, eye movements or blinks with a threshold of 150 μV were rejected for each epoch. By averaging the artifact-free epochs, the stimulus-locked ERPs could be derived for each condition. Regarding the third word, the overall rejection rate was 13.80% for younger adults, equal for both two conditions (SYN: 15.14%, CON: 12.46%); and it was 18.68% for older adults, approximately equal for both two conditions (SYN: 22.37%, CON: 15.00%). Regarding the critical word, the overall rejection rate was 13.59% for younger adults, equal for both two conditions (SYN: 16.38%, CON: 10.80%); and it was 18.86% for older adults, approximately equal for both two conditions (SYN: 24.21%, CON: 13.51%).

Two time windows were chosen on the basis of visual inspection and earlier studies: 300-500 ms for LAN effects, and 500-700 ms for SPS effects (Hagoort et al., 1993; Neville et al., 1991). The mean amplitudes for the selected time windows were used in all the statistical analyses. Three electrodes at the middle line (Fz, Cz, Pz) and six lateral electrodes (F3, F4, C3, C4, P3, P4) were selected as the representative data for statistical analysis. ERPs from the midline and lateral electrodes were analyzed separately. Omnibus ANOVAs for midline electrodes included two within-subject factors: electrode (Fz/Cz/Pz) and condition (SYN/CON). Omnibus ANOVAs for lateral electrodes included three within-subject factors: hemisphere (left/right), region (anterior/central/posterior), and condition. Crossing the variables of region and hemisphere yielded six regions of interest, with one representative electrode for each region of interest: left anterior (F3), left central (C3), left posterior (P3), right anterior (F4), right central (C4), and right posterior (P4). The group (younger/older), as a between-subject factor, was added into the models when comparing differences between the two groups.

6.2.4.2. Analysis of asymmetry and correlation

To evaluate syntactic PCA, the data for constrained production tasks in the unsuitable Ba condition and data for syntactic correctness judgement tasks were rescaled via the min-max normalization. The minimum value for every feature was converted to a 0 and the maximum value was converted to a 1; all other values were transformed into a decimal between 0 and 1. The min-max normalization method was selected because it guarantees that all features have the exact same scale as the original data (Suarez-Alvarez et al., 2012), which was important for comparing production performance and comprehension performance for the same participants. Expressive syntactic ability was indicated by the RT of the constrained production task and the syntactic complexity of the sentences produced by the participants for the task. The receptive syntactic ability was assessed by the accuracy of the syntactic correctness judgement task and the mean amplitude of the AN effect of the difference waveform. Only ERP data from the Fz electrode were used, as the AN was frontally distributed. The RT and AN amplitude were reversed when computing normalization, as shorter RT and more negative amplitude represented better abilities.

The data for younger adults and older adults were rescaled separately, as they were two different populations and showed significant differences in terms of syntactic abilities. Since the re-scaled data were not normally distributed, paired Wilcoxon signed rank tests were used to examine the PCA. If there was a significant difference between expressive syntactic performance and receptive syntactic performance, it indicated that participants were exhibiting syntactic PCA, and vice versa.

To examine the functional significance of memory abilities in PCA, we tested whether DM and PM performances were correlated with expressive and receptive syntactic performance. Correlation analysis was performed on all participants to evaluate the associations across life span. Original data, rather than re-scaled data were applied in the correlation analysis.

PCA was examined with the paired Wilcoxon signed rank test using rstatix 0.7.0

(Kassambara, 2021). The correlation matrix and its visualization were performed using corrplot 0.92 (Wei & Simko, 2021). The same settings were also applied in the analysis of semantic PCA in Chapter 7.

6.3. Results

6.3.1. Behavioral results

The behavioral results were analyzed using accuracy only (rather than RT), since the response had to be made after the full sentence was delivered, rather than immediately when the subject identified whether or not it was correct.

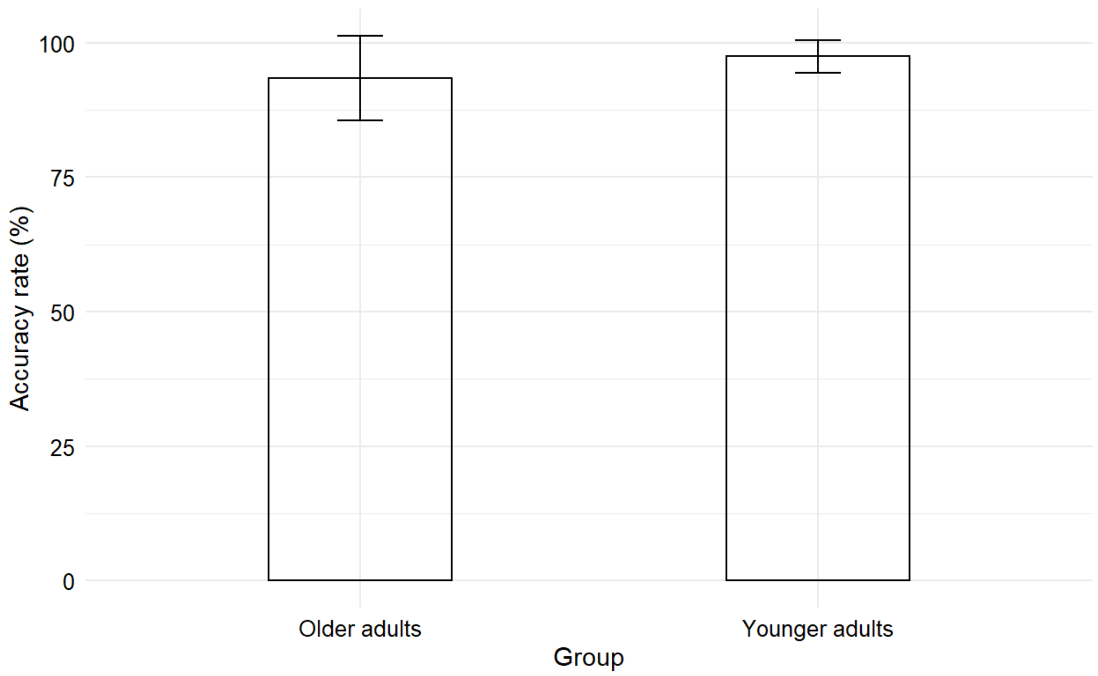


Figure 16. Mean accuracy rate for the syntactic correctness judgement task by Group
Younger adults performed slightly better than older adults in identifying syntactic anomalies.

As shown in Figure 16, the mean accuracy rate for the syntactic correctness judgement task in the older group was 93.47 (SD = 7.88), whereas the mean in the younger group was 97.43 (SD = 3.01). A Welch two-sample t-test showed that the difference was marginally significant, t(22.3) = -20.8, p = 0.0502, d = -0.66, indicating a moderate effect size; where t(26.9) is a shorthand notation for a Welch t-statistic that has 26.9 degrees of freedom.

6.3.2. EEG results

6.3.2.1. Results of younger adults

ERP responses to the critical words were first examined to identify whether there were AN and SPS effects when Chinese younger adults read sentences with or without word order violations. The time window from 300 to 500 ms at the three middle electrodes and six lateral electrodes, respectively, was investigated initially. Then, we investigated the time window from 500 to 700 ms at these electrodes again to evaluate the potential SPS component.

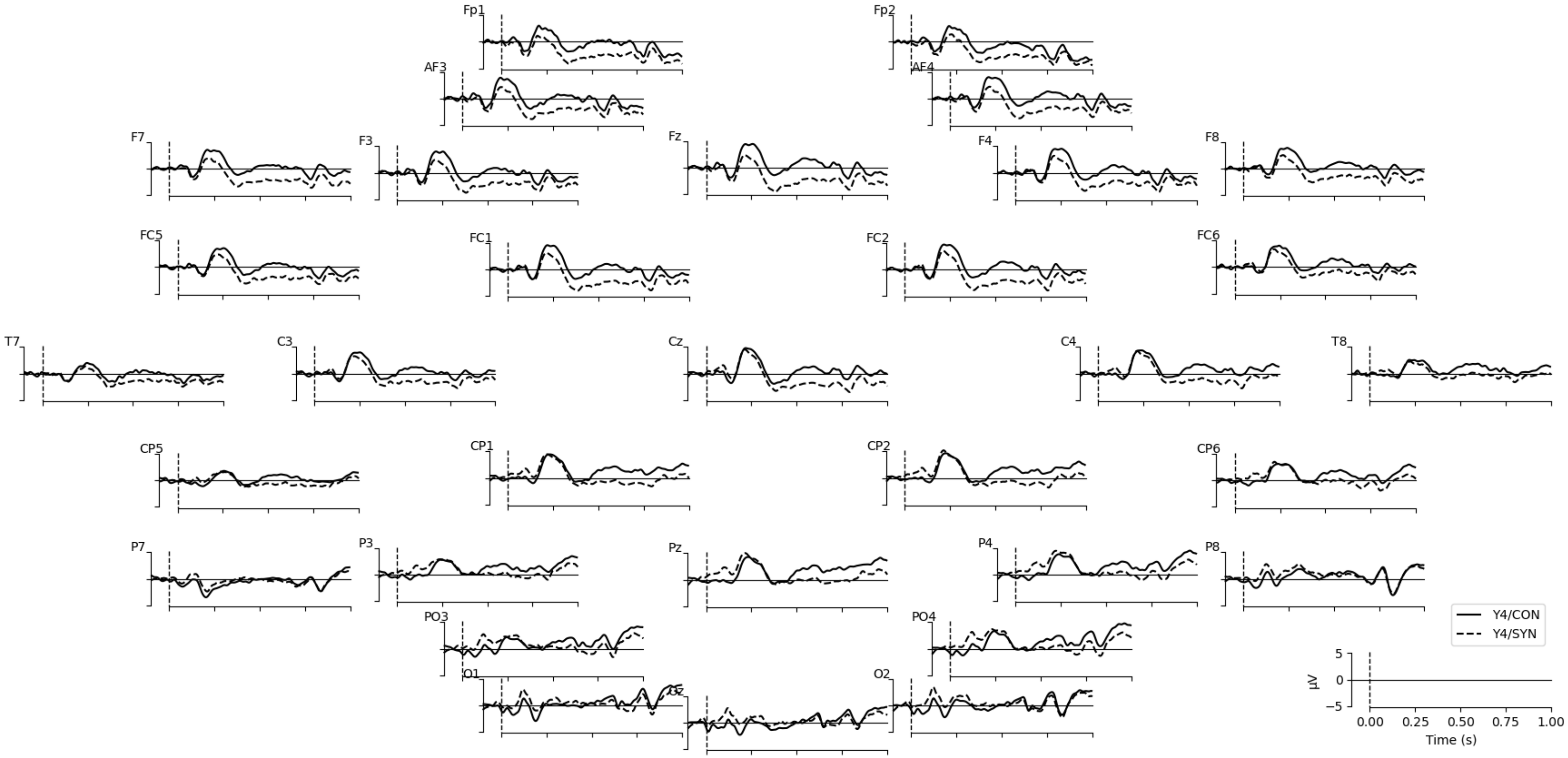


Figure 17. Grand average ERPs (across all younger adults and items), from 32 scalp electrodes, for the critical words in SYN and CON conditions

Waveforms are time-locked to the onset of the critical words. Negative voltage is plotted downward. The solid line represents the CON condition, while the dashed line represents the SYN condition. SYN waveforms tended to be more negative after they descended from the second positive peak at most anterior channels, and some parietal channels were even affected in the late time window.

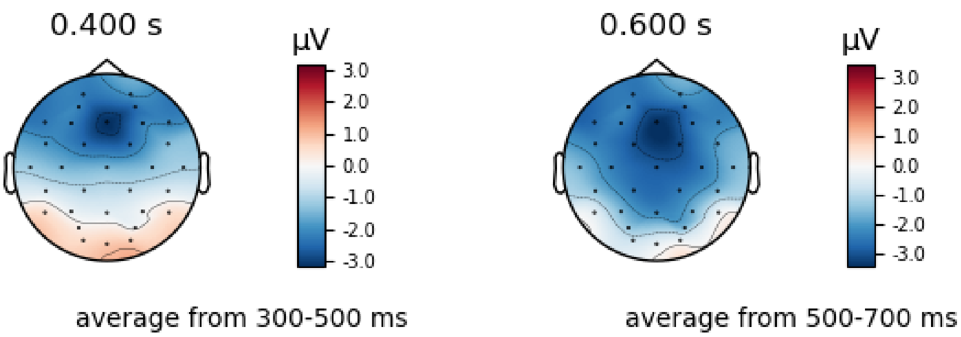


Figure 18. Topographic distribution of the condition difference (SYN - CON) for the critical words in younger adults
The figure on the left-hand side represents the topographic distribution of the syntactic effect in younger adults from 300 to 500 ms after the critical word onset, while the figure on the right-hand side represents that of the 500 to 700 ms time window. The semantic effect was distributed at the frontal regions in the 300 to 500 ms time window and tended to spread to the whole brain in the following period.

Figure 17 shows ERP responses for younger participants at all channels. Figure 18 shows the topographic distribution of the syntactic effect (SYN-CON). Responses over all channels were characterized by a negative component peaking at around 400 ms at the frontal region (AN), and this extended to the following time window from 500 to 700 ms and covered almost the whole brain. In contrast, the SPS effect was not observed.

Table 12. ANOVA results for mean amplitude of three middle channels in the 300-500 ms time window following presentation of the SYN and CON critical words in younger adults

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g
(Intercept)	1.00	22.00		135.50	545.01	5.47	.029	.14
condition	1.00	22.00		98.15	122.54	17.62	.000	.11
channel	1.17	25.83	0.59	97.90	104.28	20.65	.000	.11
channel x condition	1.86	40.86	0.93	46.49	29.51	34.65	.000	.05

Note: The results of the two-way mixed ANOVA showed that there was a significant interaction between condition and channel, indicating the condition effects differed on the Fz, Cz, and Pz channels.

A two-way ANOVA was conducted to compare the main effects of condition (SYN or CON) and channel (Fz, Cz, or Pz), as well as their interaction effects on the mean amplitude of three middle channels in the 300-500 ms time window for the critical words, as shown in Table 12. All effects were statistically significant at the .05 significance level. There was a significant interaction between condition and channel with an F ratio of F(1, 40.86) = 34.65, $p < .0001$. Following up on this interaction, post hoc analyses revealed that the mean amplitude between two conditions only significantly differed in Fz (SYN: M = -3.37, SD = 2.89; CON: M = -0.17, SD = 2.74) (t.ratio = 7.05, $p < .0001$), suggesting that the negativity was polarized on the anterior region which was consistent with the typical distribution of AN effects.

Table 13. ANOVA results for mean amplitude of six lateral channels in the 300-500 ms time window following presentation of the SYN and CON critical words in younger adults

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g
(Intercept)	1.00	22.00		49.30	942.69	1.15	.295	.03
hemisphere	1.00	22.00		6.55	34.75	4.15	.054	.00
condition	1.00	22.00		108.59	146.63	16.29	.001	.07
hemisphere x condition	1.00	22.00		0.12	20.01	0.14	.716	.00
region	1.27	27.87	0.63	208.33	179.62	25.52	.000	.13
hemisphere x region	1.33	29.25	0.66	0.46	35.28	0.29	.662	.00
region x condition	1.49	32.73	0.74	46.80	44.10	23.35	.000	.03
hemisphere x region x condition	1.51	33.16	0.75	0.05	12.91	0.08	.876	.00

Note: The results of the three-way mixed ANOVA showed that there was a significant interaction between condition and region, indicating the condition effects differed in different regions.

A three-way ANOVA was conducted to compare the main effects of condition (SYN or CON), region (anterior, central, or posterior), and hemisphere (left or right), as well as their interaction effects on the mean amplitude of six lateral channels in the 300-500 ms time window for the critical words, as shown in Table 13. There was a significant interaction between condition and region with an F ratio of F(1, 32.73) = 23.35, $p < .0001$. Following up on this interaction, post hoc analyses revealed that the mean amplitude between two conditions only significantly differed in the anterior region (SYN: M = -2.51, SD = 2.77; CON: M = -0.33, SD = 2.65) (t.ratio = 7.05, *p* < .0001), and central region (SYN: M = -1.24, SD = 2.49; CON: M = 0.16, SD = 2.25) (t.ratio = 7.05, *p* < .0001), suggesting that the negativity was polarized on the anterior region of both hemispheres, which was consistent with the distribution of the AN component.

Table 14. ANOVA results for mean amplitude of three middle channels in the 500-700 ms time window following presentation of the SYN and CON critical words in younger adults

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g
(Intercept)	1.00	22.00		1.80	657.31	0.06	.808	.00
condition	1.00	22.00		275.65	209.62	28.93	.000	.22
channel	1.28	28.10	0.64	73.44	102.23	15.81	.000	.07
channel x condition	1.40	30.88	0.70	8.49	32.50	5.75	.014	.01

Note: The results of the two-way mixed ANOVA demonstrated that there was a significant interaction between condition and channel, indicating the SYN condition differed in terms of the mean amplitude, depending on the channel.

A two-way ANOVA was conducted to compare the main effects of condition (SYN or CON) and channel (Fz, Cz, or Pz), as well as their interaction effects on the mean amplitude of three middle channels in the 500-700 ms time window for the critical words, as shown in Table 14. All effects were statistically significant at the .05 significance level. There was a significant interaction between condition and channel with an F ratio of F(1, 30.88) = 5.75, *p* = .014. Following up on this interaction, post hoc analyses revealed that the mean amplitude between two conditions significantly differed in Pz (SYN: M = -0.19, SD = 2.31; CON: M = 2.03, SD = 2.68; t.ratio = -3.71, *p* = .013), Cz (SYN: M = -2.03, SD = 2.40; CON: M = 0.80, SD = 3.21; t.ratio = -4.75, *p* = .001), and also Fz (SYN: M = -2.36, SD = 2.70; CON: M = 1.07, SD = 3.10; t.ratio = -6.92, *p* < .0001), suggesting that the negative effect was distributed across all three middle channels and extended to almost all brain regions.

Table 15. ANOVA results for mean amplitude of six lateral channels in the 500-700 ms time window following presentation of the SYN and CON critical words in younger adults

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g
(Intercept)	1.00	22.00		0.52	1084.39	0.01	.919	.00
hemisphere	1.00	22.00		3.89	31.21	2.74	.112	.00
condition	1.00	22.00		323.87	221.83	32.12	.000	.16
hemisphere x condition	1.00	22.00		0.53	22.13	0.53	.474	.00
region	1.39	30.54	0.69	107.72	160.90	14.73	.000	.06
hemisphere x region	1.24	27.31	0.62	0.31	77.35	0.09	.822	.00
region x condition	1.78	39.15	0.89	10.48	40.39	5.71	.009	.01
hemisphere x region x condition	1.53	33.55	0.76	0.00	23.06	0.00	.992	.00

Note: The results of the three-way mixed ANOVA showed that there was a significant interaction between condition and region, indicating the condition effects differed in different regions.

A three-way ANOVA was conducted to compare the main effects of condition (SYN or CON), region (anterior, central, or posterior), and hemisphere (left or right), as well as their interaction effects on the mean amplitude of six lateral channels in the 500-700 ms time window for the critical words, as shown in Table 15. There was a significant interaction between condition and region with an F ratio of $F(1, 39.15) = 5.71$, $p = .006$. Following up on this interaction, post hoc analyses revealed that the mean amplitude between two conditions significantly differed in the anterior region (SYN: M = -1.94, SD = 2.73; CON: M = 0.55, SD = 3.13) (t.ratio = -6.32, $p < .0001$), central region (SYN: M = -1.43, SD = 2.16; CON: M = 0.97, SD = 2.58) (t.ratio = -5.61, $p = .0002$), and posterior region (SYN: M = -0.01, SD = 1.84; CON: M = 1.61, SD = 2.25) (t.ratio = -3.80, $p = .011$), suggesting that the negative effect was distributed almost all brain regions.

6.3.2.2. Results for older adults

An analysis of ERP responses to the critical words was conducted to determine whether or not there were N400 and SPS effects associated with word order violations while older adults were reading sentences. In the first step, the time window from 300 to 500 ms was investigated along the three middle electrodes and six lateral electrodes. Afterwards, we investigated the 500-700 ms time window along these electrodes again to determine the occurrence of the SPS component.

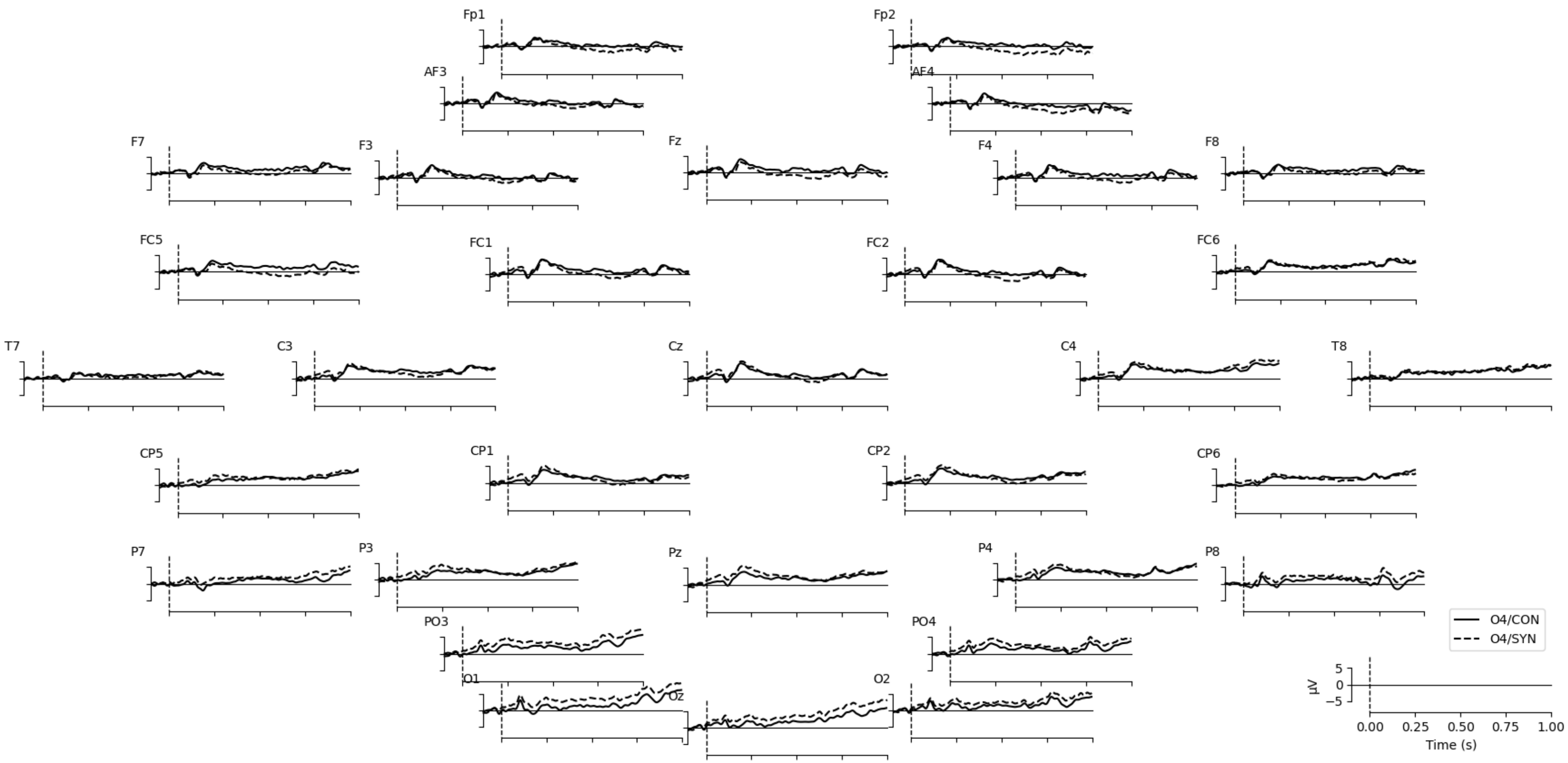


Figure 19. Grand average ERPs (across all older adults and items), from 32 scalp electrodes, for the critical words in SYN and CON conditions

Waveforms are time-locked to the onset of the critical words. Negative voltage is plotted downward. The solid line represents the CON condition, while the dashed line represents the SYN condition. There was a trend for SYN waveforms to be more negative at most anterior channels, and more positive at most posterior channels.

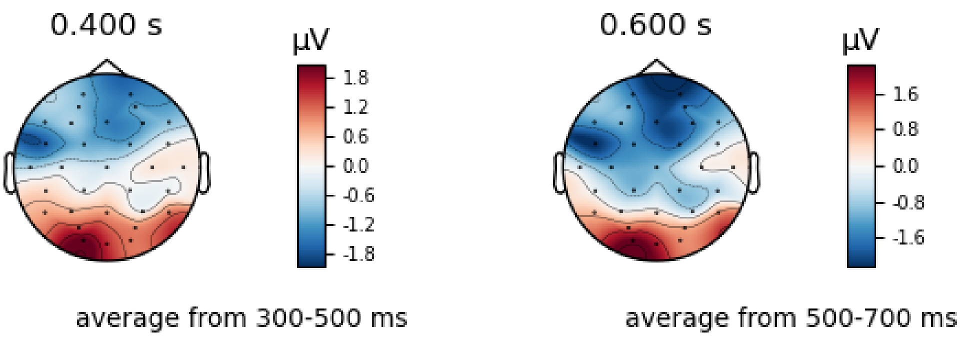


Figure 20. Topographic distribution of the condition difference (SYN - CON) for the critical words in older adults

The figure on the left-hand side represents the topographic distribution of the syntactic effect in older adults from 300 to 500 ms after the critical word onset, while the right-hand side represents the 500 to 700 ms time window. The AN effect was distributed on the frontal regions in the 300 to 500 ms time window and lingered in the following period.

Figure 19 shows ERP responses for older participants at all channels. Figure 20 shows the topographic distribution of the syntactic effect (SYN-CON). Similar to younger adults, responses over frontal channels tended to be negative, peaking around 400 ms, and continuing from 500 to 700 ms thereafter. In contrast, the SPS effect was not evident.

Table 16. ANOVA results for mean amplitude of three middle channels in the 300-500 ms time window following presentation of the SYN and CON critical words in older adults

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g
(Intercept)	1.00	18.00		147.40	433.63	6.12	.024	.17
condition	1.00	18.00		3.14	115.59	0.49	.493	.00
channel	1.55	27.82	0.77	103.38	128.08	14.53	.000	.13
channel x condition	1.47	26.42	0.73	23.64	20.99	20.27	.000	.03

Note: The results of the two-way mixed ANOVA demonstrated that there was a significant interaction between condition and channel, indicating channel effects significantly differed in condition effects.

A two-way ANOVA was conducted to compare the main effects of condition (SYN or CON) and channel (Fz, Cz, or Pz), as well as their interaction effects on the mean amplitude of three middle channels in the 300-500 ms time window for the SYN and CON critical words, as shown in Table 16. There was a significant interaction between group and condition with an F ratio of $F(1, 26.42) = 20.27$, $p < .0001$. Simple main effect analysis revealed that the mean amplitude between the two conditions did not significantly differ in all three middle channels ($p \geq .32$), suggesting that no negative effects in the 300-500 ms time window were generated in the middle line of the brain.

Table 17. ANOVA results for mean amplitude of three middle channels in the 500-700 ms time window following presentation of the SYN and CON critical words in older adults

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g
(Intercept)	1.00	18.00		14.73	600.46	0.44	.515	.01
condition	1.00	18.00		24.85	220.33	2.03	.171	.02
channel	1.56	28.02	0.78	81.99	196.66	7.50	.004	.07
channel x condition	1.85	33.36	0.93	22.81	24.11	17.03	.000	.02

Note: The results of the two-way mixed ANOVA demonstrated that there was a significant interaction between condition and channel, indicating channel effects significantly differed between different conditions.

A two-way ANOVA was conducted to compare the main effects of condition (SYN or CON) and channel (Fz, Cz, or Pz), as well as their interaction effects on the mean amplitude of the three middle channels in the 500-700 ms time window for the SYN and CON critical words, as shown in Table 17. There was a significant interaction between group and condition with an F ratio of $F(1, 33.36) = 17.03$, $p < .0001$. Simple main effect analysis revealed that the mean amplitude between the two conditions did not significantly differ in all three middle channels ($p \geq .16$), suggesting that no negative effects in the 300-500 ms time window were generated in the middle line of the brain.

Table 18. ANOVA results for mean amplitude of six lateral channels in the 300-500 ms time window following presentation of the SYN and CON critical words in older adults

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g
(Intercept)	1.00	18.00		666.97	477.39	25.15	.000	.32
hemisphere	1.00	18.00		0.67	88.78	0.14	.718	.00
condition	1.00	18.00		2.67	178.20	0.27	.610	.00
hemisphere x condition	1.00	18.00		0.66	24.49	0.49	.495	.00

region	1.74	31.40	0.87	237.33	389.53	10.97	.000	.14
hemisphere x region	1.64	29.60	0.82	3.71	124.43	0.54	.556	.00
region x condition	1.76	31.66	0.88	15.97	99.77	2.88	.077	.01
hemisphere x region x condition	1.62	29.09	0.81	4.27	30.73	2.50	.109	.00

Note: The results of the three-way mixed ANOVA showed that only the main effect of region showed significance, with both conditions showing the lowest mean amplitude on the anterior region (mean = 0.28) and the largest mean amplitude on the posterior region (mean = 2.56).

A three-way ANOVA was conducted to compare the main effects of condition (SYN or CON), region (anterior, central, or posterior), and hemisphere (left or right), as well as their interaction effects on the mean amplitude of six lateral channels in the 500-700 ms time window for the SYN and CON critical words, as shown in Table 18. Only the main effect of condition was significant [F(1, 22) = 32.12, $p < .0001$]. A Tukey post-hoc test revealed significant pairwise differences between the anterior region (M = 0.28, SD = 2.34) and central region (M = 2.30, SD = 2.52) (t.ratio = -4.27, $p = .0013$) as well as between the anterior region and posterior region (M = 2.56, SD = 2.72) (t.ratio = 3.64, $p = .005$), suggesting the negativity centered on the anterior regions.

Table 19. ANOVA results for mean amplitude of six lateral channels in the 500-700 ms time window following presentation of the SYN and CON critical words in older adults

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g
(Intercept)	1.00	18.00		215.76	1022.14	3.80	.067	.07
hemisphere	1.00	18.00		4.27	114.66	0.67	.424	.00
condition	1.00	18.00		30.12	354.16	1.53	.232	.01
hemisphere x condition	1.00	18.00		0.01	49.36	0.00	.955	.00
region	1.97	35.43	0.98	234.83	744.85	5.67	.008	.08
hemisphere x region	1.57	28.28	0.79	12.18	290.50	0.75	.449	.00
region x condition	1.78	32.09	0.89	12.14	134.68	1.62	.215	.00
hemisphere x region x condition	1.42	25.49	0.71	10.14	62.13	2.94	.086	.00

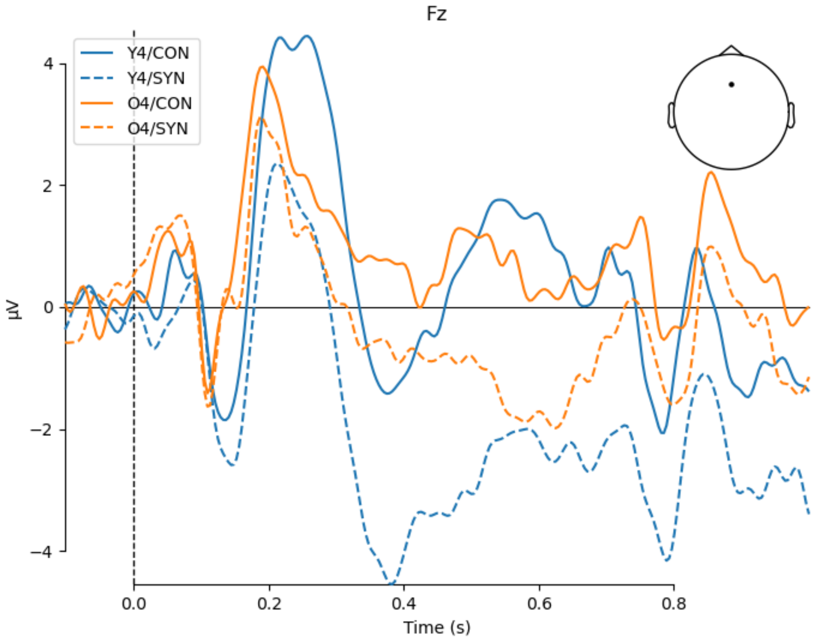
Note: The results of the three-way mixed ANOVA showed that only the main effect of region was significant, with both conditions showing the lowest mean amplitude on the anterior region (mean = -0.46) and the largest mean amplitude on the central region (mean = 1.75).

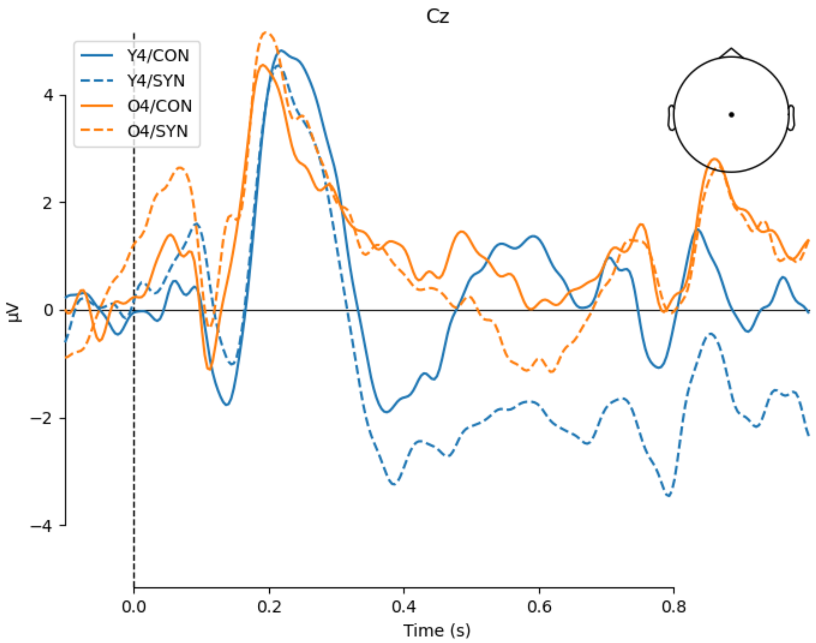
A three-way ANOVA was conducted to compare the main effects of condition (SYN or CON), region (anterior, central, or posterior), and hemisphere (left or right), as well as their interaction effects on the mean amplitude of six lateral channels in the 500-700 ms time window for the SYN and CON critical words, as shown in Table 19. Only the main effect of condition was significant [$F(1, 22) = 32.12$, $p < .0001$]. A Tukey post-hoc test revealed significant pairwise differences between the anterior region (M = -0.46, SD = 2.79) and central region (M = 1.75, SD = 3.76) (t.ratio = 3.16, $p = .0142$) as well as between the anterior region and posterior region (M = 1.63, SD = 4.00) (t.ratio = 2.69, $p = .038$), suggesting the negativity centered on the anterior regions.

6.3.2.3. Comparison between younger and older adults

In this section, we focus on the mean amplitude of difference waveform, which equals the mean amplitude of the SYN condition minus that of the CON condition. The difference waveform, rather than the SYN waveform and CON waveform was selected because it directly represented the AN effects; secondly, it was a parameter representing participants' receptive syntactic capacity, as discussed in the following sections.

A 2 (group: young vs older adults) x 2 (channel: Fz vs Cz vs Pz) ANOVA with mean amplitude of difference waveform as the dependent variable was performed to examine the differences between younger and older adults in terms of the AN effects.


Fz
Y4/CON
Y4/SYN
O4/CON
O4/SYN
µV
4
2
0
−2
−4
0.0
0.2
0.4
0.6
0.8
Time (s)


Cz
Y4/CON
Y4/SYN
O4/CON
O4/SYN
µV
4
2
0
−2
−4
0.0
0.2
0.4
0.6
0.8
Time (s)

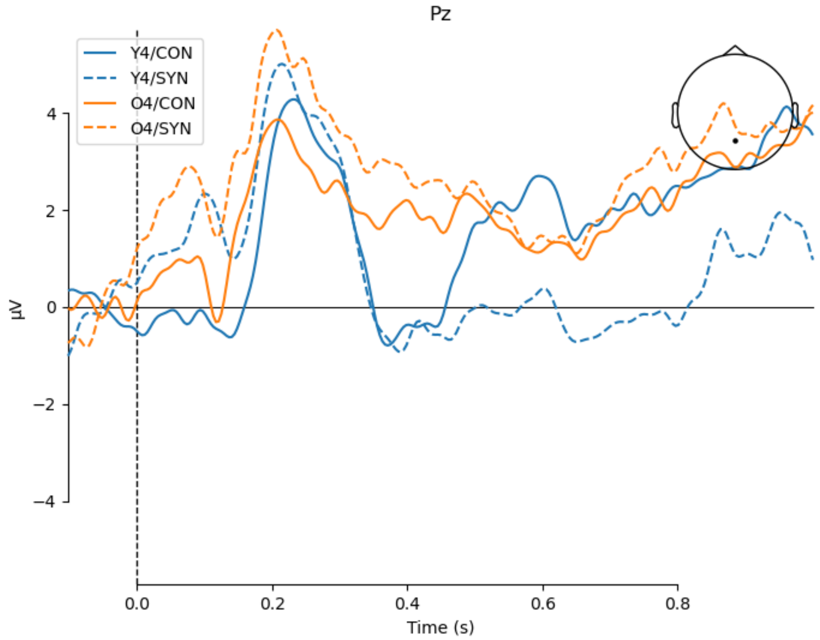


Figure 21. Grand averaged ERPs for both groups, from three middle channels, evoked by the critical words in CON and SYN conditions

Plotted are the ERP responses to critical words at three representative middle electrodes: Fz, Cz, and Pz. Negativity is plotted downwards. Responses over the frontal and central channels in the younger group were characterized by a negativity component peaking at around 350 ms, while this negativity was reduced and delayed for older adults.

As shown in Figure 21, younger adults displayed a negative response over the frontal and central channels peaking at around 350 ms, while older adults showed reduced and delayed negativity in these regions. It is noted that there was a negativity peaking at around 100 ms (N1), followed by a positivity peaking at around 250 ms (P2), which might be related to non-language-specific sensory processing (Federmeier et al., 2003).

Table 20. ANOVA results for mean amplitude of three middle channels in the 300-500 ms time window following presentation of the critical words between two groups

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g
(Intercept)	1.00	40.00		127.18	476.26	10.68	.002	.18
group	1.00	40.00		57.30	476.26	4.81	.034	.09
channel	1.72	68.66	0.86	133.06	101.01	52.69	.000	.19
group x channel	1.72	68.66	0.86	2.84	101.01	1.13	.323	.00

Note: The results of the two-way mixed ANOVA demonstrated that there was a significant main effect of group on the mean amplitude, with younger adults (mean = -1.69) showing more negative mean amplitude than older adults (mean = -0.33). In addition, there was also a significant main effect of channel, with both groups showing the lowest mean amplitude on Fz (mean = -2.39) and the largest mean amplitude on Pz (mean = 0.16). However, there was no significant interaction between condition and channel.

A two-way ANOVA was conducted to compare the main effects of group (younger or older adults) and channel (Fz, Cz, or Pz), as well as their interaction effects on the mean amplitude of three middle channels in the 300-500 ms time window for the critical words, as shown in Table 20. All the main effects were statistically significant at the .05 significance level. The main effect of group yielded an F ratio of $F(1, 40) = 4.81$, $p = .034$, indicating that the mean amplitude was significantly more negative for younger adults (M = -1.69, SD = 2.42) than for older adults (M = -0.33, SD = 2.39). The main effect of channel yielded an F ratio of $F(1, 68.66) = 52.69$, $p < .0001$. A Tukey post-hoc test revealed significant pairwise differences between Pz (M = 0.16, SD = 1.91) and Fz (M = -2.39, SD = 2.66) (t.ratio = -8.82, $p < .0001$), and between Pz and Cz (M = -0.99, SD = 2.20) (t.ratio = -5.84, $p < .0001$), as well as between Fz and Cz (t.ratio = -5.55, $p < .0001$). However, there was no significant interaction between group and channel with an F ratio of $F(1, 68.66) = 1.13$, $p = .323$. All the results suggested that older adults failed to exhibit an AN effect when reading syntactically incorrect sentences, though their neural performance exhibited AN-like distribution.

Table 21. ANOVA results for mean amplitude of three middle channels in the 500-700 ms time window following presentation of the critical words between two groups

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g
(Intercept)	1.00	40.00		441.40	859.91	20.53	.000	.31
group	1.00	40.00		111.84	859.91	5.20	.028	.10
channel	1.61	64.33	0.80	60.32	113.21	21.32	.000	.06
group x channel	1.61	64.33	0.80	5.01	113.21	1.77	.184	.01

Note: The results of the two-way mixed ANOVA demonstrated that there was a significant main effect of group on the mean amplitude, with younger adults (mean = -2.83) showing more negative mean amplitude than older adults (mean = -0.93). In addition, there was also a significant main effect of channel, with both groups showing the lowest mean amplitude on Fz (mean = -2.77) and the largest mean amplitude on Pz (mean = -1.12). However, there was no significant interaction between condition and channel.

A two-way ANOVA was conducted to compare the main effects of group (younger or older adults) and channel (Fz, Cz, or Pz), as well as their interaction effects on the mean amplitude of three middle channels in the 500-700 ms time window for the critical words, as shown in Table 21. All the main effects were statistically significant at the .05 significance level. The main effect of group yielded an F ratio of $F(1, 40) = 5.20$, $p = .028$, indicating that the mean amplitude was significantly more negative for younger adults ($M = -2.83$, $SD = 2.72$) than for older adults ($M = -0.93$, $SD = 3.09$). The main effect of channel yielded an F ratio of $F(1, 64.33) = 21.32$, $p < .0001$. A Tukey post-hoc test revealed significant pairwise differences between Pz ($M = -1.12$, $SD = 2.98$) and Fz ($M = -2.77$, $SD = 2.94$) (t.ratio = -5.56, $p < .0001$), and between Pz and Cz ($M = -2.02$, $SD = 3.01$) (t.ratio = -4.88, $p = .0001$), as well as between Fz and Cz (t.ratio = -2.83, $p = .019$). However, there was no significant interaction between group and channel with an F ratio of $F(1, 64.33) = 1.77$, $p = .184$. All the results suggested that the AN effect prolonged into the late time window for the average waveform for both groups, suggesting no P600 effect was generated. However, older adults failed to exhibit a typical AN effect.

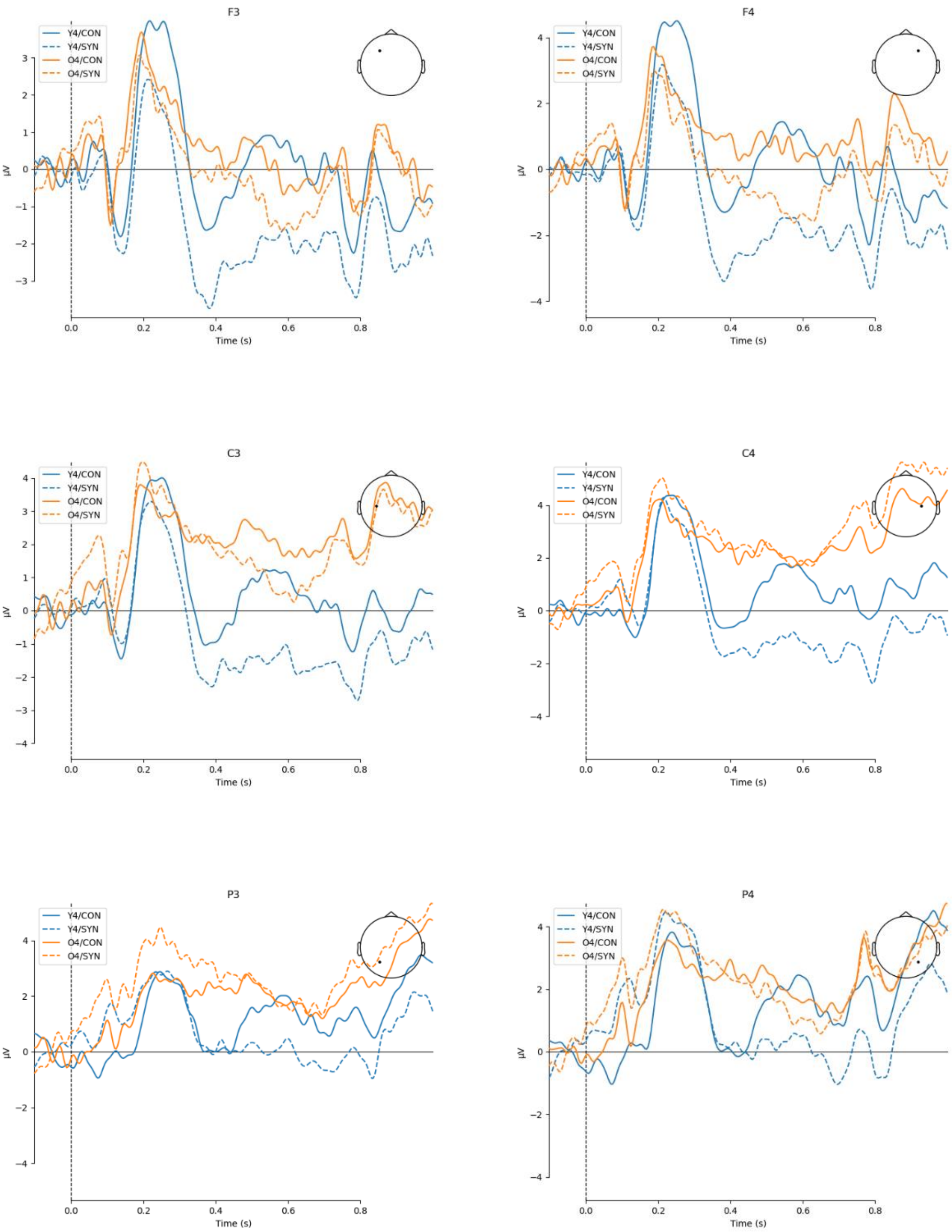


Figure 22. Grand averaged ERPs in both groups, from six lateral channels, evoked by the critical words in the CON and SYN conditions

Plotted are the ERP responses to critical words at six representative lateral electrodes: anterior (F3, F4), central (C3, C4), and posterior (P3, P4) regions. Negativity is plotted downwards. Responses over the anterior and central regions in the younger group were characterized by a negativity component peaking at around 350 ms. However, this negativity was reduced and delayed for older adults.

As shown in Figure 22, younger adults displayed a negative response over the frontal and central regions peaking at around 350 ms, while the older adults showed reduced and delayed negativity at the anterior region and the left central region. It should be noted that the N1 and P2 components were more obvious for six lateral channels compared to the three middle channels.

Table 22. ANOVA results for mean amplitude of six lateral channels in the 300-500 ms time window following presentation of the critical words between two groups

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g
(Intercept)	1.00	40.00		135.11	649.65	8.32	.006	.11
group	1.00	40.00		67.25	649.65	4.14	.049	.06
hemisphere	1.00	40.00		0.27	89.00	0.12	.731	.00
group x hemisphere	1.00	40.00		1.41	89.00	0.63	.431	.00
region	1.68	67.33	0.84	110.49	287.74	15.36	.000	.09
group x region	1.68	67.33	0.84	9.18	287.74	1.28	.282	.01
hemisphere x region	1.92	76.71	0.96	5.42	87.29	2.48	.093	.00
group x hemisphere x region	1.92	76.71	0.96	4.01	87.29	1.84	.168	.00

Note: The results of the three-way mixed ANOVA demonstrated that there was a significant main effect of region, with both groups showing the lowest mean amplitude on the anterior region (mean = -1.62) and the largest mean amplitude on the posterior region (mean = 0.04). Other main effects and interactions were not significant at the 0.05 level.

A three-way ANOVA was conducted to compare the main effects of group (younger or older adults), region (anterior, central, or posterior), and hemisphere (left or right), as well as their interaction effects on the mean amplitude of six lateral channels in the 300-500 ms time window for the critical words, as shown in Table 22. The main effect of group yielded an F ratio of F(1, 40) = 4.14, $p = .049$, indicating that the mean amplitude was significantly more negative for younger adults (M = -1.26, SD = 1.99) than for older adults (M = -0.22, SD =2.50). The main effect of channel yielded an F ratio of F(1, 67.33) = 15.36, $p < .0001$. A Tukey post-hoc test revealed significant pairwise differences between the anterior region (M = -1.62, SD = 2.23) and central region (M = -0.78, SD = 2.32) (t.ratio = -3.70, $p = .0018$), between the anterior region and posterior region (M = 0.04, SD = 2.03) (t.ratio = -4.75, *p* = 0.0001), as well as between the central region and posterior region (t.ratio = -2.61, *p* < .033). However, other main effects and interactions were not significant (*p*s > .09). All the results suggested that older adults failed to exhibit an AN effect when reading syntactically incorrect sentences, although some distribution features of their neural pattern at the three middle channels resembled the typical AN component.

Table 23. ANOVA results for mean amplitude of six lateral channels in the 500-700 ms time window following presentation of the critical words between two groups

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g
(Intercept)	1.00	40.00		522.67	1151.97	18.15	.000	.22
group	1.00	40.00		129.37	1151.97	4.49	.040	.07
hemisphere	1.00	40.00		0.63	142.98	0.18	.677	.00
group x hemisphere	1.00	40.00		0.36	142.98	0.10	.754	.00
region	1.84	73.54	0.92	39.79	350.14	4.55	.016	.02
group x region	1.84	73.54	0.92	5.77	350.14	0.66	.508	.00
hemisphere x region	1.81	72.28	0.90	10.83	170.39	2.54	.091	.01
group x hemisphere x region	1.81	72.28	0.90	11.38	170.39	2.67	.081	.01

Note: The results of the three-way mixed ANOVA demonstrated that there was a significant main effect of region, with both groups showing the lowest mean amplitude on the anterior region (mean = -1.97) and the largest mean amplitude on the posterior region (mean = -1.01). Other main effects and interactions were not significant at the 0.05 level.

A three-way ANOVA was conducted to compare the main effects of group (younger or older adults), region (anterior, central, or posterior), and hemisphere (left or right), as well as their interaction effects on the mean amplitude of six lateral channels in the 500-700 ms time window for the critical words, as shown in Table 23. The main effect of group yielded an F ratio of F(1, 40) = 4.49, *p* = .04, indicating that the mean amplitude was significantly more negative for younger adults (M = -1.97, SD = 2.16) than for older adults (M = -0.73, SD =3.32). The main effect of channel yielded an F ratio of F(1, 73.54) = 4.55, p = .016. A Tukey post-hoc test revealed significant pairwise differences between the anterior region (M = -1.97, SD = 2.76) and posterior region (M = -1.01, SD = 2.67) (t.ratio = -3.00, p = 0.0125). However, other main effects and interactions were not significant (ps > .09). All the results suggested that the AN effect prolonged into the late time window for the average waveform for both groups, suggesting no P600 effect was generated. However, older adults failed to display a typical AN effect.

6.3.3. Comparison between expressive and receptive performance

Rescaled data of expressive and receptive syntactic performance were examined with the paired Wilcoxon signed rank test to evaluate production and comprehension asymmetries. The RT and accuracy were chosen as indicators at the behavioral level while syntactic complexity and AN amplitude of the difference waveform were chosen as indicators at the neural level. It was noted that although syntactic complexity equated to behavioral performance, it directly reflected syntactic processing which is similar to the function of the AN effect. Additionally, it was different from the RT and accuracy which indicated the overall outcome of comprehending sentences and involved many other related cognitive abilities, though the main part was syntactic processing in the current task.

Table 24. Paired Wilcoxon signed rank test results for expressive and receptive syntactic performance

Variable			Median	IQR	V	p	r
Behavioral	Young	RT of production	0.80	0.22	153	0.20	0.28
		accuracy of comprehension	0.88	0.13			
	Old	RT of production	0.76	0.24	120	0.33	0.23
		accuracy of comprehension	0.90	0.31			
Neural	Young	Syntactic complexity	0.57	0.46	153	0.20	0.28

	Amplitude of AN component	0.40	0.29			
Old	Syntactic complexity	0.23	0.37	90	0.86	0.05
	Amplitude of AN component	0.26	0.41			

Note: IQR indicates interquartile range. The paired Wilcoxon signed rank tests revealed that both younger and older adults demonstrated comparable syntactic performance on expressive and receptive modalities at both the behavioral and neural levels.

According to Wilcoxon signed rank tests, as shown in Table 24, both younger adults and older adults demonstrated similar syntactic performance on expressive and receptive modalities both behaviorally and neurally. There was no PCA related to syntactic ability in older adults.

6.3.4. Correlation between syntactic abilities and memory abilities

Using the original data for all participants, Pearson correlation coefficients were computed in order to determine whether there was any linear relationship between semantic ability and memory ability. In the correlation analysis, both the declarative memory performance and the procedural memory performance on the day-two phase were taken into account because they were representative of the long-term effects of memory.

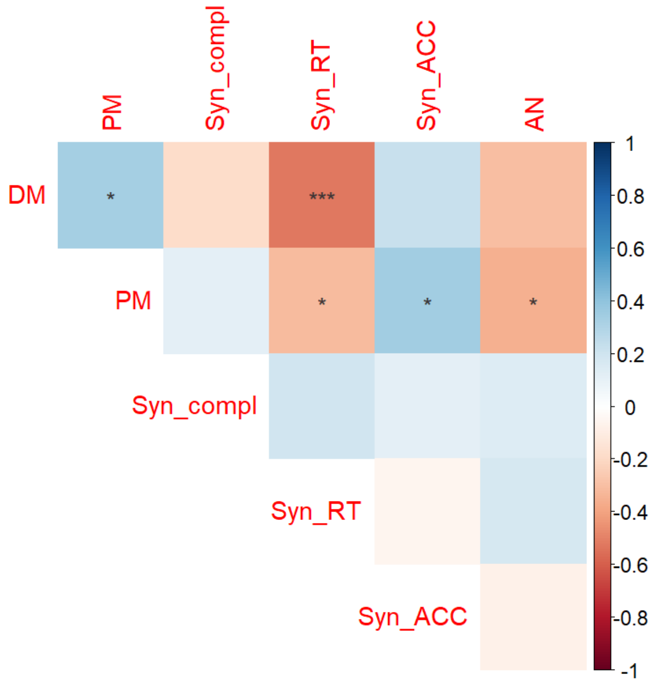


Figure 23. Correlation matrix for syntactic abilities and memory abilities for all participants
**p* < 0.05; ***p* < 0.01; ****p* < 0.001. Syn_RT, RTs of the unsuitable verb condition for the constrained production task; Syn_compl, syntactic complexity of produced sentences for the unsuitable verb condition; Syn_ACC, accuracy for the syntactic correctness judgement task.

Among all the participants [8], the PM ability was moderately negatively correlated with the RTs for the unsuitable verb condition in the constrained production task, r(38) = -.31, *p* = .049, and moderately positively correlated with the accuracy of the syntactic correctness task, r(38) = .35, *p* = .028, as well as being moderately negatively correlated with the mean amplitude of the N400 component, r(38) = -.36, *p* = .024. The DM ability was strongly negatively correlated with the RTs for the unsuitable verb condition in the constrained production task, r(38) = -.52, *p* = .0005. The results suggested that participants with better procedural memory were able to produce sentences more quickly in addition to identifying syntactic violations with greater accuracy. In contrast, individuals with superior declarative memory were only

[8] Noted that no statistically significant correlations between syntactic abilities and memory abilities were observed at the significance level of 0.05, when participants were divided into younger and older groups to calculate the Pearson correlation coefficients.

able to produce sentences faster but not to detect syntactic violations more accurately.

6.4. Discussion

This was, to our knowledge, the first study to investigate the neural mechanisms of syntactic processing in word order violations in Chinese, though our overarching aims were to examine age-related receptive syntactic changes in Chinese populations and further, to make comparisons between expressive and receptive syntactic abilities to probe PCA.

When reading a Chinese sentence with word order violations, younger adults displayed an AN effect, rather than an SPS effect. Hagoort et al. (1993) observed an SPS component when comparing neural patterns elicited by sentences with and without a word order violation on the adverb in the noun phase. He made similar findings when asking participants to listen to the same sentences, indicating a consistent SPS effect for misplacing the adverbs (Hagoort & Brown, 2000). However, the current study did not find SPS effects, though it did find AN effects when younger participants read a sentence containing a word order violation on the verb in the Ba construction. This was unlikely to be the result of the fact that the critical words in the current study were content words rather than function words, as similar AN effects have also been observed in other studies that used function words as critical words (Morgan-Short et al., 2012; Neville et al., 1991; Newman et al., 2007).

The AN effect was even sustained into the late period and extended its distribution (Friederici et al., 1993; Martín-Loeches et al., 2005). Thus, we conjecture that the AN effect reflected domain-general ability for sequential and structural manipulation, and that it was transformed to support the rule-based automatic structure-building computations in language processing, as participants relied on syntactic rules to identify if the presented words could be serially combined into a sentence with or without a congruent word order. For instance, in the current study, participants could always predict, based on the syntactic rule, what should be followed by “整理/tidy”. If it was “的”, then they could identify this sentence as correct immediately. This is due to the fact that in Chinese, there is most likely a “的/particle” in the noun phrase of the verb plus a noun structure, except in certain instances of uncommon usages, like “红烧牛肉/stewed beef”.

In terms of the age-related changes, the results revealed that there was no significant difference in terms of the accuracy rate between younger adults and older adults. Similar to younger adults, older adults were able to identify the syntactic incongruence in the online task (Waters & Caplan, 2001). Older adults preserved the ability to recognize linguistic forms and simultaneously organize them into a grammatical structure. They could only complete the online syntactic correctness judgement task with this ability intact, at least, at the behavioral level.

However, there was a significant difference between younger and older adults in terms of neural patterns when they were detecting word order violations. Younger adults exhibited a typical AN component when reading a sentence with a word order violation compared to reading a correct sentence. In contrast, older adults failed to exhibit the AN effect. Although the neural pattern of older adults seemed to demonstrate an AN-like effect, the difference waveforms between the syntactically congruent and incongruent conditions were not significant at the 0.05 level. That is to say, older adults suffer from neural decline in syntactic processing even when reading syntactically simple sentences (Kemmer et al., 2004; Zhu et al., 2018).

Moreover, we found that both younger and older adults exhibited balanced syntactic performance in expressive and receptive modalities. There seemed to be no

PCA in syntactic ability for older adults. In addition, although declarative and procedural memory systems were related to syntactic ability, the exact combinations were different in terms of the expressive and receptive modalities. This point will be elaborated on in Chapter 8, in a general discussion on syntactic and semantic production and comprehension asymmetries in older adults.

Chapter 7. Production/comprehension asymmetries in semantic processing

7.1. Introduction

It has been well-established that the N400 effect is closely related to semantic processing since it was first discovered. In that seminal study, an N400 component was observed when participants read semantically incongruent sentences compared to semantically congruent sentences (Kutas & Hillyard, 1980). Moreover, various research had reported that aging impacted this negative component, and older adults tended to exhibit a reduced negative potential (DeLong et al., 2012; Federmeier et al., 2010; Federmeier et al., 2002; Federmeier et al., 2003; Kutas & Iragui, 1998; Zhu et al., 2019), for a review, see Joyal et al. (2020). For instance, Kutas and Iragui (1998) found that there was an N400 congruity effect when participants performed a semantic categorization task, and this N400 effect decreased linearly in amplitude with age. The N400 effect was a robust indicator to demonstrate age-related changes in receptive semantic abilities.

In addition to the N400 effect, there seemed to be a late positive component (LPC)[9] when readers comprehended a sentence containing a word that violated the semantic constraints, for a review, see Van Petten and Luka (2012). Additionally, it seemed that the LPC effect connected the expressive modality and the receptive modality for older adults, as it was correlated with verbal fluency scores (Federmeier et al., 2010). Older adults who displayed a greater LPC effect tended to generate more words in a category fluency task. However, it remains unclear whether the LPC effect

[9] It is noted that recent research reported there was a semantic readiness potential or semantic prediction potential appeared before the critical words were presented to the participants (Grisoni et al., 2017; Grisoni et al.,2019; Grisoni et al.,2021). However, the current study focused on the N400 effect and LPC effect, as there were robust evidence suggesting these two effects displayed age-related changes.

is associated with expressive semantic ability at the sentence level.

Research based on Chinses populations has found that ChOA performed worse at both the behavioral and neural levels with a low accuracy rate in identifying semantic incongruency and reduced N400 mean amplitude (Xu et al., 2020; N. N. Xu et al., 2017; Zhu et al., 2018). In addition, the age-related changes in the N400 effect were not related to working memory (Zhu et al., 2019), and were not prevented by increased world knowledge (Xu et al., 2020). A similar LPC component was also observed when ChOA read semantically incongruent sentences compared to congruent sentences (N. N. Xu et al., 2017).

In the current study, we recycled some of the experimental stimuli from the study of Ye et al. (2006). The semantically congruent sentences with a Ba construction were paired with corresponding semantically incongruent sentences. Subjects were asked to identify whether a sentence was semantically correct in order to measure their receptive semantic abilities and ultimately compare it with their expressive semantic abilities and memory abilities. In line with previous studies, we predicted that older adults would exhibit a low accuracy rate and reduced N400 effects. We posited that, unlike younger adults, older adults, based on retrogenesis theory, may display semantic PCA. Moreover, we hypothesized that it was likely that receptive semantic ability was related to DM ability.

7.2. Methods

7.2.1. Subjects

Data from 24 Chinese younger adults (mean age = 24.1 ± 2.7, range = 19-30; 11 males) and 24 healthy ChOA (mean age = 68.4 ± 2.6, range = 65-76; 11 males) were included for receptive semantic ability analysis in this section. To ensure that the sample size was matched for the following analysis on both semantic and syntactic production and comprehension asymmetries, three younger adults and five older adults were excluded. These participants were rejected as their reject rates for the syntactic correctness judgement task were too high. For more details, see Section 6.2.4.1. As a result, 40 subjects remained for the analysis of production and comprehension asymmetries.

7.2.2. Stimuli

There were four types of sentences given in all conditions, including congruent and incongruent experimental sentences as well as congruent and incongruent filler sentences, as shown in Table 25. Each condition was made up of 60 stimuli. In total there were 240 sentences.

Table 25. Example sentences used in semantic comprehension tasks

Condition	Stimuli
Congruent sentence (CON)	园丁/整理/花园，把/杂草/**拔**/了。 Gardener/trim/garden, Ba/weed/pull/ aspect particle The gardener pulled up the weeds when trimming the garden.
Semantically incongruent sentence (SEM)	*园丁/整理/花园，把/杂草/**宰**/了。 Gardener/trim/garden, Ba/weed/kill/ aspect particle *The gardener killed the weeds when trimming the garden.
Congruent filler	村民/办/酒席，特地/请来/**村支书**/了。 villager/prepare/banquet, particularly/invite/village secretary/aspect particle Villagers prepared a banquet and particularly invited the village secretary.
Incongruent filler	*村民/办/酒席，特地/购买/**村支书**/了。 villager/prepare/banquet, particularly/buy/village secretary/aspect particle *Villagers prepared a banquet and particularly bought the village secretary.

Note: In all the sentences, the critical word appears as the penultimate word of the sentence and has been highlighted in bold. In each example sentence, the first line is the stimuli in Mandarin with slash marks between words. On the second line, the pinyin for each word is presented. On the third line, the English translation is given for each word. Below that the full meaning of the sentence is given. An asterisk is placed next to the incongruent sentence.

The two types of experimental sentences were replicated from Ye et al. (2006).

Although the experimental sentences were originally used as auditory stimuli, they can also be used in the visual modality without significant discrepancy (Hagoort & Brown, 2000). These sentences were obtained using the constraints listed below. Firstly, there was a greater likelihood that the critical words would be interpreted as verbs rather than as nouns or adjectives. Secondly, the frequency of the critical verb was matched for congruent and incongruent conditions. Thirdly, the syntactic structure and information structure of all the sentences were well-designed. Fourthly, semantic compatibility was controlled for in both conditions. Following these constraints, we designed the filler sentences.

7.2.3. Procedures

The procedure for the syntactic correctness judgement task closely followed that of the previous semantic correctness judgement task. The stimuli were presented on an LCD screen via a Surface Book 2 PC laptop running Windows 10, using E-Prime version 3.0 (Psychology Software Tools). All Chinese sinograms were presented using the Simsun font at a size of 100. All the sinograms were white and on a black background. In each semantic comprehension trial, a cross fixation was centered on the screen for 1000 milliseconds after a random period of 500, 1000, or 1500 milliseconds of a blank black screen. When the fixation disappeared, the first word was immediately presented in the center of the screen and displayed for 500 milliseconds. There was then an ISI of 100 milliseconds with a blank screen before the next word appeared. Following the final word disappearing from the screen, a response interface was presented to remind the subject to press the left or right buttons according to the "correct" or "incorrect" answer. The response interface remained on the screen until a reply was provided, or lasted for a maximum period of 3000 milliseconds if subjects didn’t reply.

EEG recording was undertaken using similar settings to those used for the receptive semantic tasks. During the experiment, each participant sat about 100cm away from the LCD monitor that displayed the experimental stimuli in a quiet and dark room. An ActiveTwo 32-channel EEG system (BioSemi B.V., Amsterdam, The Netherlands) with Ag/AgCl active electrodes was used to obtain the EEG data. The electrodes were placed in the following positions: Fp1, Fp2, AF3, AF4, Fz, F3, F4, F7, F8, FC1, FC2, FC5, FC6, Cz, C3, C4, T7, T8, CP1, CP2, CP5, CP6, Pz, P3, P4, P7, P8, PO3, PO4, Oz, O1, and O2 (Acharya et al., 2016). Two additional electrodes were employed to support a feedback loop to drive the average electrical potential as closely as possible to the amplifier reference voltage (BioSemi, 2017). These electrodes were placed on either side of the vertex at positions C1 and C2, respectively. A 0.1 Hz to 40 Hz digital bandpass filter was applied to the EEG data which were sampled at a rate of 1024 Hz. Vertical/horizontal electro-oculograms (HEOG/VEOG) were collected with four electrodes which were stuck near the two outer canthi, and above /below the left eye respectively. There was no online artifact correction applied to tackle eye blinks and eye movements. To allow offline re-referencing in the subsequent data processing, two additional electrodes were placed on both mastoids.

7.2.4. Data analysis

7.2.4.1. EEG data preprocessing

The preprocessing of EEG data was performed according to the standard analysis pipelines provided by MNE-Python (Gramfort et al., 2013; Gramfort et al., 2014). The raw EEG data were firstly downsampled to 256 Hz and then re-referenced to the average mastoid. The power line frequency was set as 50 Hz as the EEG data were collected in mainland China and Hong Kong. After that, a filter between 0.1 and 30 Hz was applied to the data. Stimulus-locked epochs were obtained from 100 ms pre-stimulus to 1000 ms post-stimulus. The pre-stimulus 100 ms was used for the baseline correction. The ICA method was used for artifact repair with the picard algorithm provided by the MNE-Python built-in modules. For the following artifact rejection, only trials with correct responses were considered. Epochs with voltage fluctuation of over 200 μV or below 1μV in any of the scalp electrodes were excluded. Besides, eye movements or blinks with a threshold of 150 μV were rejected for each epoch. By averaging the artifact-free epochs, the stimulus-locked ERPs could be derived for each condition. The overall rejection rate was 15.59% for younger adults, and equal for both two conditions (SEM: 18.19%, CON: 12.99%). The overall rejection rate was 24.72% for older adults, and equal for both two conditions (SEM: 25.83%, CON: 23.61%).

Peak latency and mean amplitude were measured based on procedures which were frequently utilized in previous studies (Federmeier et al., 2010; Kutas & Iragui, 1998; Wlotko & Federmeier, 2012; Zhu et al., 2018). Peak latency of the N400 effects was assessed according to the difference waveforms derived from a point-by-point subtraction of the ERPs to correct sentences from the ERPs to anomalous sentences. A time window of 300-500 ms was set to scan the largest N400 effects for both younger adults and older adults at six central-posterior electrode sites (C3, Cz, C4, P3, Pz, P4) in which N400 effects are typically reported to be maximal (Federmeier & Kutas, 2005; Wlotko et al., 2012). The peak of N400 effects was located at around 420 ms for both groups (younger adults: $M = 415$, $SD = 40.4$; older adults: $M = 424$, $SD = 56.8$; $F(1,42) = 0.4$, $p = .53$, $MSE = 14770.94$). After obtaining the time point of the largest effects, a 200 ms window from 320 ms to 520 ms which centered around the peak latency was selected to measure the mean amplitude at all electrode sites. Regarding the LPC effect, a time window from 500 ms to 700 ms was chosen on the basis of visual inspection and earlier studies (Federmeier et al., 2003; Federmeier et al., 2007; Van Petten & Luka, 2012). The mean amplitudes in the selected time windows were used in all statistical analyses. Three electrodes at the middle line (Fz, Cz, Pz) and six lateral electrodes (F3, F4, C3, C4, P3, P4) were selected as the representative data for statistical analysis. ERPs from the midline and lateral electrodes were analyzed separately. Omnibus ANOVAs for midline electrodes included two within-subject factors: electrode (Fz/Cz/Pz) and condition (SYN/CON). Omnibus ANOVAs for lateral electrodes included three within-subject factors: hemisphere (left/right), region (anterior/central/posterior), and condition. Crossing the variables of region and hemisphere yielded six regions of interest, with one representative electrode for each region of interest: left anterior (F3), left central (C3), left posterior (P3), right anterior (F4), right central (C4), and right posterior (P4). The group (younger/older), as a between-subject factor, was added into the models when comparing differences between two groups.

7.2.4.2. Analysis of asymmetry and correlation

The procedure for analysis of semantic PCA and correlation between memory abilities and semantic abilities was similar to that used to analyze syntactic abilities, as described in detail in the previous chapter. Here the main steps are described again.

To evaluate semantic PCA, the data for constrained production tasks in the suitable Ba condition and data for semantic correctness judgement tasks were rescaled via the min-max normalization (Suarez-Alvarez et al., 2012). Expressive semantic ability was represented by the RT for the constrained production task and the semantic complexity of the sentences that participants produced in the task. Receptive semantic ability was assessed by using the accuracy of the semantic correctness judgement task and the mean amplitude of the N400 and LPC components. Only ERP data from the Pz electrode were used to represent N400, as it was centro-parietally distributed. And only ERP data from the Fz electrodes were used to represent LPC, as it was distributed and peaked at the frontal region. The RT and N400 amplitude were reversed when computing normalization, as shorter RT and more negative amplitude represented better abilities.

The data for younger adults and older adults were rescaled separately, and paired Wilcoxon signed rank tests were applied to the rescaled data. If expressive semantic performance and receptive semantic performance differed significantly, there was semantic PCA, and vice versa. We then tested whether declarative memory and procedural memory performances were correlated with expressive and receptive semantic performance. Correlation analysis was performed on the original data from all participants.

7.3. Results

7.3.1. Behavioral results

Behavioral results were analyzed solely based on accuracy (rather than RT) because the subject had to respond after the whole sentence had been delivered, as opposed to identifying the correctness of the sentence immediately after the critical word was delivered.

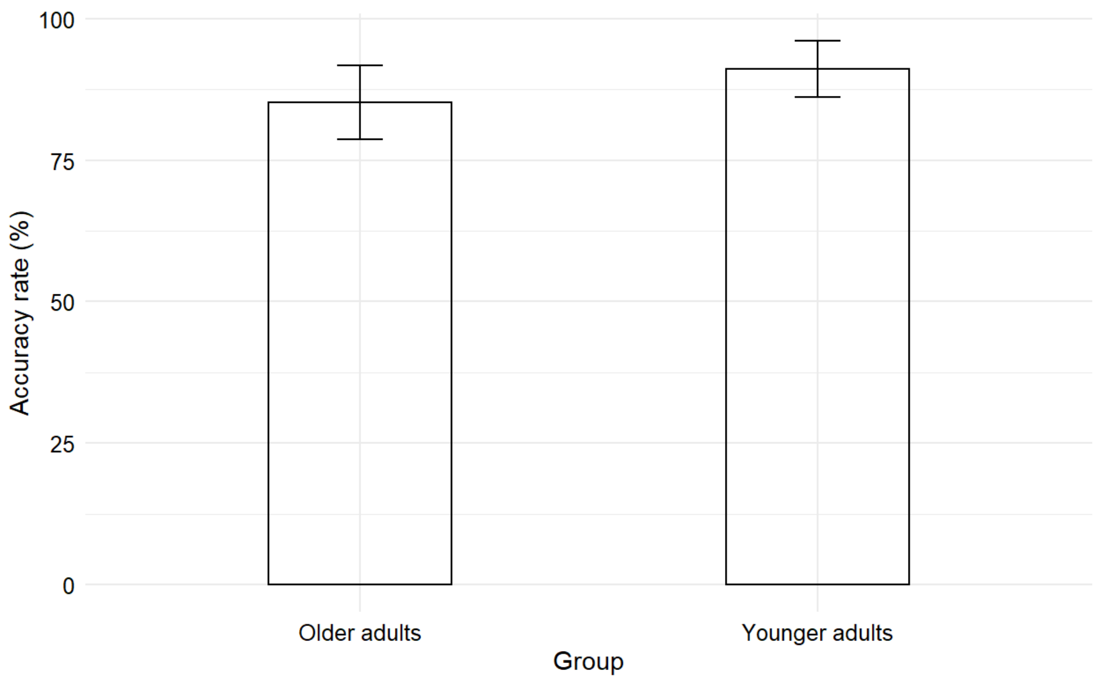
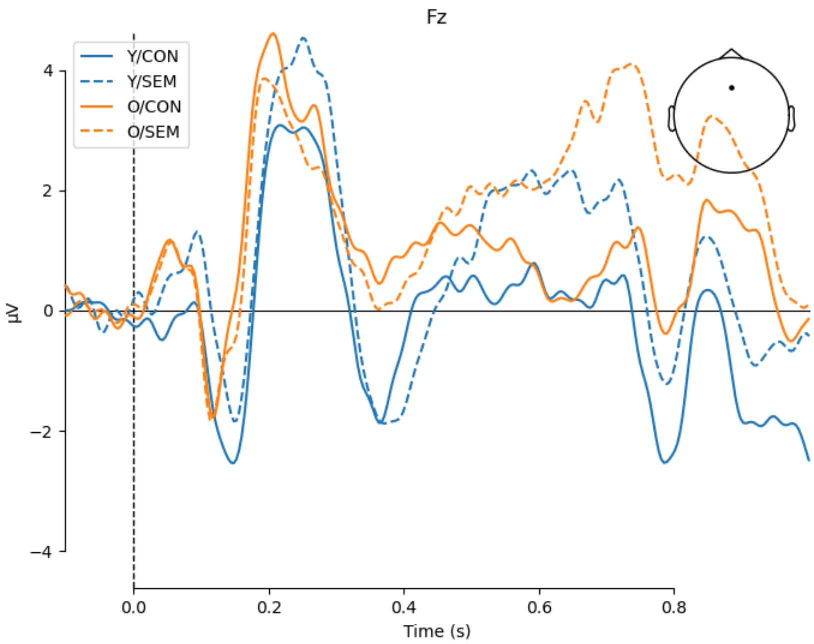


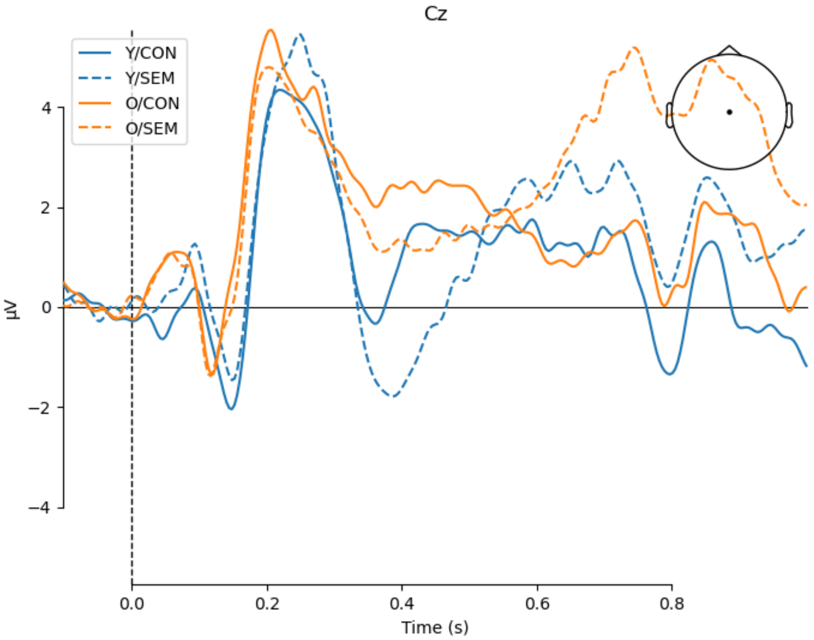
Figure 24. Mean accuracy rate for semantic correctness judgement task by Group
Younger adults performed much better than older adults in identifying semantic anomalies.

As shown in Figure 24, the mean accuracy rate for the semantic correctness judgement task in the older group was 85.14 (SD = 6.53), whereas the mean in the younger group was 91.15 (SD = 5.01). A student two-sample t-test showed that the difference was statistically significant, t(46) = -20.8, *p* < .001, d = -1.03, indicating a large effect size.

7.3.2. EEG results

ERP responses to critical words were examined to identify age-related changes in the size of the N400 and LPC components. The 300 to 500 ms time window was first probed, at three middle electrodes and six lateral electrodes, respectively. Then, we investigated the 500 to 900 ms time window at these electrodes again to evaluate the LPC component.





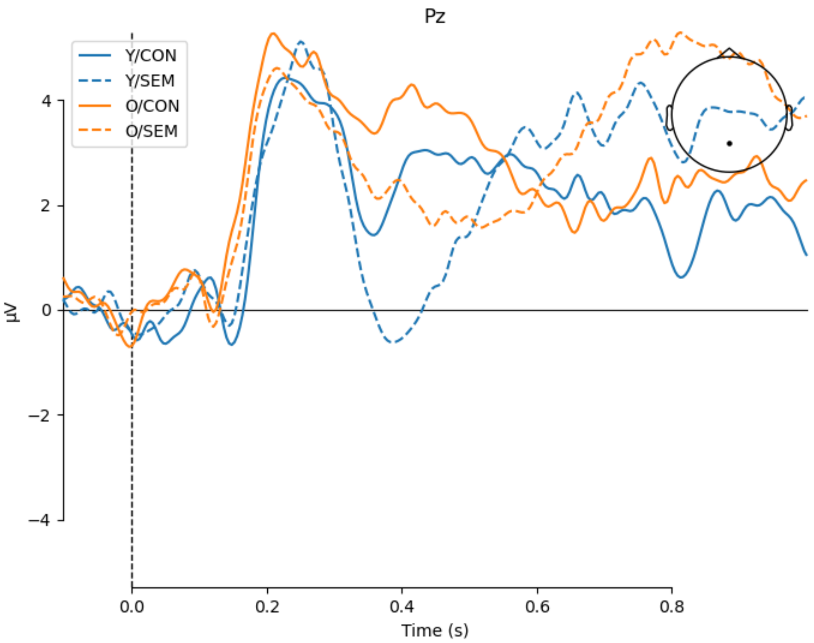


Figure 25. Grand averaged ERPs in both groups, from the three middle channels, evoked by the critical words in the SEM and CON conditions

Plotted are the ERP responses to critical words at three representative middle electrodes: Fz, Cz, and Pz. The negative voltage is plotted downwards. Responses in both groups were characterized by a negativity peaking at around 350 ms (N400) over the central and parietal channels, followed by a positivity peaking at around 700 ms (LPC) over the three middle channels.

As shown in Figure 25, both groups displayed a negative response over the central and parietal channels peaking at around 350 ms. This was followed by a positive peak at around 700 ms (LPC) over three channels. Compared to younger adults, older adults exhibited a reduced N400 effect size and an enlarged LPC effect size. It should be noted that both groups displayed a negativity peaking at around 100 ms (N1), followed by a positivity peaking at around 250 ms (P2), which might be related to non-language-specific sensory processing (Federmeier et al., 2003).

Table 26. ANOVA results for mean amplitude of the three middle channels in the 320-520 ms time window following presentation of the SEM and CON critical words between the two groups

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g
(Intercept)	1.00	46.00		439.88	1668.50	12.13	.001	.16
group	1.00	46.00		161.31	1668.50	4.45	.040	.07
condition	1.00	46.00		86.32	361.50	10.98	.002	.04
group x condition	1.00	46.00		0.72	361.50	0.09	.763	.00
channel	1.42	65.48	0.71	184.73	209.80	40.50	.000	.07
group x channel	1.42	65.48	0.71	0.98	209.80	0.22	.730	.00
channel x condition	1.73	79.74	0.87	41.04	51.63	36.57	.000	.02
group x channel x condition	1.73	79.74	0.87	0.37	51.63	0.33	.687	.00

Note: The results of the three-way mixed ANOVA demonstrated that there were no significant interactions related to group factor, suggesting that on the three middle channels, N400 effects were similar between the younger and older adults.

A three-way ANOVA was conducted to compare the main effects of group (younger or older adults), condition (SEM or CON), and channel (Fz, Cz, or Pz), as well as their interaction effects on the mean amplitude of three middle channels in the 320-520 ms time window for the critical words, as shown in Table 26. All the main effects were statistically significant at the .05 significance level. Moreover, there was a significant interaction between channel and condition with an F ratio of $F(1, 79.74) = 36.57$, $p < .0001$. Following up on this interaction, post hoc analyses revealed that the mean amplitude of the average value for both groups between two conditions differed significantly in Cz (SEM: M = 0.47, SD = 2.95; CON: M = 1.72, SD = 3.17; t.ratio = -3.37, p = .0178) and Pz (SEM: M = 1.31, SD = 2.49; CON: M = 3.24, SD = 2.98; t.ratio = -5.77, p < .0001). All the results suggested that younger adults and older adults demonstrated similar N400 effects distributed in the central and parietal regions across the middle line.

Table 27. ANOVA results for mean amplitude of three middle channels in the 500-900 ms time window following presentation of the SEM and CON critical words between two groups

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	F	p	η^2_g
(Intercept)	1.00	46.00		1149.74	2077.70	25.46	.000	.29
group	1.00	46.00		53.98	2077.70	1.20	.280	.02
condition	1.00	46.00		173.47	354.46	22.51	.000	.06
group x condition	1.00	46.00		4.87	354.46	0.63	.431	.00
channel	1.55	71.49	0.78	154.69	254.73	27.94	.000	.05
group x channel	1.55	71.49	0.78	9.32	254.73	1.68	.198	.00
channel x condition	1.68	77.49	0.84	3.31	97.37	1.56	.218	.00
group x channel x condition	1.68	77.49	0.84	3.34	97.37	1.58	.215	.00

Note: The results of the three-way mixed ANOVA demonstrated that there were no significant interactions related to group factor, suggesting that in the three middle channels, both younger adults and older adults exhibited a late positive component.

A three-way ANOVA was conducted to compare the main effects of group (younger or older adults), condition (SEM or CON), and channel (Fz, Cz, or Pz), as well as their interaction effects on the mean amplitude for the three middle channels in the 500-900 ms time window for the critical words, as shown in Table 27. The main effect of condition yielded an F ratio of F(1, 46) = 22.51, p < .0001, indicating that the mean amplitude was significantly more positive for the SEM condition (M = 2.77, SD = 3.30) than for the CON condition (M = 1.22, SD = 3.19). This suggests that the younger adults and older adults demonstrated a similar neural pattern that an LPC component was distributed across the three middle channels.

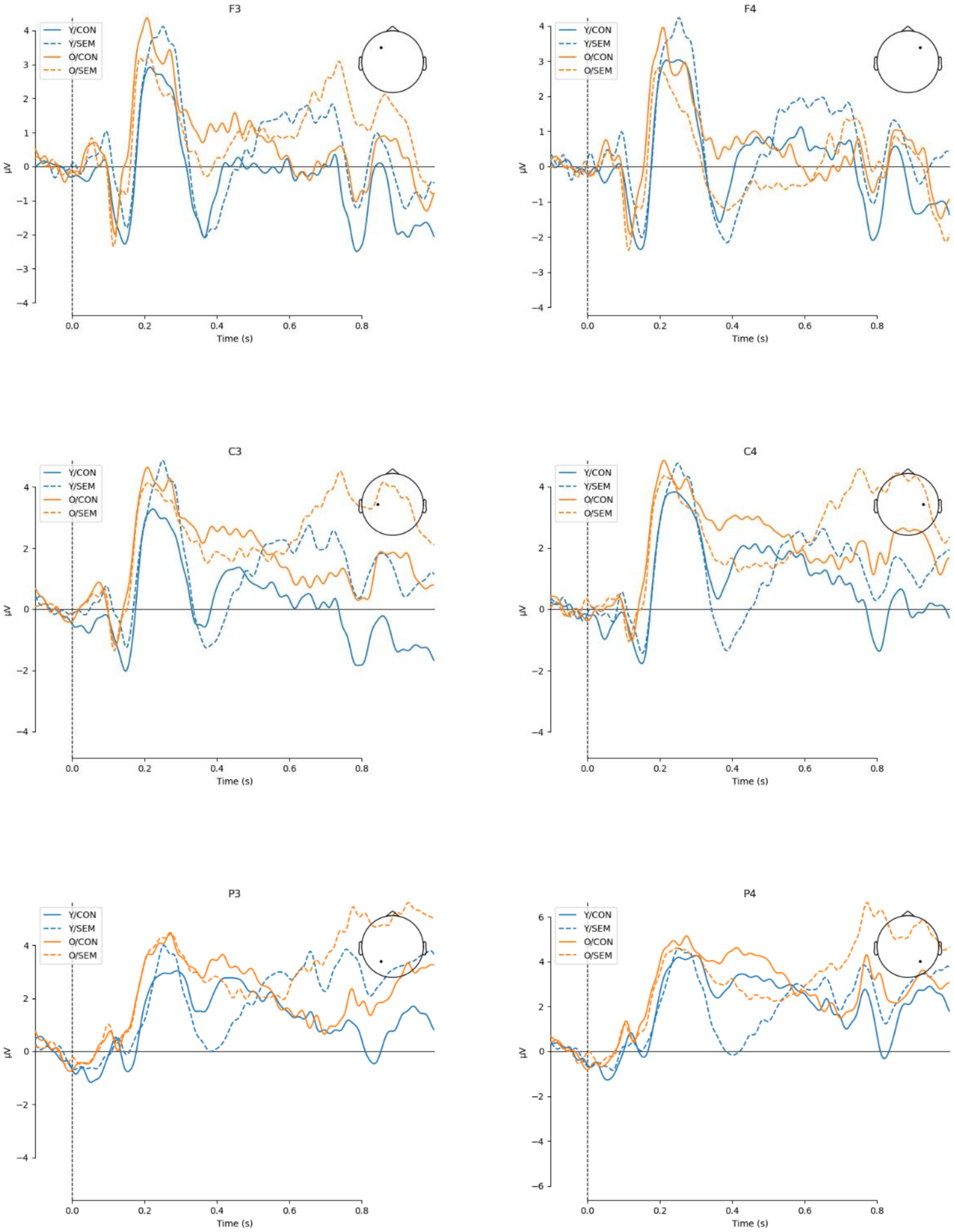


Figure 26. Grand averaged ERPs for both groups, from six lateral channels, evoked by the critical words in the SEM and CON conditions

Plotted are the ERP responses to critical words at six representative lateral electrodes: for the anterior (F3, F4), central (C3, C4), and posterior (P3, P4) regions. The negative voltage is plotted downwards. Responses over the anterior and central regions in the younger group were characterized by a negative component peaking at around 350 ms. However, this negativity was reduced and delayed for older adults.

As shown in Figure 26, both groups displayed a negative response over the central and parietal channels peaking at around 350 ms. This was followed by a positive peaking at around 700 ms (LPC) over three channels. Compared to the younger adults, the older adults exhibited reduced N400 effects and enlarged LPC effects.

Table 28. ANOVA results for mean amplitude of six lateral channels in the 320-520 ms time window following presentation of the SEM and CON critical words between two groups

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g
(Intercept)	1.00	46.00		953.59	2658.92	16.50	.000	.17
group	1.00	46.00		258.20	2658.92	4.47	.040	.05
condition	1.00	46.00		162.98	581.57	12.89	.001	.03
hemisphere	1.00	46.00		3.13	109.91	1.31	.258	.00
group x condition	1.00	46.00		0.00	581.57	0.00	.998	.00
group x hemisphere	1.00	46.00		5.18	109.91	2.17	.148	.00
condition x hemisphere	1.00	46.00		27.28	61.07	20.55	.000	.01
group x condition x hemisphere	1.00	46.00		0.00	61.07	0.00	.981	.00
region	1.17	53.65	0.58	651.87	948.32	31.62	.000	.12
group x region	1.17	53.65	0.58	19.11	948.32	0.93	.355	.00
condition x region	1.22	56.00	0.61	9.91	248.49	1.83	.180	.00
hemisphere x region	1.80	82.58	0.90	16.58	78.10	9.77	.000	.00
group x condition x region	1.22	56.00	0.61	12.78	248.49	2.37	.124	.00
group x hemisphere x region	1.80	82.58	0.90	11.82	78.10	6.96	.002	.00
condition x hemisphere x region	1.94	89.20	0.97	0.11	44.83	0.11	.889	.00
group x condition x hemisphere x region	1.94	89.20	0.97	0.91	44.83	0.93	.396	.00

Note: The results of the multivariate analysis of variance (MANOVA) demonstrated that there were significant interactions between the hemisphere and condition, between the hemisphere and region, as well as between the group, hemisphere, and region.

A MANOVA was conducted to compare the main effects of group (younger or older adults), condition (SEM or CON), hemisphere (left or right), and region (anterior, central, or posterior), as well as their interaction effects on the mean amplitude for six lateral channels in the 320-520 ms time window for the critical words, as shown in Table 28. The main effect of group yielded an F ratio of $F(1, 46) = 4.47$, $p = .04$, indicating that the mean amplitude was significantly more negative for younger adults (M = 0.62, SD = 3.13) than for older adults (M = 1.96, SD = 3.14). The main effect of condition yielded an F ratio of $F(1, 46) = 12.89$, $p = .001$, indicating that the mean amplitude was significantly more negative for the SEM condition (M = 0.76, SD = 3.23) than for the CON condition (M = 1.82, SD = 3.10). Moreover, there was a significant interaction between hemisphere and condition with an F ratio of $F(1, 46) = 20.55$, $p < .0001$. Following up on this interaction, post hoc analyses revealed that the mean amplitude between two conditions significantly differed on the right hemisphere (SEM: M = 0.61, SD = 3.45; CON: M = 2.11, SD = 3.22; t.ratio = -4.87, $p < .0001$). There were significant interactions by group by hemisphere and by region [$F(1, 82.58) = 6.96$, $p = .002$]. Simple main effects revealed that, firstly, only older adults showed a significant hemispheric difference in the anterior and posterior regions for the average mean amplitude for both conditions (*ps* < .01); secondly, younger adults showed a significant difference for the average mean amplitude between the central region and posterior region in both hemispheres (*ps* < .01), while older adults exhibited this feature only in the right hemisphere ($p < .00001$) and showed significant differences between the anterior region and central region (*ps* < .01); thirdly, younger adults showed significantly more negative average amplitude than older adults in the central region in both hemispheres and the posterior region in right hemisphere (*ps* < .05). To sum up, though there were no significant differences in terms of the semantic effects (SEM-CON) between the two groups in six lateral channels, the average mean amplitude for the SEM condition and the COM condition differed in the central region and right posterior region between younger and older adults.

Table 29. ANOVA results for the mean amplitude of six lateral channels in the 500-900 ms time window following presentation of the SEM and CON critical words between the two groups

Predictor	df_{Num}	df_{Den}	*Epsilon*	SS_{Num}	SS_{Den}	*F*	*p*	η^2_g
(Intercept)	1.00	46.00		1475.04	3244.45	20.91	.000	.20
group	1.00	46.00		107.27	3244.45	1.52	.224	.02
condition	1.00	46.00		261.56	561.50	21.43	.000	.04
hemisphere	1.00	46.00		9.26	143.49	2.97	.092	.00
group x condition	1.00	46.00		0.49	561.50	0.04	.842	.00
group x hemisphere	1.00	46.00		1.79	143.49	0.58	.452	.00
condition x hemisphere	1.00	46.00		27.91	86.37	14.87	.000	.00
group x condition x hemisphere	1.00	46.00		0.01	86.37	0.01	.931	.00
region	1.11	51.09	0.56	470.07	1472.94	14.68	.000	.07
group x region	1.11	51.09	0.56	39.86	1472.94	1.24	.275	.01
condition x region	1.33	61.22	0.67	11.55	325.04	1.64	.208	.00
hemisphere x region	1.81	83.24	0.90	11.37	131.71	3.97	.026	.00
group x condition x region	1.33	61.22	0.67	6.69	325.04	0.95	.360	.00
group x hemisphere x region	1.81	83.24	0.90	15.74	131.71	5.50	.007	.00
condition x hemisphere x region	1.97	90.71	0.99	0.17	86.45	0.09	.909	.00
group x condition x hemisphere x region	1.97	90.71	0.99	6.00	86.45	3.19	.046	.00

Note: The results for the MANOVA demonstrated that there was a significant main effect of condition and a significant main effect of region on the mean amplitude. In addition, there was a significant group by condition by hemisphere by region interaction.

A MANOVA was conducted to compare the main effects of group (younger or older adults), condition (SEM or CON), hemisphere (left or right), and region (anterior, central, or posterior), as well as their interaction effects on the mean amplitude of six lateral channels in the 500-900 ms time window for the critical words, as shown in Table 29. There were significant interactions among group, condition, hemisphere, and region [F(1, 90.71) = 3.19, p = .046]. Simple main effects revealed that both younger and older adults exhibited a significant difference in the mean amplitude between the SEM condition and CON condition in the anterior region and posterior region in the left hemisphere (ps < .05), while only older adults showed larger mean amplitude in the SEM condition compared to the CON condition in the right posterior region (p = .0056). This suggested that compared to younger adults, older adults need to exploit additional neural resources from the right hemisphere to complete semantic processing.

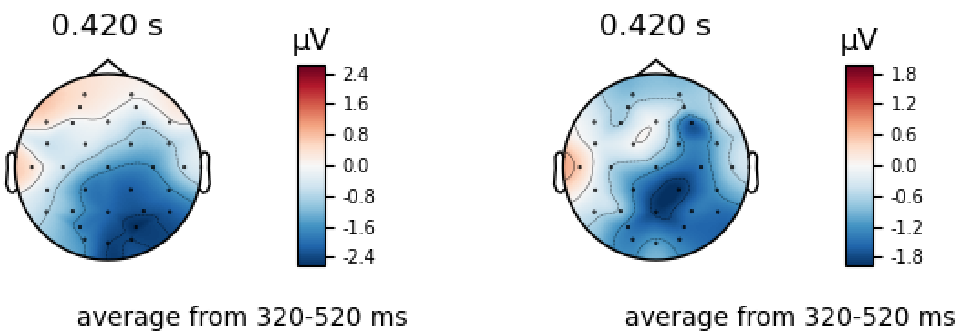


Figure 27. Topographic distribution of the condition difference (SEM - CON) in the 320-520 ms time window for the critical words in younger (left) and older (right) adults

The figure on the left-hand side represents the topographic distribution of the semantic effect in younger adults from 320 to 520 ms after the critical word onset, while the right-hand side represents that of older adults. The semantic effects for both groups were distributed across the central parietal regions and tended to be more prominent in the right hemisphere.

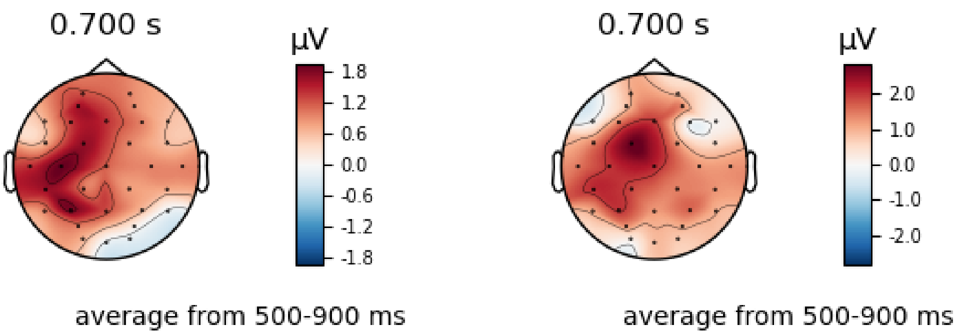


Figure 28. Topographic distribution of the condition difference (SEM - CON) in the 500-900 ms time window for the critical words in younger (left) and older (right) adults

The figure on the left-hand side represents the topographic distribution of the semantic effect in younger adults from 500 to 900 ms after the critical word onset, while the right-hand side represents that of older adults. Though the semantic effects of both groups were distributed in the central regions of the left hemisphere, older adults showed a relative peak in the posterior region of the right hemisphere.

As shown in Figure 27 and Figure 28, younger adults and older adults exhibited similar neural patterns in both time windows. Both groups demonstrated N400 effects and LPC effects when reading sentences with semantic violations. However, the distribution of the two neural components was slightly different between the two groups, and the difference was more prominent for the LPC component.

7.3.3. Comparison between expressive and receptive performance

To assess production and comprehension asymmetries, rescaled data for expressive and receptive semantic performance were evaluated with the paired Wilcoxon signed rank test. The test was similar to that for syntactic performance in that the RT and accuracy were chosen as measures to indicate the behavioral level while the semantic complexity and AN amplitude were chosen as indicators at the neural level. It should be noted that semantic complexity was derived from the behavioral results. In spite of this, it directly reflected the semantic processing, which is the same as the AN effect. Additionally, the semantic complexity differed from both RT and accuracy which were both the overall measures for comprehending sentences and involved many other cognitive abilities, although the most prominent aspect was semantic processing.

Table 30. Paired Wilcoxon signed rank test results for expressive and receptive semantic performance

Variable			Median	IQR	V	*p*	r
Behavioral	Young	RT of production	0.80	0.35	114	0.97	0.01
		accuracy of comprehension	0.72	0.32			
	Old	RT of production	0.77	0.51	93	0.95	0.02
		accuracy of comprehension	0.70	0.18			
Neural	Young	Semantic complexity	0.53	0.45	156	0.17	0.31
		Amplitude of N400[10]	0.72	0.31			
	Old	Semantic complexity	0.20	0.20	158	0.009	0.58
		Amplitude of N400	0.49	0.21			

Note: IQR indicates interquartile range. The paired Wilcoxon signed rank tests suggested that younger adults demonstrated parallel semantic performance for the expressive and receptive modalities at both the behavioral and neural levels. In contrast, older adults showed semantic PCA at the neural level but not the behavioral level.

As shown in Table 30, the Wilcoxon signed rank tests demonstrated that younger adults displayed similar semantic performances in the expressive and receptive modalities both behaviorally and neurally. However, older adults showed a neural but not behavioral asymmetry in semantic production and comprehension.

7.3.4. Correlation between semantic abilities and memory abilities

Pearson correlation coefficients were computed on the original data for all the participants to assess the linear relationship between semantic abilities and memory abilities. Since the declarative and procedural memory performance on the day-two phase were indicative of long-term memory effects, they were taken into consideration

[10] The mean amplitude of LPC was not presented in the table as it exhibited similar asymmetrical pattern as the N400 (Young: V = 155, *p* = .90, r = 0.03; Old: V = 79, *p* = .04, r = 0.41).

in the correlation analysis.

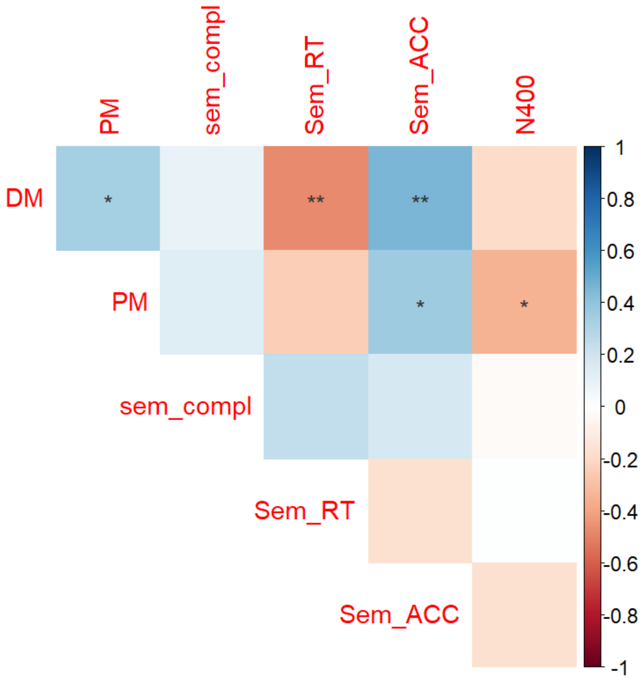


Figure 29. Correlation matrix for semantic abilities and memory abilities for all participants

**p* < 0.05; ***p* < 0.01; ****p* < 0.001. Sem_RT, RTs for the suitable verb condition for the constrained production task; Sem_compl, semantic complexity for produced sentences for the unsuitable verb condition; Sem_ACC, accuracy for the semantic correctness judgement task. The LPC effect was not included, as no statistically significant correlations were observed between it and others at the 0.05 significance level.

Among all the participants[11], the DM ability was moderately negatively correlated with the RTs for the unsuitable verb condition for the constrained production task, r(38) = -.48, *p* = .002, and moderately positively correlated with accuracy for the semantic correctness task, r(38) = .45, *p* = .003. The PM ability was moderately positively correlated with accuracy for the semantic correctness task, r(38) = .36, *p* = .024, and moderately positively correlated with mean amplitude for the N400 component, r(38) = -.35, *p* = .028. The results suggest that participants with better DM

[11] When participants were divided into younger and older groups for the purpose of calculating Pearson correlation coefficients, no statistically significant correlations were observed between semantic abilities and memory abilities at the 0.05 significance level.

and PM were able to produce sentences more quickly as well as detect syntactic violations more accurately. It is important to note that procedural memory ability is much less correlated with expressive semantic ability than it is with receptive semantic ability.

7.4. Discussion

The aim of the current study was to investigate age-related changes in receptive semantic processing and to examine PCA in ChOA. In order to achieve the goal, we replicated part of the study of Ye et al. (2006) as its experimental stimuli were based on the Ba construction. We then made a comparison between the receptive data and expressive data to examine PCA. Ultimately the language data were computed with the memory data to investigate the correlation between semantic abilities and declarative and procedural memory abilities.

Although the experimental stimuli were auditorily presented in the study of Ye et al. (2006), we obtained similar neural results when the same stimuli were visually presented (Hagoort & Brown, 2000; Kutas & Federmeier, 2011). The semantic violation elicited an N400 effect in a 320 to 520 ms time window for younger adults. The N400 effect may reflect an attempt to connect to semantic memory to decode the meaning of the sentence (Federmeier et al., 2002; Kutas & Federmeier, 2011). Alternatively, it may indicate that participants managed to integrate the preceding context and make a prediction about the critical words (DeLong et al., 2012; Federmeier et al., 2010). Moreover, there is an LPC effect during the 500 to 900 ms time window after the N400 component (Federmeier et al., 2010; Van Petten & Luka, 2012). The LPC effect may be linked with disconfirmation and/or reanalysis of semantic predictions derived from the preceding context (Van Petten & Luka, 2012; N. N. Xu et al., 2017).

Compared to younger adults, older adults exhibited a significantly lower accuracy rate, suggesting that they have difficulty in detecting semantic anomalies due to age-related decline in semantic abilities (Kutas & Iragui, 1998; Xu et al., 2020). The age-related semantic decline of older adults may be related to decreased temporal-spatial dynamic N400 change with reduced amplitude, especially in the central region of both hemispheres and right posterior region. Older adults seemed to fail to use context predictively (Federmeier et al., 2002) and/or fail to apply the acquired semantic knowledge in comprehending sentences (Xu et al., 2020). Moreover, the mismatch between the inferior behavioral performance and the intact LPC effect may reveal futile efforts by older adults to make use of semantic reanalysis of predictions to facilitate sentence comprehension (Federmeier et al., 2010; N. N. Xu et al., 2017). While older adults recruited a network in a similar way to younger adults, their use of the network was inefficient (Cabeza et al., 2002).

Additionally, we found that young adults displayed balanced semantic performance across the expressive and receptive modalities. In contrast, older adults were unable to achieve this standard at the neural level and exhibited superior comprehension performance. In other words, older adults had a semantic PCA. Furthermore, while declarative and procedural memory systems were related to semantic ability, the specific combinations were different between the expressive and receptive modalities. This point will be elaborated on in Chapter 8 of the general discussion on production and comprehension asymmetries in aging.

Chapter 8. General discussion

8.1. Retrogenic decline in declarative memory

A child's intelligence development does not be compressed into one stage (Piaget, 1999), and an older adult's cognitive abilities do not diminish overnight (Park & Reuter-Lorenz, 2009). Language and cognitive abilities are acquired and degraded in different sequences during one’s life course, and these sequences are reversed at the two ends of the lifespan, as proposed by B. Reisberg et al. (1999). For instance, a recent study systematically examined children's and older adults' categorical perception capabilities in a Chinese context (Feng, 2022), which was the first study to examine language abilities in both children and older adults and discover a reversed pattern of language acquisition and dissolution in the Chinese population. This study observed that there was an earlier acquisition and a later loss of categorical perception of vowels, whereas consonant categorical perception developed later and declined earlier (Feng, 2022). When testing the memory ability of older adults, we serendipitously discovered that older Chinese adults have retrogenic performance, and we first extended the retrogenesis theory to DM.

Observations demonstrated that older adults were able to retain more real objects after delays of 10 minutes and 24 hours, compared to made-up objects. The performance of older adults was the reverse of the outcome for children (Hedenius, Ullman, et al., 2013; Lukács et al., 2017). Knowledge of real objects was acquired in early life and has already been incorporated into the semantic network. As described by Hebb's Rule, a cell that consistently activates another cell nearby strengthens the connection between the two cells (Hebb, 1949). After accumulating usage across various contexts, the real object, which is stored in the brain, gradually establishes relationships with other related semantic nodes (Steyvers & Tenenbaum, 2005). This in turn facilitates its activation when recalled or recognized (Duñabeitia et al., 2008), for example when recognizing it again after a delay of 10 minutes in the current study. In contrast to that, made-up objects were being presented to the participants for the first time, and their relationship to other semantic knowledge was relatively weak. Consequently, it was difficult for participants to track back over made-up objects when they were encountered after a delay due to the fact that connections were not solidified. In the end, the participants forgot fewer real objects acquired earlier and more made-up objects acquired later, in accordance with retrogenesis theory (B. Reisberg et al., 1999; Reisberg et al., 2002).

It is important to note that Reisberg presented some caveats that are exceptions to the retrogenesis model (Reisberg et al., 2002). As an example, AD patients may be able to recall previously acquired knowledge and skills which are unavailable to children. This might explain why, compared to younger adults, older adults performed similarly in recognizing made-up objects but exhibited poorer recognition of recognizing real objects after a ten-minute delay. A real object would inevitably trigger many linked items as it was deeply connected to them in the memory system (Brown & Hagoort, 1993; Rabovsky et al., 2016; Tulving & Schacter, 1990), even in patients with AD, this automatic spread of activation at lexicosemantic levels remains intact (Duñabeitia, Marín, & Carreiras, 2009). In consequence, such connections probably interfered with and hindered later recognition, particularly in older adults who tend to have difficulty in inhibiting unrelated information (Fong et al., 2021). Alternatively, the broad and aggregate crystallized knowledge of older adults (Tucker-Drob et al., 2022) might allow them to encode made-up objects and build temporary connections with preexisting knowledge. As a result, with a ten-minute delay, made-up objects can be recognized by older adults to a similar degree as younger adults. The acquisition and dissolution of cognitive ability were explicable in terms of retrogenesis theory. It is imperative to thoroughly explore random exceptions before sweepingly rejecting retrogenesis theory (Caramazza et al., 1994). It is only then that general principles governing linguistic and cognitive variations in early and late life can be identified.

Caramazza et al. (1994) proposed two different types of constraints on the mirror pattern of language acquisition and dissolution, namely, "form constraint" and "order constraint". In several pioneering language studies on WEIRD populations, the order constraint for retrogenesis theory has been directly probed by illustrating the reverse sequences of semantic development and breakdown (De Bleser & Kauschke, 2003; Kim et al., 2011; Pozueta et al., 2020; Simoes Loureiro & Lefebvre, 2016). It is, however, necessary to note that retrogenesis research on Chinese populations is still in its infancy. The few retrogenesis studies on Chinese populations have stemmed from the form constraint that there exist corresponding stages between development and senescence. For example, a recent study found that older adults tended to overuse the general classifier of "个/Ge" to describe objects where specific classifiers are more appropriate (Feng et al., 2021). This reflects the idea that the semantic network of older adults is likely to be disorganized and the boundaries between different semantic categories seem to be fragile and blurry. The phenomenon corresponds to a stage in children's development when fine-grained semantic items tend to be overgeneralized (e.g., *doggie to refer to all animals), for a review, see Ambridge et al. (2013). The observation of corresponding forms is still in a superficial phase in retrogenesis theory. The ultimate goal is to render a graphic that depicts the order constraint or even the rate constraint. This would enable us to determine whether the rates of development and decline can be matched. Only in this way, can we theoretically enunciate the universal principle of development in children and degeneration in older adults, and illuminate the trace and mechanism of age-related decline. We can therefore provide appropriate care to older adults and promote "successful aging in a post-retired society "(p. 35) (Baltes & Baltes, 1993).

There is one point that should be highlighted here. It is a serendipitous discovery that DM declines with a retrogenic trace. Originally, the declearn task was designed to examine declarative memory ability and its effects on semantic change in older adults, specifically in relation to PCA. In light of the fact that the degeneration of DM follows retrogenesis theory, we discussed this point here to highlight the strength and broad application of this theory. We also suggest that comparison abilities should not be unlimited, and they should have some features in common. For example, it may not be appropriate to compare DM and PM since they are entirely different memory systems. The capabilities of production and comprehension can be compared because they are supported by separate brain regions, as well as shared ones (Giglio et al., 2022; Menenti et al., 2011; Segaert et al., 2012) Furthermore, production and comprehension asymmetries in older adults also represent a type of retrogenic phenomenon that has frequently been observed in children. The PCA and its relationship to DM and PM will be elaborated on in the following sections.

8.2. Production/comprehension asymmetries

Contributing to an ongoing debate on age-related changes in syntactic and semantic abilities, our results clarify that age-related differences in syntactic and semantic processing exhibit different features at different levels. In terms of production performance, older adults performed much worse than younger adults as they needed significantly longer to produce a proper sentence, especially when the task difficulty increased. However, the sentences produced by older adults were comparable to those produced by younger adults in terms of their syntactic and semantic complexity. This suggests that older adults were capable of expressing information with sentences as complicated as those used by younger adults. One possible reason is that older adults can take advantage of various strategies to compensate for age-related deficits, as proposed by the cognitive reserve model (Stern, 2002, 2009; Stern et al., 2020). In this context, it is plausible that older adults took advantage of the slack processing speed strategy to complete the task. The slack processing speed means that older adults slow down their RTs on purpose in order to maximize their performance if there is no time pressure. For instance, in the constrained production task, this strategy enabled them to construct a sentence with sufficient semantic and syntactic complexity such that their language production was comparable to that of younger adults. Nonetheless, the slack processing speed strategy may exacerbate language decline of older adults. It is likely that older adults may indulge in the slack processing speed strategy in order to maximize their performance. Ultimately, older adults are likely to be unable to boost their processing speed as they were when they were younger, and unable to appropriately complete tasks with time limitations. It is possible that there is a significant difference between younger and older adults in terms of semantic and syntactic complexity if there is a time limitation. More research needs to be conducted to investigate this possibility.

In addition, older adults also displayed distinct receptive syntactic performance at the behavioral level and neural level. There was no difference in the syntactic ability of the two groups in terms of detecting a word order violation. In contrast, older adults exhibited an exceedingly reduced AN effect compared to younger adults. It is not surprising that behavioral level and neural level would have distinct patterns as

Snowdon (2002) previously reported similar patterns in the nun study[12]. For instance, Sister Maria only had some plaques and tangles in the brain and was labeled as Braak stage II, but she was unable to live independently. In contrast, Sister Bernadette was mentally intact when she was labeled as Braak stage VI. Previous research also reported that the relationship between behavioral performance and neural activation declines with age (Diaz et al., 2014). The age-related decline in the relationship is likely to cause a mismatch between the performance at the behavior level and the performance at the neural level. This is why older adults were able to display equivalent behavioral performance in syntactic correctness judgement tasks compared to younger adults, although neural activations significantly change during normal aging (Lacombe et al., 2015). The age-related language decline is not a monolithic phenomenon.

Based on the normalized data, PCA was systematically examined. We found that PCA, as we expected, did indeed exist in the area of semantic ability for older adults. Semantic PCA also involved different patterns at the behavioral level and the neural level. Older adults exhibited equal receptive ability and expressive ability at the behavioral level. On the other hand, they exhibited unbalanced expressive ability and receptive ability at the neural level. Moreover, it appeared to be the case that PCA follows a particular trajectory, as shown in Figure 30.

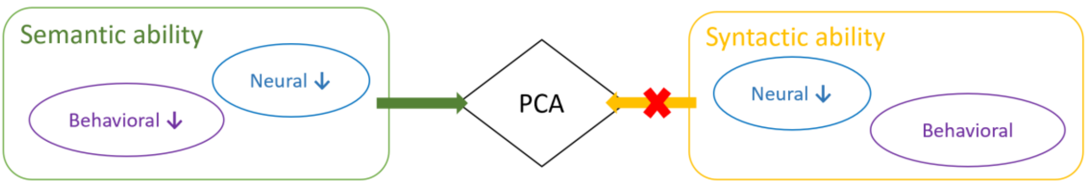


Figure 30. Schematic representation of the developmental pathway for PCA in older adults

Older adults exhibited receptive semantic decline at both the behavioral and neural

[12] It is noted that some researchers criticized the book of Snowdon, for instance, it "has an oddly introspective feel" and may be failed to "control for the many variables that confound its interpretation" (p. 255). For more details, see Kirkwood, T.O.M.(2003).

levels and demonstrated PCA in terms of semantic ability. In contrast, this same group exhibited receptive syntactic decline solely at the neural level and demonstrated no syntactic PCA.

Previous studies have found that PCA plays an influential role in lexical processing in older adults. The results of the study indicate that PCA also plays a role in the semantic processing of sentences. In addition, our results indicate when PCA begins to emerge. It seems to be the case that PCA is apparent in older adults only when they display a decline at both the behavioral and neural levels, and that this is reflected by receptive semantic ability. In contrast, PCA is not observed in syntactic processing as receptive syntactic ability only decreases at the neural level. It is worth investigating whether this reversed sequence happens in the language development stage. More research needs to be conducted to examine whether PCA disappears when the corresponding language ability is well-developed in children at both behavioral and neural levels. Likewise, it is necessary to investigate whether the same situation occurs in the expressive modality via recording the speaker's neural signals as they produce utterances.

Another question is then raised. Why is there an asymmetry between semantic production and comprehension? It may be related to declarative/procedural memory, and we will elaborate on this issue in the next section.

8.3. The association between production/comprehension asymmetry and declarative/procedural memory

The declarative and procedural memory systems are selectively correlated with the semantic and syntactic abilities for all participants. As summarized in Figure 31, DM is associated with semantic memory in both the expressive modality and receptive modality. The association between PM and syntactic ability is also observed in both modalities. This is consistent with the original declarative/procedural model that the mental lexicon and mental grammar are subserved by DM and PM respectively (Ullman, 2001a, 2004).

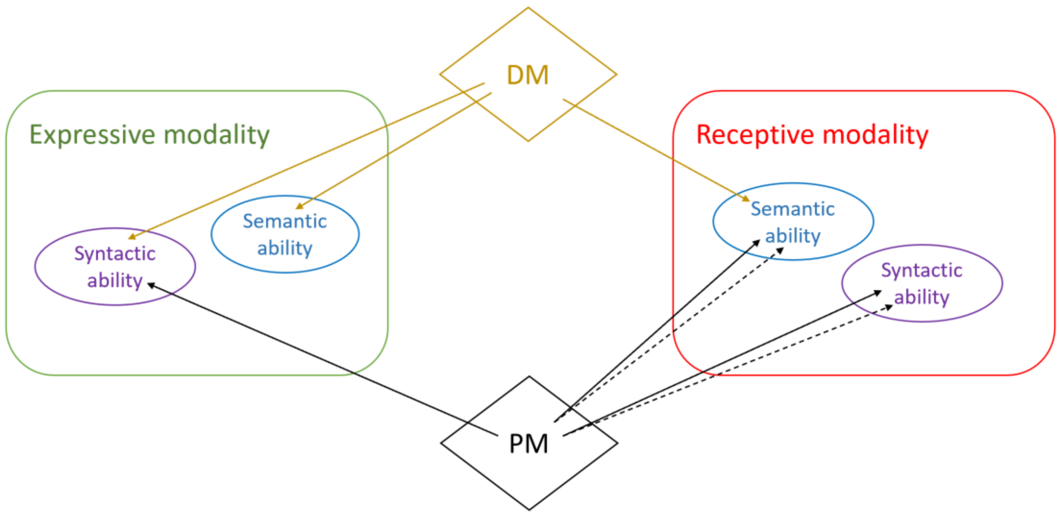


Figure 31. Asymmetrical correlations between declarative/procedural memory and semantic/syntactic ability in the expressive and receptive modalities
Different colors represent different cognitive abilities. The solid arrow indicates the relationship between the overt parameters of the ability, such as accuracy and RTs. The dashed arrow indicates the relationship between the covert parameters of the ability, such as the neural potential and semantic/syntactic complexity. The DM was related to semantic ability in both modalities, and solely related to expressive syntactic ability. The PM was related to syntactic ability in both modalities, and solely related to receptive semantic ability.

Language abilities can be associated with various basic cognitive abilities and these cognitive abilities can be reused to support their functioning (Wang, 1982). Moreover, the reuse of cognitive abilities is purposeful and selective. Based on the analogous features of language and memory, DM and PM support semantic processing and syntactic processing, respectively (Ullman, 2004). However, this support is not limited to one-to-one connections. Language is the hub of various basic cognitive abilities, and language is accessible to these cognitive abilities. It is possible to reuse DM and PM and build multiple connections to language in useful ways as long as it is beneficial for the functioning of language. Except for PM, syntactic processing was also related to DM. The connection between DM and syntactic ability exists solely and selectively in the expressive modality, as shown in Figure 31. On the other hand, the connections between PM and semantic ability take effect exclusively and selectively in the receptive modality. The connections between declarative/procedural memory and semantic/syntactic processing might not be equally robust. Besides, unequal connections persist from adulthood to old age. Previous research has found that semantic decline may relate to DM and a lifetime of reinforcement (Williams et al., 2021). It is plausible that semantic PCA is related to the accumulation of lifelong divergent support from the PM.

The unequal connections between DM and receptive/expressive syntactic ability are probably due to age-related decline in the prediction mechanism. During sentence comprehension, listeners can make use of prediction, which is derived from the so-called production-based language emulator, to facilitate their comprehension (Pickering & Garrod, 2007). The emulator model holds that listeners can always make use of predictions to anticipate upcoming words to assist their comprehension. This prediction mechanism is supported by various neuroimaging studies (Bonhage et al., 2015; Grisoni et al., 2021; Lau et al., 2006; Silbert et al., 2014; Van Petten & Luka, 2012). However, this production-based prediction ability suffers from age-related decline (Federmeier et al., 2010). Therefore, DM can support syntactic processing by chunking multiple components as a unit in production, as discussed in Chapter 5 where it was noted that participants sometimes considered Ba as a morpheme rather than an auxiliary word. The chunking function can assist comprehension via prediction, but older adults fail to take advantage of the prediction. This, at least to some extent, results in a disconnection between receptive syntactic processing and DM.

Production can also be enhanced by comprehension through the so-called monitor mechanism as stated in the forward model which was proposed by Pickering and Garrod (2007, 2013). This model holds that when producing sentences, speakers can always monitor their utterance via the comprehension implementer and therefore self-repair their speech simultaneously. Besides, cognitively healthy older adults exhibit similar monitoring performance in production tasks to their younger counterparts (McNamara et al., 1992). It is suggested that DM can support syntactic processing in comprehension by chunking language units, and this chunking function can also assist production via monitoring, and older adults can still take advantage of this monitoring mechanism. Therefore, the connection between expressive syntactic processing and DM is well-preserved in older adults which is in contrast to the impaired connection between receptive syntactic processing and DM. This is why the contribution of DM to syntactic processing is divergent in the areas of production and comprehension.

It is likely that the unequal correlation between PM and receptive/expressive semantic abilities is a result of competitive interactions between two neural circuitry underlying DM and PM learning functions (Janacsek & Nemeth, 2022). This is possible as implicit learning may also be constrained by higher cognitive mechanisms (Smalle et al., 2022). In the constrained production task, the suitable verb condition was used to measure semantic ability. The syntactic difficulty of this condition was relatively low compared to the semantic difficulty. As a result, it is likely that the DM is exaggerated due to the high semantic difficulty, and the PM is suppressed due to the low syntactic ability. Therefore, the connection between PM and expressive semantic ability is not visible. On the other hand, although the semantic correctness judgement task mostly requires the semantic ability to decode the semantic information, at least partially, it also involves feature detection. The DM first subserves retrieval of the lexical meaning and decoding of the semantic information of the context. The subsequent semantic feature detection can not be avoided if the semantic features of the critical word and the preceding context are to be matched. Feature detection undoubtedly relies on automatic processing (Kempler et al., 1987), and it is likely to require the PM to support its functioning. In the end, divergent connections emerged in the expressive and receptive modalities. It should be noted that this hypothesis needs to be confirmed with further studies which are designed with this particular goal in mind.

However, there are two caveats to the interpretation of the results of the correlation between language performance and memory performance. An obvious caveat to keep in mind is that language measurement may not be pure. This could lead to an over-interpretation of the data. There are many parts of the language system, including the lexicon or semantics as well as syntax. One traditional view is the “dual-system model” which regards semantics and syntax as dissociable and independent molecules that have their own “maturational course, neural representation, and processing profile” (Bates & Goodman, 1997; Ullman, 2001a, 2001c, 2004). For instance, there are two discontinuous phases for developing utterance acquisition (semantic mechanisms) and utterance analysis (syntactic mechanisms), respectively (Locke, 1997). During each phase, distinct neural mechanisms are involved, and each phase matures on its own genetic schedule. Furthermore, the temporal dynamics and spatial distributions of the neural foundations differ between semantic and syntactic processing, both for word production and recognition (Hagoort & Levelt, 2009; Indefrey & Levelt, 2004), as well as for sentence construction and comprehension (Friederici, 2002, 2011). Lastly, syntactic information can be activated automatically and independently, such as gender selection in noun phase production, garden-path sentence comprehension and structure priming from implausible sentences (Cai et al., 2022; Christianson et al., 2006; Qian et al., 2018; Schiller & Caramazza, 2003, 2006).

The automatic activation of syntactic information implies that semantic processing and syntactic processing operate on distinct principles.

On the other hand, the other view is the "single-system" model which regards semantic and syntactic processing as a unified processor (Bates & Goodman, 1997; Ullman, 2001a, 2001c, 2004). Firstly, for instance, although children differ in their development of semantic and syntactic abilities, semantic acquisition builds the foundations for syntactic acquisition. There is a strong correlation between vocabulary size and grammatical complexity for children (Fenson et al., 1994). It is suggested that "the capacity to acquire a grammar relies on a reworking of the same mechanisms that are used to build a lexicon (p. ix)" (Bates et al., 1991). Secondly, the breakdown of language ability also illustrates the connection between semantic and syntactic processing. As an example, Broca's patients are capable of interpreting passive sentences when semantic information is additionally available in the syntactic structure for identifying the agent (e.g. "The apple was eaten by the girl."), but they fail with sentences where semantic cues are naturalized and not discernible (e.g. "The boy was pushed by the girl.") (Bates & Goodman, 1997). This implies that semantic ability and syntactic ability are mixed together as a whole to support language operation. A more recent theory adopted the concept of the Elman recurrent neural network to explain language processing (Bates & Goodman, 1997; Elman et al., 1996; Goldstein et al., 2022). This system is primarily concerned with prediction and context rather than semantics and syntax. In order to process sentences, the artificial neural network combines the current input with the previous context to predict the next linguistic element.

Our contention is that language is an intricate and composite system and consists of many separate and connected components, including semantics and syntax.

Each component or aspect is different from the other, and purposefully and selectively reuses preexisting cognitive abilities. Syntax and semantics are closely connected at the birth stage. Phylogenetically, syntax emerged in a mosaic way due to the explosion of semantic complexity (Schoenemann & Wang, 1996; Wang, 1982). As the degree of complexity of our ancestors' minds increased, it became necessary to invent finite rules to deliver infinite meaning for efficient communication. Due to repeated use, these finite rules eventually became conventional for the whole community, resulting in syntax. During this process, preexisting cognitive abilities that originally assisted non-syntactic processing were gradually calibrated for optimal syntactic functioning. On the other hand, ontogenetically, children develop a rule-based device from a certain amount of lexical material (Bates & Goodman, 1997). During the breakdown phase, semantics and syntax are also associated and show a trade-off in language production (Rezaii et al., 2022). Considering that these aspects interact to support language functioning, it is easy to understand why language measurements may not be pure. When one aspect is measured, other aspects will also be involved and contaminate the measurement results (no matter how other aspects are supposed to be controlled initially). But since other aspects were controlled when designing the tasks, their involvement should be minimized. In view of this, our findings that semantic ability is also associated with procedural memory should be reflective of the real world at least in part. It is still pertinent to be cautious as to how much semantic ability is measured by the semantic correctness judgment task.

Additionally, there is a caveat regarding the nature of the tasks. Memory tasks evaluate DM learning ability, while language tasks assess language use and may also involve the learning of violation patterns. In the declarative procedural model, both DM and PM refer to "the entire system involved in the learning, representation and use of relevant knowledge, not just to those parts of the system underlying the learning of new memories" (p. 237) (Ullman, 2004). However, the delearn task and serial reaction time tasks employed in this study focus on the learning of newly acquired memories. Though memory performance used in correlation analysis was from the day-two session, it still mainly reflects the memory learning process rather than memory use. The language tasks, on the other hand, primarily evaluated the ability to use language rather than to acquire it. Because of this characteristic difference between memory and language tasks, the results may not be as valid as they could be. Aside from this, the language tasks required participants to detect syntactic and semantic anomalies in sentences, which differs from the way language is processed in daily life. Consequently, participants had to learn the violation paradigm of the task, which may involve a learning process. Due to the fact that both types of tasks require a learning process, these results are likely to be contaminated and cause a correlation between memory and language performance. The association between DM and expressive syntactic ability, as well as the association between PM and receptive semantic ability, should be considered cautiously and need further research to confirm.

Chapter 9. Conclusion

The proverb “once a man, twice a child” refers to the life cycle of a man. It begins with his birth as a child and continues through his adulthood until he enters old age, when he begins to decline and returns to his childhood state. In the current study, we investigated whether older adults go through a period of PCA which is frequently observed in the language development stage. We found a semantic PCA in older adults. We then further explained how this asymmetry emerged by examining the relationship between semantic/syntactic ability and declarative/procedural memory.

9.1. Major findings and significance

Our research examined age-related changes in DM and PM in a systematic manner. We found that older adults displayed a decline in both DM and PM. Compared to younger adults, older adults performed poorly in the declearn task on both consecutive days, suggesting a decline in DM. In the SRT task, older adults exhibited inferior performance on the day-one session compared to younger adults, and even failed to recall the sequence that was stored in the PM on the day-two session. Moreover, we found that the forgetting of the items in DM was in line with retrogenesis theory. Older adults tended to remember more real objects and forget more made-up objects, which was the reverse of the pattern in children.

We systematically investigated semantic processing and syntactic processing for production tasks and comprehension tasks in the Chinese population, especially in ChOA. We found that although older adults were able to express relevant information with intact syntactic and semantic complexity, they required much more planning time to initialize the sentence production compared to younger adults. The semantic comprehension performance of older adults was considerably worse than that of younger adults due to their relatively low accuracy rate and failure to demonstrate the N400 effect. When performing a syntactic correctness judgement task, older adults had a comparable accuracy rate to younger adults. However, older adults failed to exhibit the AN effect which was obviously observed in the neural potential of younger adults. The receptive syntactic ability of older adults diverged at the behavioral level and the neural level.

The current study investigated, for the first time, PCA in ChOA. It has been frequently reported that children develop language production and communication abilities asymmetrically. The semantic performance of older adults also fluctuated in terms of the receptive and expressive modalities, resulting in similar PCA as that exhibited by children. This supports retrogenesis theory which hypothesizes that the trajectory of language decline is the reverse of the developmental pathway. Moreover, it seemed to be a precondition for semantic PCA that the semantic ability had already declined at both the behavioral and neural levels. The asymmetry can be hidden at the neural level and invisible at the behavioral level.

We tried to apply the declarative/procedural model to analyze semantic processing and syntactic processing, especially at the sentence level, in ChOA. The declarative/procedural model had attracted a great deal of attention for its explanatory power in DLD children, and we also discovered an association between declarative/procedural memory and semantic/syntactic performance in younger and older adults. We extended the original declarative/procedural model as the two memory systems tended to be unequally connected to language abilities in the expressive modality and receptive modality. It is likely that the unequal associations contributed to the PCA.

The current study has significant theoretical and practical implications. Our results give a complete picture of age-related language attrition and memory decline, and elucidate the underlying behavioral and neural mechanisms. We assert that our results on age-related changes in language usage provide solid foundations for detecting, preventing, and recovering from dementia for older adults (Ammar & Ayed, 2020). Our results on retrogenic production and comprehension asymmetries implicate that it is our responsibility to take care of the elderly in the same way that we take care of our children, and to give them the attention and concern they deserve (Reisberg et al., 2002; Venturelli et al., 2012). Further, it is unreasonable to infantilize older adults given that some of their language abilities remain intact to some extent.

9.2. Limitations and future directions

Production and comprehension are two important aspects of communication. We investigated whether older adults would maintain similar abilities in terms of both production and comprehension or exhibit PCA. Although we made every endeavor to explore this issue, there were some limitations that need to be investigated further in future research.

First of all, although we considered the performance of younger controls as a reference point to examine whether older adults would exhibit a deterioration in production or comprehension, it was not within the scope of the study to identify the extent to which ChOA's production is superior or inferior to their comprehension. This was also a common problem inherited from the PCA research on language development. Future studies should consider a more direct method of comparing production performance and comprehension performance.

Secondly, we only recruited one group of healthy older adults and one group of younger adults as the control to examine PCA. Future investigations of aging need to be extended to include various age groups in order to depict the continuous lifespan trajectory. Different cognitive abilities, even abilities within particular cognitive domains exhibit multifaceted changes, including stability, growth and decline during adult lifespan development(Cohen et al., 2022; Hartshorne & Germine, 2015; Nyberg et al., 2012; Park et al., 2002; Rönnlund et al., 2005). Retrogenesis entails an inverted U-shaped pattern of changes (Douaud et al., 2014). An analysis of the language and cognitive abilities of children and older adults can only probe these two ends, making it difficult to detect the nonlinear effects of aging (Veríssimo et al., 2021). Moreover, due to the lack of data from children, we cannot make a direct comparison between children and older adults. Therefore, although the current study confirmed the existence of retrogenic PCA, it was insufficient to provide a systematic explanation from the perspective of retrogenesis.

Thirdly, as mentioned in the previous chapters, the current study lacked a neural measurement for production performance due to technical issues. Even though we defined a neural level when examining PCA, it was not a true comparison between neural performance in the expressive and receptive modalities. This might also reduce the efficacy of our explanations of the associations between DM and syntactic abilities, as discussed in Section 8.2. Despite the fact that data from all participants showed divergent associations between DM and syntactic abilities, we focused on the results of older adults to explain the PCA. Moreover, a recent study, which found a way to overcome technical problems in neuroimaging, suggested that the left middle temporal gyrus was more engaged in comprehension than production (Giglio et al., 2022). Based on their results, we may conjecture that DM is more closely related to receptive syntactic ability as they share common brain regions. This was inconsistent with our results which found that DM is more closely related to expressive syntactic ability.

More neuroimaging research needs to be conducted to clarify this issue.

Additionally, we focused on the Chinese Ba construction to probe the relationship between semantic/syntactic processing and declarative/procedural memory and how it might explain PCA. Other language patterns, such as the Bei construction, should also be taken into consideration in future work. In addition to semantic and syntactic domains, other linguistic domains, such as the phonological domain, should also be investigated to examine their relationship with PM and DM in older adults. In this case, the whole picture of retrogenic PCA could be depicted.

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Appendices

Appendix A. Stimuli of constrained production tasks

	Unsuitable verbs			**Suitable verbs**			**Filler**		
Two-word condition	把	开始		把	堆积		流浪汉	挑选	
	Ba	begin		Ba	pile		hobo	select	
	把	怀疑		分享	把		博士	避免	
	Ba	doubt		share	Ba		doctor	avoid	
	遇见	把		把	保存		失去	律师	
	meet	Ba		Ba	save		lose	lawyer	
	阵亡	把		关闭	把		承认	姑娘	
	fall	Ba		close	Ba		admit	girl	
Three-word condition	把	保洁员	听见	公开	把	绅士	企业家	毛巾	逃跑
	Ba	cleaner	hear	publicize	Ba	gentleman	entrepreneur	towel	escape
	回家	理发师	把	聚集	画家	把	字典	叛徒	打扰
	return	barber	Ba	gather	painter	Ba	dictionary	traitor	bother
	获得	陌生人	把	佩戴	把	杀手	乘务员	导致	子弹
	obtain	stranger	Ba	wear	Ba	killer	attendant	induce	bullet
	把	上车	评委	召唤	孕妇	把	受到	将军	餐巾纸
	Ba	board	judge	summon	gravida	Ba	expose	general	tissue

Four-word condition	香蕉	把	路人	值得	实现	耳机	把	小学生	新郎	斧头	寺庙	尊重
	banana	Ba	passerby	deserve	realize	earphone	Ba	pupil	groom	ax	temple	respect
	庆祝	连衣裙	战士	把	剃须刀	把	压低	女朋友	建立	餐厅	运动员	面具
	celebrate	dress	warrior	Ba	razor	Ba	depress	girlfriend	build	restaurant	athlete	mask
	哭泣	把	班主任	资金	把	贬低	卡车	局长	认为	早餐	外星人	楼梯口
	cry	Ba	mentor	fund	Ba	belittle	truck	chief	think	breakfast	alien	stair
	观看	面包	把	流氓	提高	邮件	妇女	把	遵守	耳朵	失败者	游泳池
	watch	bread	Ba	rogue	improve	mail	woman	Ba	obey	ear	loser	pool

Appendix B. Stimuli of semantic ERPs experiment

1. 园丁整埋花坛，把杂草拔/宰了。

To make the parterre neat, the gardener pulled out/butchered the weed.

2. 邻居掉换工作，把家搬/撤了。

After changing the job, the neighbor moved/withdrew the house.

3. 小伙子找到对象，把婚事办/印了。

After finding his true love, the young man had/printed a wedding.

4. 值日生清扫教室，把黑板擦/截了。

When cleaning the classroom, the student on duty cleaned/intercepted the blackboard.

5. 设计师制作新衣，把布料裁/砍了。

To make new dresses, the stylist cut/hewed the cloth.

6. 矿工进入矿井，把煤采/分了。

After entering the mine, the miners excavated/distributed coal.

7. 施工队拓宽马路，把旧房子拆/拔了。

To make the street wider, the builders broke/pulled out old houses.

8. 部队击退敌军，把前哨撤/砸了。

After beating the enemy, the army withdrew/smashed the vaunt-courier.

9. 老农撒上农药，把害虫除/染了。

Using pesticides, the old farmer killed/dyed pests.

10. 学生参加考试，把考卷答/丢了。

When attending the examination, the students answered/threw away the questions.

11. 老王打完草稿，把废纸丢/闪了。

After scratching, Lao Wang threw away/twisted the waste paper.

12. 人流涌上街道，把路口堵/除了。

Gathering on the street, people jammed/removed the crossing.

13. 人们过春节，把鞭炮放/洗了。

In the spring festival, people ignited/washed the firecracker.

14. 兄弟俩死了父亲，把家产分/拐了。

After the death of their father, the brothers divided/defrauded the bequest.

15. 妈妈补衣裳，把袖子缝/拆了。

When mending the dress, the mother sewed on/broke the sleeves.

16. 爷爷听取意见，把老习惯改/堵了。

Following the advice, the grandfather changed/jammed his old habit.

17. 骗子坑了许多人，把巨款捞/落了。

After befooling many people, the bilker got/lost a lot of money.

18. 电工修理机器，把机床焊/涂了。

When repairing, the electrician soldered/varnished the machine.

19. 老人感到口渴，把矿泉水喝/咽了。

Feeling thirsty, the old man drank/eat the mineral water.

20. 儿子买电脑，把钱花/漏了。

The son spent/left the money on a computer.

21. 同学来到图书馆，把书还/答了。

Coming into the library, the classmate returned/answered the book.

22. 小张做早餐，把鸡蛋煎/杀了。

To make breakfast, Xiao Zhang fried/killed the egg.

23. 海关检查货物，把走私品截/放了。

In customs inspection, the Customs House intercepted/freed the contraband.

24. 木匠需要木材，把树柱锯/扫了。

To get timber, the carpenter sawed/sweetened the stump.

25. 检查员清查危险品，把邮包卡/擦了。

When checking dangers, the inspector intercepted/cleaned the parcel post.

26. 伐木工开采森林，把松树砍/裁了。

Exploiting the forest, the timberjack hewed/cut pine trees.

27. 老汉走路摔到，把牙磕/做了。

Falling on the road, the old man broke/made the teeth.

28. 顾客走得匆忙，把皮包落/送了。

Leaving in a hurry, the buyer left/sent the bag.

29. 交警处理交通事故，把肇事车拦/搬了。

Dealing with the traffic accident, the policeman stopped/moved the car of the peacebreaker.

30. 作者写作疏忽，把标点漏/填了。

Writing carelessly, the author neglected/fulfilled the punctuation.

31. 小赵缺钱，把金戒指卖/花了。

Lacking money, Xiao Zhao sold/spent the golden ring.

32. 消防队赶到现场，把大火灭/抹了。

Coming to the locale, the firemen put out/cleaned the fire.

33. 店小二拿着抹布，把灰尘抹/灭了。

Taking a piece of duster cloth, the waiter cleaned/put out the dust.

34. 摄影师架起相机，把风景拍/采了。

Setting up the camera, the photographer took/pick pictures of the landscape.

35. 法官听完陈词，把案子判/破了。

After hearing the statement, the justice judged/broke the case.

36. 运动员超常发挥，把记录破/切了。

Going beyond himself, the athlete broke/cut the record.

37. 匪徒手持枪械，把银行抢/卖了。

Holding the guns, the robber robbed/sold a bank.

38. 小偷溜进财务室，把保险柜撬/判了。

Entering the finance office secretly, the stealer prized up/judged the strongbox.

39. 主人招待客人，把西瓜切/轧了。

Serving the guests, the host divided/rolled the watermelon with a knife.

40. 女孩追求时尚，把头发染/縫了。

Following the fad, the girl dried/sewed the hair.

41. 渔民出海打鱼，把鱼网撒/脱了。

Going to fish, the fisherman cast/took off the net.

42. 清洁工打扫卫生，把垃圾扫/炸了。

When dusting, the dustman swept/bombed out the garbage.

43. 刺客躲在暗处，把总统杀/拍了。

Hiding in the dark, the killer killed/filmed the president.

44. 运动员动作过猛，把腰闪/卸了。

Acting overly, the athlete twisted/unloaded his waist.

45. 厨师切完配料，把菜烧/锯了。

After cutting the vegetable, the chef cooked/sawed the food.

46. 邮递员走街窜巷，把信送/卡了。

Walking through streets and roads, the mail carrier sent/intercepted the mail.

47. 小周申请出国，把表格填/改了。

To go abroad, Xiao Zhou fulfilled/changed the forms.

48. 油漆工粉刷新房，把墙涂/焊了。

Stuccoing the new house, the painter varnished/soldered the wall.

49. 我感觉太热，把小背心脱/摘了。

Feeling too warm, I took off/picked off the little waistcoat.

50. 王大妈拿出肥皂，把床单洗/烧了。

Taking out the soap, aunty Wang washed/burned the sheet.

51. 搬运工走上货车，把货物卸/抢了。

Walking up the truck, the hamaul unloaded/robbed the cargo.

52. 工人开动机器，把钢管轧/煎了。

Turned on the machine, the worker rolled/fried the steel tube.

53. 孩子嘴馋，把糖果咽/喝了。

The greedy children eat/drank the candies.

54. 老师准备教程，把讲义印/撒了。

Preparing the tutorial, the teacher printed/cast teaching materials.

55. 男孩一失手，把玻璃瓶砸/还了。

Carelessly the boy smashed/returned the glass vase.

56. 屠夫挥动屠刀，把鸡宰/拦了。

Using a butcher knife, the meatman butchered/stopped chickens.

57. 石匠举起锤子，把墙壁凿/磕了。

Holding up the hammer, the stoneman cut/broke a hole in the wall.

58. 爆破手点燃火药，把碉堡炸/凿了。

Igniting the powder, the dynamiter bombed out/cut a hole in the blockhouse.

59. 果农迎来丰收，把桃子摘/撬了。

Having a plentiful harvest, the fruit grower picked/prized up the peaches.

60. 小学生打开练习本，把作业做/办了。

Opening the exercise book, the pupil did/managed the homework.

Appendix C. Stimuli (correct word order) of syntactic ERPs experiment

1. 管家把房间整理了。

The housekeeper cleaned up the room.

2. 妹妹把苹果吃完了。

My sister ate the apples.

3. 哥哥把牛奶打翻了。

My brother spilled the milk.

4. 劫匪把花瓶砸碎了。

The robber smashed the vase.

5. 乘客把车票退换了。

The passenger refunded the ticket.

6. 空姐把毛毯拿走了。

The stewardess took the blanket away.

7. 奶奶把手机摔坏了。

Grandma broke the phone.

8. 商家把广告撤销了。

The merchant canceled the advertisement.

9. 农民把小麦收割了。

The farmer harvested the wheat.

10. 厨师把灶台收拾了。

The cook cleared the stove.

11. 作家把新书发布了。

The writer released the new book.

12. 工人把电梯修好了。

The workers repaired the elevator.

13. 嫌犯把证据销毁了。

The suspect destroyed the evidence.

14. 顾客把奖品兑换了。

The customer redeemed the prize.

15. 新娘把面纱揭开了。

The bride lifted the veil.

16. 编辑把文章修改了。

The editor revised the article.

17. 法官把案件移交了。

The judge transferred the case.

18. 邮差把信件带走了。

The postman took the letter away.

19. 工厂把污水处理了。

The factory has treated the sewage.

20. 船长把火把点燃了。

The captain lit the torch.

21. 老师把答案公布了。

The teacher announced the answer.

22. 司机把汽车发动了。

The driver started the car.

23. 护工把头发剪短了。

The nurse cut the hair short.

24. 市长把计划延后了。

The mayor postponed the plan.

25. 暴徒把雕塑推倒了。

The mob knocked down the sculpture.

26. 助理把衣服弄脏了。

The assistant soiled the clothes.

27. 技工把设备拆解了。

The mechanic disassembled the equipment.

28. 阿姨把牛奶加热了。

The aunt heated the milk.

29. 保安把大门反锁了。

The security guard locked the gate.

30. 总理把外套脱掉了。

The Prime Minister took off his coat.

31. 同桌把眼镜戴上了。

The deskmate put on the glasses.

32. 导演把镜头删减了。

The director cut off the shot.

33. 敌军把供给掐断了。

The enemy cut off the supply.

34. 房东把快递签收了。

The landlord signed for the courier.

35. 盗贼把财物瓜分了。

The thieves divided up the property.

36. 主任把问题解决了。

The director solved the problem.

37. 玩家把游戏卸载了。

The player uninstalled the game.

38. 学徒把手指划破了。

The apprentice cut his finger.

39. 水手把手臂擦伤了。

The sailor bruised his arm.

40. 用户把账号注销了。

The user logs out of the account.

41. 士兵把腰板挺直了。

The soldier straightened his waist.

42. 店长把价钱抬高了。

The store manager raised the price.

43. 客人把食物浪费了。

The guest wasted food.

44. 卧底把任务完成了。

The undercover agent completed the task.

45. 会计把表格更新了。

The accountant updated the form.

46. 客户把订单取消了。

The customer canceled the order.

47. 敌人把高地占领了。

The enemy captured the high ground.

48. 考生把错误纠正了。

The examinee corrected the mistake.

49. 富商把烟头熄灭了。

The rich businessman put out his cigarette.

50. 对方把消息屏蔽了。

The other party blocked the message.

51. 旅客把行李寄存了。

The passenger left the luggage.

52. 作者把原文删除了。

The author deleted the original text.

53. 校长把活动暂停了。

The principal suspended the activity.

54. 同事把抽屉塞满了。

The colleague filled the drawer.

55. 上级把部门合并了。

The superior merged the departments.

56. 卖家把商品下架了。

The seller removed the product.

57. 馆长把档案恢复了。

The curator restored the file.

58. 老板把员工辞退了。

The boss fired the employee.

59. 主管把系统还原了。

The supervisor restored the system.

60. 教练把课程调整了。

The coach adjusted the course.