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The Role of Sensory Function in Processing Speed and Working Memory Aging

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ABSTRACT

Background: Sensory function, processing speed, and working memory are considered to be mechanisms that play important explanatory roles in age-related decline of cognitive abilities. As individuals age, sensory function declines along with other cognitive abilities, including processing speed and working memory. Moreover, the relationship between sensory function, processing speed, and working memory, which represent the most basic mechanism, is one of the important issues in the field of cognitive aging.

Methods: To explore the role of sensory function, especially visual function, in processing speed and working memory aging, the present study adopted a 2 (age: young and old) × 4 (visual perceptual stress: high, medium, low, and non-stress) mixed design and explored age differences in tasks testing processing speed and working memory. To generate different levels of visual perceptual stress, test materials were masked with Gaussian noise according to each individual's visual function.

Results: The results indicated that age differences in processing speed were not influenced by different levels of visual perceptual stress, while age differences in working memory performance decreased gradually with the increase of visual perceptual stress.

Conclusion: Visual function affected age differences in working memory rather than in processing speed. The common-cause hypothesis and information-degradation hypothesis were applied to interpret the relationships between visual function and processing speed and between visual function and working memory, respectively. Moreover, sensory function may not directly affect working memory function, which was also consistent with a resource decrement model of aging.

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Introduction

Several studies have confirmed that cognitive abilities generally decline with age, especially in old age (Anstey, Horswill, Wood, & Hatherly, 2012; Gerstorf, Ram, Lindenberger, & Smith, 2013; Salthouse, 2009). Sensory function (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994), processing speed (Salthouse, 1996), and working memory (Craik & Byrd, 1982) are considered to be mechanisms that play important explanatory roles in age-related decline of cognitive abilities (Baldwin & Ash, 2011; Park, 2000). As

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individuals age, sensory function declines along with other cognitive abilities, including processing speed and working memory. Moreover, the relationship between sensory function, processing speed, and working memory, which represent the most basic mechanism, is one of the important issues in the field of cognitive aging. Previous research about this relationship used mainly cross-sectional or correlational designs (Lindenberger & Baltes, 1994; Salthouse, 1996), and few studies adopted a laboratory design to infer the possible causal relationship between these factors. Thus, the present study attempted to manipulate sensory function to explore the relationship between sensory function, processing speed, and working memory.

Relationship between Sensory Function, Processing Speed, and Working Memory

Several cross-sectional studies confirmed that processing speed and sensory function were the two most basic mechanisms that could explain a large portion of the age-related variance in cognitive function (Anstey, Luszcz, & Sanchez, 2001; Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Salthouse, 1996). La Fleur and Salthouse (2014) concluded that visual acuity had weak direct effects on cognitive function; however, a decrease in the age–cognition relation when the visual measure was statistically controlled, which meant the visual measure may be accounted for the age-related variances in cognition. This result is consistent with earlier reports (e.g., Salthouse, Hancock, Meinz, & Hambrick, 1996). Other research findings indicated that cognitive processing speed accounted for the largest variance in general cognitive status in older people (Tam, Lam, Huang, Wang, & Lee, 2015) and shared large proportions of their age-related variance (Salthouse & Meinz, 1995). Moreover, both sensory function and processing speed were evaluated as mediators of the relationship between age and cognitive function. For example, Clay et al. (2009) found that the direct associations between age and memory span and between age and fluid intelligence were non-significant after accounting for age-related declines in vision and processing speed (Clay et al., 2009). However, the relationship between sensory function and processing speed remains unclear since these studies almost belong to the correlational design. Thus, the present study aimed to explore the relationship between sensory function and processing speed from the perspective of experimental manipulation.

The age-related variance accounted for by working memory was lower than that by sensory function (Ghisletta & Lindenberger, 2005) and processing speed (Salthouse, 1996). Previously, we had explored the mediating effects of sensory function, processing speed, and working memory on the relationship between age and primary mental abilities, and concluded that sensory function, processing speed, and working memory were three important mediators that affected cognitive aging. The effect of these three mechanisms on aging of primary mental abilities presented a hierarchical relation, in that sensory function and processing speed could predict the decline of working memory and further predict the aging of primary mental abilities (Peng, Shen, & Wang, 2004; Shen, Wang, Peng, & Tang, 2003). Thus, the role of working memory in cognitive aging may be less basic than that of sensory function and processing speed. Moreover, several studies, which investigated the relationships between these functions, found that sensory function aging had a significant effect on memory decline but not on the decline in processing speed (Baldwin & Ash, 2011). When participants' auditory acuity declined, their corresponding auditory working memory performance was also poorer than that of the control group

(Lindenberger, Scherer, & Baltes, 2001). Since the present study mainly investigated the relationship between these three cognitive abilities, the question arises on exploring the mental mechanisms between sensory function, processing speed, and working memory. The following two theories may provide some explanations.

Theoretical Explanations

The *common-cause hypothesis* and *information-degradation hypothesis* were considered the two theoretical explanations of the relationship between sensory function and other cognitive abilities. More recently, interpretations of the associations between sensory function and cognitive domains have focused on shared age-related variance and common factor models. Baltes and Lindenberger (1997), relying on the Berlin Aging Study, proposed the *common-cause hypothesis* that attributes the relationship between sensory function and cognitive abilities to a common cause, which is an index of central neural system degeneration, that affects the whole cognitive system (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994). This has become a theme in the current cognitive aging research and linked sensory function and cognitive performance at the levels of brain function. Some research found that loss of white matter integrity was a significant cause of age-related slowing among otherwise cognitively normal old adults (Gunning-Dixon & Raz, 2000; Papp et al., 2014). Age differences in intellectual and sensory functioning are thus seen as the outcome of a third common factor or ensemble of factors, that is, age-related changes in the physiological state of the brain. Based on the notion that both sensory function and processing speed were evaluated as mediators of the relationship between age and cognitive function, Anstey et al. (2001) found a common variance in the cognitive factor shared by age, speed, vision, and hearing. Hofer, Berg, and Era (2003) reviewed the research on associations between physiological and cognitive functioning in adulthood from 1960 to 2002 and found substantial amounts of shared age-related variance that were accounted for by other variables, such as speed and sensory function (Hofer et al., 2003). Additionally, several studies found that both processing speed and sensory function could explain a large portion of age-related variance in cognitive function (Anstey et al., 2001; Salthouse, 1996), which indicated that sensory function and processing speed may play the same important roles in aging of other cognitive abilities. Moreover, age-related disinhibition is another factor that has been posited to act as a common cause mechanism. Thus, based on the *common-cause hypothesis*, we infer that age differences in processing speed are not influenced by manipulating sensory function, and may inversely be influenced by a common factor beyond sensory processes.

However, cross-sectional studies found that the common factor could not explain all the age-related variation between sensory and cognitive function (Anstey et al., 2001; Baltes & Lindenberger, 1997; Salthouse et al., 1996). A recent meta-analysis of 456 studies suggested that visual acuity is not significantly related to age group differences in higher-level cognitive performance (Houston, Bennett, Allen, & Madden, 2016). In addition, quite a few studies found direct effects of sensory impairment on cognitive abilities, such as listening to discourse with distraction (Schneider, Daneman, Murphy, & See, 2000), short-term memory (Murphy, Craik, Li, & Schneider, 2000), and reading (Speranza, Daneman, & Schneider, 2000), which could not be explained by the *common-cause hypothesis*. Therefore, another theory was proposed to explain the strong link between sensory function and cognitive aging.

Schneider and Pichora-Fuller (2000) described this relationship according to their *information-degradation hypothesis* from the perspective of processing resource allocation (Schneider & Pichora-Fuller, 2000). Sensory and cognitive processes are considered to be a unitary information-processing system, where the sensory process occurs relatively earlier, and the cognitive process occurs relatively later in the processing sequence. There is a strong link between these two processes, which share some overlapping resources. In particular, a sensory process needs more processing resource to obtain information if sensory function declines, which may result in less resource allocation to cognitive tasks. Further, the quality of the cognitive process is impaired by the poor sensory input, leading to a deficit in cognitive processing, which results in older adults' poorer cognitive performance.

According to this hypothesis, the poorer performance in working memory tasks in old adults cannot solely be attributed to a working memory itself decline but rather to the greater resource engagement by sensory processing. Thus, working memory aging may be influenced by the decline in sensory function due to the allocation of resources. Sensory function is an important impact factor that affect working memory. When old adults experience a reduction in overall processing resources, performance deficits caused by sensory function decline become more dramatic since sensory process needs more processing resource. If young adults engaged more resources for sensory processing, they could exhibit the same poor working memory performance as old adults. To clarify the hypotheses about the relationship between sensory function, processing speed, and working memory, experimental manipulations of sensory function were used in the present study.

Present Study

The general aim of this study was to examine the role of sensory function in processing speed and working memory aging through the perceptual stress paradigm proposed by Schneider and Pichora-Fuller (2000). In this paradigm, the target stimuli are masked by visual noise. The level of masking noise is adjusted to produce different levels of visual perceptual stress. The perceptual stress for each participant can be matched through a threshold elevation, which can be indexed by the signal-to-noise ratio (SNR). If old adults continue to perform less well than young adults when presented with equivalent perceptual stress, it can be inferred that the age difference is not due to the inability of old adults to see the target stimuli. Rather, the difference can be attributed to age-related declines in cognitive functioning. On the other hand, if age differences decreased or disappeared under this manipulation, it would be reasonable to attribute age differences in cognitive performance to the higher degree of perceptual stress usually experienced by old adults (Schneider & Pichora-Fuller, 2000). In our previous research, we manipulated visual perceptual stress of old and young adults to investigate the influence of visual function on age differences in primary mental abilities. When the two age groups were tested under equivalent perceptual stress, the age differences in reductive reasoning, numerical ability and inhibition decreased, or even disappeared, which confirmed that visual function can influence aging of cognitive abilities (Mao & Peng, 2015; Peng, Gao, & Mao, 2017). Therefore, multi-level noise conditions (visual perceptual stress: high, medium, low, and non-stress) were manipulated in the present study, which can help us better explore how the age differences, respectively, in working memory and processing speed vary with visual perceptual stress. Moreover, the SNR was manipulated according to each participant's visual function in the present study. Thus, old and young adults completed processing speed and working memory tasks under different visual perceptual stress and non-stress conditions. We propose that if visual deficits contribute to age differences in working memory tasks, these age differences will decrease or disappear if visual perceptual stress increases, which supports the *information-degradation hypothesis*. In contrast, if age differences in processing speed do not vary with this manipulation, it can be concluded that the relation between processing speed and visual function may be influenced by a third factor, which supports the *common-cause hypothesis*. Consequently, the specific expectations consist of the following hypotheses:

Hypothesis 1: Age differences in processing speed performance will not vary under different visual perceptual stress.

Hypothesis 2: Age differences in working memory performance will vary under different visual perceptual stress. Specifically, when compared with a non-stress condition, age differences will decrease or disappear when visual perceptual stress becomes higher.

Methods

Participants

Thirty-three young (14 men and 19 women, M_{age}= 22.24, *SD*= 2.25) and 31 old (11 men and 20 women, M_{age}= 71.10, *SD*= 5.63) participants were recruited. All participants had a normal or corrected-to-normal vision. The old group had on average 15.52 education years (*SD*= 1.68) and the young group 16.61 (*SD*= 1.94). The average self-report health status (1 = excellent health, 2 = good health, 3 = poorer health) of the old group was 1.77 (*SD*= .50), and that of the young group was 1.36 (*SD*= .49). The age effect of education years was significant, $t\ (1, 62) = 2.82,\ p < .01$, *Cohen's* $d = .72$. The age effect of self-report health status was significant, t (1, 62) = −3.33, $p< .01$, *Cohen's* $d = .85$. The clock drawing test was used to screen for possible Alzheimer disease or other types of cognitive impairment (Tuokko, Hadjistavropoulos, Miller, & Beattie, 1992).

To conduct a power analysis, we searched for previous studies about sensory function and found that Hofer et al. (2003) examined the interdependence between aging-related changes in cognition, sensory acuity, balance, and presumably more distal measures of physiological aging processes (Hofer et al., 2003). One of their results showed that associations across sensory and cognitive domains were between .20 and .40. Thus, when the sample size was 64 in the present study and the average correlation between sensory function and cognitive aging was .3, the result of GPower showed that the present study's statistical power reached .79.

Design

The present study adopted a 2 (age: young and old) × 4 (visual perceptual stress: high, medium, low, and non-stress) mixed design, in which age was the between-subjects variable and visual perceptual stress was the within-subjects variable. In the visual perceptual stress conditions, all stimuli were masked by Gaussian noise. High, medium, and low visual perceptual stress indicated that participants could correctly identify 60%, 80%, and 100% of the materials, respectively (Mao & Peng, 2015). In the non-stress condition, the stimuli were not masked with noise. Participants were asked to complete the digit comparison test and operation span under the high, medium, and low visual perceptual stress and non-stress conditions. The dependent variables were the performance in processing speed and working memory tasks.

Measures

Digit Comparison Test

This test was used as a measure of general information processing speed (Shen et al., 2003). Two digital strings (number of digits per string ranged randomly from 3 to 9 between trials) with the same length were presented on the computer screen. Participants needed to identify as quickly and accurately as possible whether these two digital strings were the same by pressing "Yes" or "No" on a keyboard. In the formal experiment, trials with "Yes" and "No" responses were equally frequent. There were three practice trials before the formal experiment, which contained 84 trials. The participants' reaction time and accuracy were recorded. The average reaction time was regarded as the indicator of processing speed performance.

Operation Span

Operation span was used to measure participants' working memory span (Gao, Peng, & Wen, 2014; Peng, Wen, Wang, & Gao, 2012). Participants needed to calculate several sets of additions and subtractions and remember the answer for each calculation. After one set of calculations, the participants were asked to recall all answers of the set in order.

The answer to each calculation ranged from 0 to 9. Set size varied from 1 to 9 and increased gradually. There were three sets of about the same size. If the participants could not correctly calculate or recall two sets in a row, the experiment ended. If set size was n when participants finished, the maximum number of correct calculation and recall was n-1, which corresponds to working memory span. Two practical trials were completed before the formal experiment. The maximum number of correct calculation and recall was regarded as the indicator of working memory performance.

Generation of Visual Perceptual Stress

The level of perceptual stress was indexed by the percent correct identification of signal stimuli under the masking noise conditions, with a higher percentage indicating lower perceptual stress. The ratio of signal stimuli to noise luminance was manipulated to produce various SNR sets. The threshold of each participant to reach an equivalent level of perceptual stress was measured through psychophysical methods before the formal experiment. The participants with better visual function exhibited a lower threshold in identifying the signal stimuli, and the SNR they needed to reach the same level of perceptual stress was relatively lower.

Because the materials in the digit comparison test and operation span were digits, the thresholds for identifying digits were measured. In the visual perceptual stress measure, one black digit (randomly selected from 0 to 9) masked by Gaussian noise was presented on the white computer screen in each trial (see example displays in Figure 1). The participants' task was to name the displayed digit. During the experiment, all participants

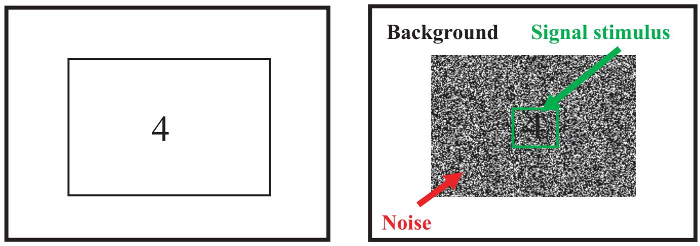

Figure 1. Display examples showing the non-stress stimulus (left panel) and the same stimulus masked by Gaussian noise (right panel).

saw the display from a distance of 60 cm. The SNR generation method was adapted from the research of Speranza et al. (2000) (Speranza et al., 2000). The background luminance (L_{av}) and signal stimulus luminance (L_{sig}) were fixed, while the noise luminance was manipulated. Higher SNR corresponded to clearer signal stimuli. The contrast of noise and background luminance was calculated with the formula Cn = {Σ [(L_i-L_{av})/L_{av}] 2/n} 1/2, where L_i was the pixel luminance and n was the number of pixels. SNR was calculated with the formula SNR = log(c/Cn).

Seven sets of SNR were produced to measure participants' threshold, which was based on the psychophysical method of constant stimuli. Under the lowest SNR, participants could barely identify any signal stimulus; while under the highest SNR, they could almost always identify each signal stimulus. In the present measure, young and old adults' SNR of digits ranged from −8.2 to −7.2 and from −8.0 to −7.0, respectively. (The values were the calculated results of noise generation software, and larger values mean high SNR.) Each SNR set included 30 trials, resulting in 210 trials totally for measuring the digit identification threshold. Participants were instructed to respond on a keyboard. The response accuracy was recorded, and the percentage of correct identification and SNR was fit with a logistic function as follows:

$$y = \frac{1}{1 + e^{-\sigma(x-\mu)}}$$

where y represents the probability of correctly identifying the signal stimuli, x is the SNR, μ represents the SNR level corresponding to 50% correct performance, and σ determines the slope of the fitted function. The value of μ can be calculated by the identification threshold measure. Special perceptual stress, which is indexed by SNR (x), can then be calculated by this logistic function.

In this study, 60%, 80%, and 100% correct identification were selected to represent high, medium, and low perceptual stress, respectively. With respect to manipulation check of the SNR, lower SNR should correspond to lower digit identification accuracy. For young group, the average specific values of SNR corresponding to 60%, 80%, and 100% correct identification were −8.04, −7.76 and −7.06, respectively. For old group, the corresponding average specific values of SNR were −8.28, −7.78 and −6.62. Two repeated-measures analysis of variance (ANOVAs) were conducted. Mauchly's sphericity test showed that sphericity was violated (young group: *Mauchly's* $W = .07$, $df = 20$, $p < .001$; old group: *Mauchly's* $W = .12$, $df = 20$, $p < .001$). The Greenhouse-Geisser adjusted results of within-subjects tests showed that the main effect of SNR was significant in both the young, $F\ (3.50,\ 192) = 214.48,\ p < .001,\ \eta^2_p = .87$, and old group, $F\ (3.56,\ 180) = 66.93,\ p < .001,\ \eta^2_p = .69$. As shown in Table 1, the manipulation check of SNR in the present study confirmed that this manipulation was effective.

Procedure

All participants filled in the background information and signed an informed consent form. Afterward, the old participants completed the clock drawing test. At the formal experiment stage, the measure of perceptual stress threshold was first administered to establish the SNR corresponding to 60%, 80%, and 100% correct identification. Then, participants performed the processing speed and working memory tasks under different visual perceptual stress conditions. Each block contained one stress condition. Four blocks with the different experimental conditions (i.e., three perceptual stress levels and non-stress) were presented in random order. The order of the processing speed and working memory tasks was also balanced among the participants. After finishing all tasks, participants received their remuneration.

This study was approved by the Ethics Committee of the School of Psychology, Beijing Normal University, and written informed consent was obtained from all participants.

Results

Processing Speed

Accuracy

Using a 2 (age group: young and old) × 4 (visual perceptual stress: high, medium, low, and non-stress) repeated-measures ANOVA revealed a non-significant effect of age group, $F\ (1,\ 59) = 2.51,\ p > .05,\ \eta^2_p = .04$. Mauchly's sphericity test showed that sphericity was violated, *Mauchly's W = .82, df = 5, p < .05*. The Greenhouse-Geisser adjusted results showed that there were no age differences in accuracy of the digit comparison test under the four experimental conditions, $F\ (2.67,\ 177) = 2.44,\ p > .05,\ \eta^2_p = .04$, and a significant effect of visual perceptual stress, $F\ (2.67,\ 177) = 3.97,\ p < .01,\ \eta^2_p = .06$, which showed that participants' accuracy decreased gradually with the increase of visual perceptual stress (Bonferroni corrections were controlled for multiple comparisons).

However, under high visual perceptual stress, the old adults' average reaction time was faster than that under the medium, $t\ (29) = -2.47,\ p < .05$, *Cohen's d = .64*, and low-stress conditions, $t\ (29) = -.20,\ p > .05$, *Cohen's d = .05*. Because the response consisted of a two-choice yes/no response, a one-sample t test was used to compare accuracy under high visual perceptual stress with the chance probability of .5. The result showed that, in the

Table 1. The relationship between the SNR and the recognition accuracy of digits.

	SNR1 Young −7.20 Old −7.00	SNR2 -7.38 −7.18	SNR3 -7.56 −7.36	SNR4 -7.73 −7.53	SNR5 -7.89 −7.69	SNR6 -8.05 −7.85	SNR7 -8.20 −8.00
Age	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*
Young	.95 ± .04	.94 ± .05	.91 ± .06	.85 ± .07	.76 ± .11	.61 ± .13	.40 ± .13
Old	.96 ± .04	.94 ± .05	.94 ± .06	.90 ± .08	.87 ± .07	.80 ± .08	.71 ± .12

SNR1 represented the highest recognition accuracy, and SNR7 represented the lowest recognition accuracy. The data in the table was average accuracy of the target stimulus under each SNR. The specific values of the seven SNR of each group were also presented in the table.

high-stress condition, the accuracy of young adults was significantly greater than .5, $t\ (32) = 2.53,\ p < .05,\ Cohen's\ d = .63$, while there was no significant difference for the old adults, $t\ (29) = 0.80,\ p > .05,\ Cohen's\ d = .21$, which indicated that older adults used a guessing strategy under the high visual perceptual stress condition. Therefore, in the following analysis, both young and old adults' performance of the digit comparison test under high visual perceptual stress was excluded. The descriptive statistics of performances of processing speed under the different visual perceptual stress conditions are shown in Table 2.

Speed-Accuracy Trade-Off Check

The correlations of reaction time and accuracy under the different visual perceptual stress conditions were calculated to check whether a speed-accuracy trade-off occurred. Both under the medium and non-stress conditions, the correlations of reaction time and accuracy were not significant, $r = .14$ and $r = .10$, respectively, $ps > .05$. Under low visual perceptual stress, however, the correlation was significant, $r = -.30$, $p < .05$, which suggests that the more quickly the participants responded, the higher their accuracy was. Moreover, as the descriptive statistics in Table 2 show, except for the high visual perceptual stress, young and old adults' reaction time and accuracy presented this trend under the other three conditions: reaction time increased gradually while accuracy declined, which may be related to task difficulty. These results indicated that there was no speed-accuracy trade-off. Therefore, the average reaction time was an effective indicator for the present study.

Reaction Time

To explore whether age differences of processing speed were influenced by visual function, a 2 (age group: young and old) × 3 (visual perceptual stress: medium, low, and non-stress) repeated-measures ANOVA was used. Mauchly's sphericity test showed that sphericity was conformed, $Mauchly's\ W = .92,\ df = 2,\ p > .05$. The results revealed a significant effect of age group, $F\ (1, 61) = 36.08,\ p < .001,\ \eta^2_p = .37$, and a significant effect of visual perceptual stress, $F\ (2, 122) = 60.48,\ p < .001,\ \eta^2_p = .50$. These results showed that young adults reacted significantly faster than old adults, and participants' reaction time increased gradually with the increase of visual perceptual stress. The age group × visual perceptual stress interaction was not significant, $F\ (2, 122) = 0.89,\ p > .05,\ \eta^2_p = .01$, which meant that age differences did not vary with different visual perceptual stress, as shown in Figure 2.

Table 2. descriptive statistics of performance of processing speed and working memory under different visual perceptual stress.

		Processing speed (accuracy)	Processing speed (average reaction time)	Working memory
Visual perceptual stress	Age group	$M \pm SD$	$M \pm SD$	$M \pm SD$
Higher	Young	.54 ± .10	4394.64 ± 1647.21	.53 ± .98
	Old	.51 ± .10	4600.32 ± 3635.50	.10 ± .30
Middle	Young	.74 ± .11	4024.11 ± 1146.67	1.19 ± .78
	Old	.68 ± .15	6004.43 ± 2830.72	.58 ± .92
Lower	Young	.92 ± .11	2924.66 ± 697.47	4.66 ± 2.24
	Old	.89 ± .15	4744.36 ± 2339.21	2.65 ± 2.37
Non-stress	Young	.96 ± .04	1649.77 ± 263.06	7.28 ± 1.02
	Old	.97 ± .03	3001.29 ± 705.03	5.65 ± 2.03

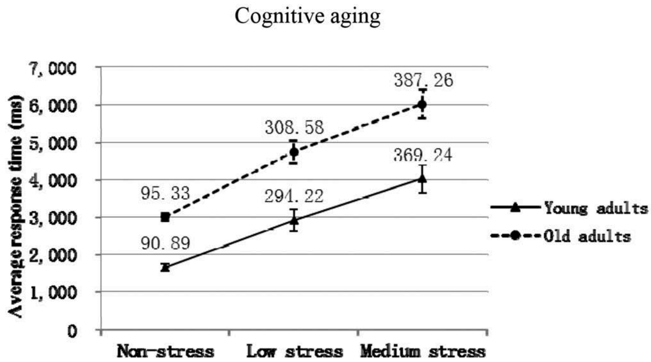

Figure 2. Reaction times (ms) for processing speed under different visual perceptual stress.
Note. Plotted values are the means, and error bars represent standard errors. The values of standard errors were marked next to error bars.

Working Memory

The descriptive statistics results of operation span are also shown in Table 2. A 2 (age group: young and old) × 4 (visual perceptual stress: high, medium, low and non-stress) repeated-measures ANOVA revealed a significant effect of age group, $F\ (1,\ 61) = 29.65$, $p < .001$, $\eta^2_p = .33$, which showed that young adults' performance was significantly higher than that of old adults. Mauchly's sphericity test showed that sphericity was violated, *Mauchly's* $W = .44$, $df = 5$, $p < .001$. The Greenhouse-Geisser adjusted results of within-subjects tests showed that a significant effect of visual perceptual stress, $F\ (2.15,\ 183) = 243.24$, $p < .001$, $\eta^2_p = .80$, which showed that participants' operation span decreased gradually with the increase of visual perceptual stress. The age group × visual perceptual stress interaction was significant, F (2.15, 183) = 4.52, $p < .05$, $\eta^2_p = .07$. A simple effect analysis of the interaction between age group and visual perceptual stress found that young adults' performance was overall better than that of old adults under the four conditions (Table 2): high visual perceptual stress, $F\ (1,\ 61) = 5.55$, $p < .05$, $\eta^2_p = .08$; medium visual perceptual stress, $F\ (1,\ 61) = 7.96$, $p < .05$, $\eta^2_p = .12$; low visual perceptual stress, $F\ (1,\ 61) = 11.98$, $p < .01$, $\eta^2_p = .16$; non-stress, $F(1,\ 61) = 16.53$, $p < .001$, $\eta^2_p = .21$. Age differences in operation span under non-stress, low, medium, and high visual perceptual stress were 1.63, 2.01, .61, and .43, respectively, and the η^2_p were .21, .16, .12, and .08, respectively, which indicates that age differences in working memory performance decreased when visual perceptual stress became higher. The changing trend of these age differences is shown in Figure 3.

Particularly, older adults‘ performance in the high visual perceptual stress condition was too low (the average number of correct calculation and recall was .10) that closed to the floor effect, which may overestimate the interaction between two independent variables. Therefore, we re-analyzed the data excluding participants‘ performance under high visual perceptual stress. Another 2 (age group: young and old) × 3 (visual perceptual stress: middle, lower and non-stress) repeated-measures ANOVA was also conducted. Mauchly's sphericity test showed that sphericity was violated, *Mauchly's* $W = .87$, $df = 2$, $p < .05$. The Greenhouse-Geisser adjusted results of within-subjects tests revealed that the age group × visual perceptual stress interaction was significant, $F\ (1.77,\ 122) = 3.54$, $p < .05$, $\eta^2_p = .06$.

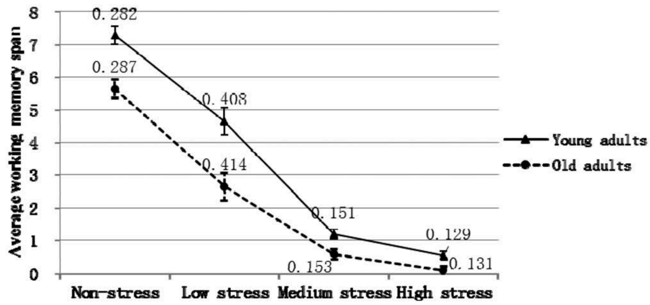

Figure 3. Average operation span (working memory) under different visual perceptual stress.

Note. Working memory span corresponds to the number of correct calculation and recall. Plotted values are the means and error bars represent standard errors. The values of standard errors were marked next to error bars.

A simple effect analysis of the interaction between age group and visual perceptual stress found that young adults' performance was overall better than that of old adults under the four conditions (Table 2): medium visual perceptual stress, $F\ (1,\ 61) = 7.96,\ p < .05,\ \eta^2_p = .12$; low visual perceptual stress, $F\ (1,\ 61) = 11.98,\ p < .01,\ \eta^2_p = .16$; non-stress, $F\ (1,\ 61) = 16.53,\ p < .001,\ \eta^2_p = .21$. Though the mean value of age differences in operation span under non-stress and low visual perceptual stress were 1.63 and 2.01, respectively, the results of a 2 (age group: young and old) × 2 (visual perceptual stress: lower and non-stress) repeated-measures ANOVA revealed that the age group × visual perceptual stress interaction was not significant, $F\ (1,\ 61) = .37,\ p > .05,\ \eta^2_p = .00$, which means that age differences for the non-stress condition and low visual perceptual stress condition did not differ significantly. Additionally, the mean value of age differences in operation span under low and medium visual perceptual stress were 2.01 and .61, respectively, the η^2_pwere .16 and .12, respectively, which indicates that age differences in working memory performance decreased when visual perceptual stress became higher. The changing trend of these age differences is shown in Figure 4.

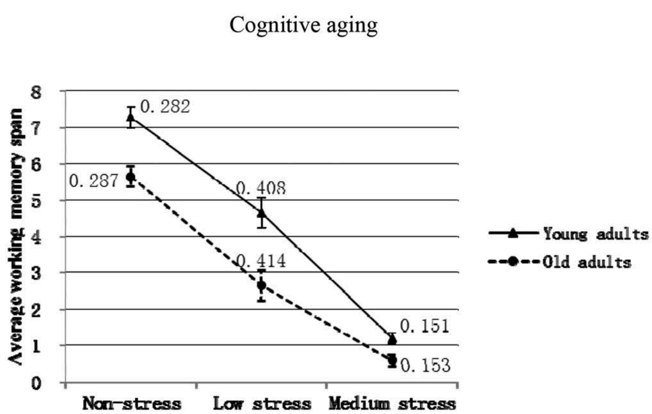

Figure 4. Average operation span (working memory) under different visual perceptual stress.

Note. Working memory span corresponds to the number of correct calculation and recall. Plotted values are the means and error bars represent standard errors. The values of standard errors were marked next to error bars.

Discussion

This study explored the effect of sensory function on age-related differences in processing speed and working memory by manipulating the level of visual perceptual stress. The results indicated that visual function did not affect the age difference of processing speed. In contrast, the age difference of working memory decreased as visual perceptual stress became higher. We will discuss these results according to the *common-cause hypothesis* and *information-degradation hypothesis.*

Role of Sensory Function in Processing Speed Aging

As shown in Figure 2, both young and old adults' average reaction time gradually increased from the non-stress condition to the medium stress condition, which confirmed that the increasing noise slowed the participants' response. However, age differences in average reaction time did not vary with the different visual perceptual stress, which indicated that sensory function did not influence processing speed aging, thus, supporting Hypothesis 1. This result was consistent with previous research, which showed that sensory function could not sufficiently account for the age-related variance in processing speed (Anstey et al., 2001; Lindenberger et al., 2001). For example, Lindenberger et al. (2001) reduced sensory acuity during cognitive assessment to explore the relation between sensory function and cognitive abilities, and showed that manipulating young and old adults' visual acuity did not significantly influence age differences in processing speed performance, which suggests that there is no direct relationship between these two mechanisms (Lindenberger et al., 2001). Lindenberger and Baltes (1994) evaluated the relative importance of speed and sensory function in cross-sectional models of age differences in cognition (Lindenberger & Baltes, 1994). In one model, they found that speed did not fully mediate the effect of age on sensory function but fully mediated the effect of age on cognition. This means that the role of processing speed on cognition is direct and not influenced by sensory function. The present result that aging of processing speed was not affected by sensory function indicated that it may be influenced by a common factor beyond the sensory process.

The classical common cause literature has examined processing speed, sensory function, working memory, and disinhibition as common causes. From the perspective of the *common cause hypothesis* and more contemporary work, it is possible that a common factor related to the general integrity of the aging brain contributes to this relation between sensory function and processing speed. This common factor, which reflects age-related physiological changes of the central nervous system, links sensory function and cognitive performance at the level of brain function (Baltes & Lindenberger, 1997) and accounts for the age-related variance. In addition, neurobiological research showed that processing speed aging may be related to changes in brain morphology, for example, affecting white matter integrity (Kerchner et al., 2012) and other morphological markers (Null, 2008). The white matter neural atrophy causes neural impulses to slowdown, which in turn can explain the slowing in behavioral responses (Salthouse, 2000). Therefore, processing speed aging is more likely to be influenced by the common factor than by sensory function.

Role of Sensory Function in Working Memory Aging

As expected, both young and old adults' performance in the working memory task gradually decreased from the non-stress to the high-stress condition. Furthermore, compared with the non-stress condition, age differences of working memory decreased when visual perceptual stress becomes higher, as shown in Figures 3 and 4, supporting Hypothesis 2. However, age differences were greater in the low-stress condition than in the medium-stress condition, suggesting that the low-stress condition had a greater influence on old adults than on young adults. Thus, the relationship between age and working memory was affected by visual sensory function. Our findings are largely consistent with the notion that sensory function, as a fundamental cognitive processing mechanism, can influence working memory aging (Baldwin & Ash, 2011; Pichora-Fuller, Schneider, & Daneman, 1995; Wood et al., 2010). The relationship between sensory function and working memory aging can be interpreted by the *information-degradation hypothesis*. Age differences in the working memory task varied with manipulation of visual perceptual stress, and one possible mechanism is that the decline in sensory function requires aging individuals to invest an increasing amount of cognitive resources (e.g. attention) in the perceptually blurred operation span. Specifically, sensory function decline results in increased effortful perceptual processing of stimuli, thereby leaving fewer resources for processing the working memory task and leading to the deterioration of more central functions underlying cognitive performance (Sekuler & Blake, 1987). Another explanation, the *direct cause perceptual degradation hypothesis*, proposes that the perceptual degradation of stimuli due to sensory decline prevents their correct identification, thereby resulting in poorer cognitive performance in tasks relying on such stimuli (Owsley et al., 1998). Perceptual and cognitive functions represent parts of an integrated system, sharing a number of processing resources. It should be evident that losses in any part of the system will stress other parts of the system, especially when informational, complex operations are performed.

Additionally, working memory age differences could be accounted for by processing speed in the previous studies. In the current study results, the age differences in working memory still existed even under medium stress. This indicated that there may be another factor accounting for the age differences in working memory. Processing speed may be one of those factors. Thus, to clarify the effect of processing speed on age differences in working memory, the predictive effect of processing speed on the age differences in working memory, respectively, under non-stress, low and medium visual perceptual stress was analyzed. The results showed that processing speed indeed had a predictive effect on age differences in working memory under non-stress ($B = -.001, SE = .000, t = -2.29, p < .05, \Delta R^2 = .06$). Under visual perceptual stress, the effect of processing speed disappeared, which may indicate that the effect of processing speed is not as great as that of vision (low visual perceptual stress: $B = .000, SE = .001, t = .09, p > .05, \Delta R^2 = .00$; medium visual perceptual stress: $B = .000, SE = .000, t = 1.43, p > .05, \Delta R^2 = .03$). Thus, the remaining age differences in working memory under medium visual perceptual stress may be due to memory itself, or another unknown factor.

The present research is consistent with several previous studies (Lindenberger et al., 2001; Pichora-Fuller et al., 1995). For example, Pichora-Fuller et al. (1995) explored age-related differences in identification and recall of sentence-final words heard on a babble background. They proposed that as SNR decreased, more processing resources were allocated to auditory perception in the old subjects, which made these resources unavailable for more central cognitive processes such as the storage and retrieval functions of working memory.

Consequently, the age effect on recall would be reduced or perhaps even disappear if there were no age-related differences in perceptual processing. Another similar study in the visual modality explained the effect of sensory function aging on cognitive aging with the sum of cognitive resources that can be divided into sensory and cognitive processing resources (Mao & Peng, 2015). When sensory processing occupies more resources, fewer resources remain for cognitive processing. Due to the aging process, young adults' total capacity of cognitive resources is greater than that of old adults. Moreover, young adults have better visual function, which makes their sensory processing occupy fewer resources, and more resources for cognitive processing will be available. Therefore, as visual perceptual stress increased, the young adults' visual function was compromised in the present study, and they needed to allocate more resources to sensory processing, leaving fewer resources to perform the working memory task. Thus, they performed as poorly as the old adults, which caused age differences to decrease as visual perceptual stress increased.

Although the present results are consistent with greater sensory load being associated with cognitive performance, this also consistent with a resource decrement model of aging. Moreover, Li, Allen, Lien, and Yamamoto (2017) were not consistent with even a resource decrement model of aging. They found similar perceptual learning (on a slant detection task) in both younger and older adults, but older adults seem to show a larger improvement in working memory after training than younger adults did (Li et al., 2017). Thus, we infer that sensory function may not directly affect working memory function. There may be other factors, such as strategy (Craik & Byrd, 1982), executive functioning and perceptual learning (Li et al., 2017) that together with sensory function affect working memory aging since age differences in the working memory task did not completely disappear with the increase of visual perceptual stress.

Limitations and Future Directions

The present study found that visual function decline had a negative impact on working memory and processing speed performance, and age differences in working memory, but not in processing speed, were affected by visual function. Due to the age-related decline of visual function, it is necessary to provide old adults with favorable sensory circumstances, such as bright illumination and clear appropriate typeface, which will benefit old adults and lead to better cognitive performance. Old adults can also wear appropriate prescription glasses or use magnifying glasses when they browse for information so as to eliminate the influence of visual function. Although the two proposed hypotheses were confirmed, there are some limitations in the current study.

First, the present study only investigated the role of visual function in processing speed and working memory aging. To achieve this, the generation of visual perceptual stress was based on contrast sensitivity, which is typically defined as the threshold an individual needs for distinguishing between object and background (Langagergaard, Ganer, & Baggesen, 2003). However, in daily life, old adults face many other kinds of visual function decline affecting visual acuity, visual fields, visual search, and others (Glynn et al., 1991; Nebes & Madden, 1983). Whether these kinds of visual function decline will have a similar impact on processing speed and working memory aging needs to be considered in future studies.

Second, age differences in the working memory task did not completely disappear with the increase of visual perceptual stress; namely, old adults' operation span performance was still poorer than that of young adults under high visual perceptual stress. This result may indicate that except for the allocation of resources, there may be other factors, such as strategy (Craik & Byrd, 1982), executive functioning and perceptual learning (Li et al., 2017) that together with sensory function affect working memory aging. Thus, working memory deficits are not just affected by visual task difficulty. Thus, the essential factors of working memory aging and their relationships with other cognitive mechanisms need to be further explored.

Third, it is worth noting that the essential cause of processing speed aging is not yet completely clear and unlikely to be revealed with behavioral research only. Therefore, research applying various neurobiological methods is necessary to further investigate the essential causes of age-related processing speed changes. Future research needs to explore the structure and function of specific brain regions associated with processing speed aging. In addition, a multidisciplinary, holistic perspective to reveal the mechanisms of processing speed aging is imperative, which will also contribute to a better understanding of the relationship between sensory function and processing speed aging.

Fourth, the experimental manipulation of stimulus visual quality likely overestimates the impact of sensory function on age group differences, since experimental manipulations should have a greater effect on older adults due to age-related slowing of perceptual processing (Monge & Madden, 2016; Salthouse, 1996, 2000) and in some cases insufficient cognitive/neural top-down mechanisms, as a result of age-related neural degeneration (Raz et al., 2005), being unable to compensate for decreased bottom-up, perceptual signals in older adults. There was no reference made to the top-down accommodation that occurs in healthy aging that enables aging individuals to maximize performance based on their remaining resources, which also urge us to explore the internal processing mechanism of resource allocation in our future research.

Disclosure of interest

The authors report no conflicts of interest.

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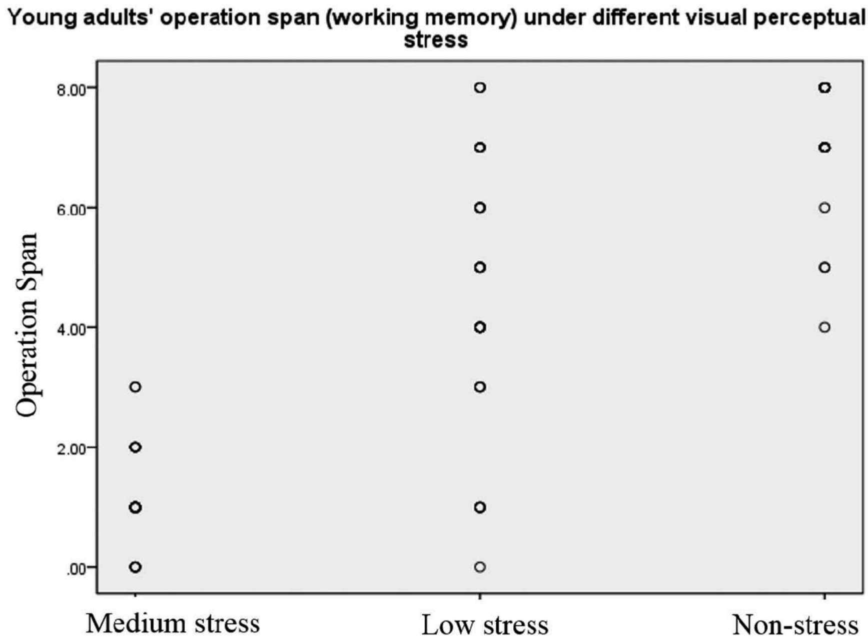
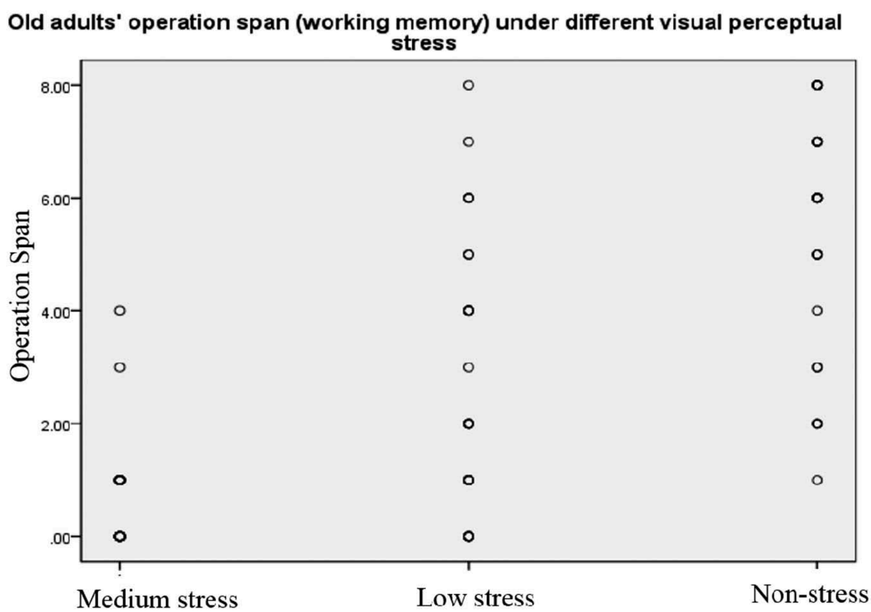
Appendix



Note. Working memory span corresponds to the number of correct calculation and recall.



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