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Review

An examination of age-related differences in attentional control by systems factorial technology

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ABSTRACT

A recent study by Ben-David et al. (2014) indicated that older adults process redundant targets with a larger workload capacity than younger adults, even though older adults exhibit generally slower response times (RTs). To investigate the organization of mental processes that underlie age-related differences, we conducted four experiments with redundant-target tasks. In a series of discrimination-type redundant-target tasks (Experiments 1–3), we replicated the age-related capacity advantage; however, the differences were eliminated in a detection-type redundant-target task (Experiment 4). Our results supported the distractor inhibition account, which suggests that age-related differences were due to less efficiency in attentional control to resolve the response conflict when making discrimination decisions. Moreover, we conducted a simulation using a Poisson parallel interactive model, which assumes an inhibitory interaction between two parallel channels that is a result of a limited attentional capacity. An analysis of the model's predictions indicated the two key findings that may account for the age-related capacity differences: the older adults (1) processed the redundant targets with a higher decision criterion (i.e., more conservative in decision-making) and (2) exhibited a greater violation of context invariance (i.e., less degree of controlled attention in dealing with the response conflict). The extensive modeling analyses highlighted the effect of a decline in attentional control on age-related differences in workload capacity.

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1. Age-related differences in redundant-target signal processing

In our daily life, we operate in a high-workload environment that forces us to divide attention between multiple sources of information to make decisions. An ecologically valid example is that an air control operator may fail to detect critical signals when false signals are simultaneously presented. To mimic this scenario, researchers developed a *redundant-target task*, which can be used to evaluate an individual's capability of simultaneously monitoring multiple channels or displays. In one specific version of the redundant-target tasks, a trial may include two targets (redundant targets, e.g., XX), one target and one distractor (single target, e.g., XO or OX), or two distractors (no target, e.g., OO). With an OR stopping rule, an affirmative response is emitted when any X is detected. In general, the response time (RT) in the redundant-target condition is faster than the faster RT of the two single-target conditions, referred to as a *redundancy gain* (RG) or *redundant-target effect* (RTE) (Miller, 1982). It is worth noting that the redundant-target task enables the assessment of the *workload capacity*, a theory-driven model-based index of the relative processing efficiency when the redundant targets are presented simultaneously to when a single target is presented alone (Townsend & Nozawa, 1995; Wenger & Townsend, 2000) (Please refer to the following section for the details regarding workload capacity).

Despite its ecological pertinence, the redundant-target task, however, has less been studied in aging research than other forms of attentional tasks, such as switching tasks and flanker tasks (Rey-Mermet & Gade, 2018). Among the few available aging studies that used the redundant-target task, the RG has been found to be larger for older adults than younger adults (e.g., Allen, Madden, Groth, & Crozier, 1992; Linnet & Roser, 2012). One may conclude that the RG effect could provide a useful tool to study the age-related differences in cognitive processes. The current study's goal is to demonstrate how another measure — workload capacity can be used to study age-related differences and even more sensitive to reveal the age differences.

In previous literature, the speed of mental processes measured by RTs has been extensively explored in age differences studies. There has been a plethora of research showing the overall RT advantage for the younger when compared to older participants. This phenomena has been best explained by a well-known aging hypothesis: the *general slowing hypothesis* (e.g., Cerella, 1985; Salthouse, 1996), which suggests that the age-related slowing has been affected by a decline in cognitive functioning associated with advancing ages (Choi & Feng, 2016). The age-related slowing has been accounted by different theoretical models, among which the most prominent accounts include the Cerella's linear rate model (Cerella, 1985) and the processing-speed theory (Salthouse, 1996). Both accounts introduced a general slowing factor describing older adults' performance as an approximately linear function of younger adults' performance (Dirk & Schmiedek, 2012). Overall, the general slowing hypothesis is regarded as the most influential and detailed descriptive approach to explain age-related differences in cognitive processes.

One of the major limitations of the general slowing hypothesis is that it cannot be directly used to create predictions regarding the exact relationship between age groups and the expected RG effect. This is primarily due to the absence of a precise mechanistic explanation underlying mental processes as a result of age differences (Birren, 1974; Cerella, 1985, 1990; Salthouse, 1992, 1996). For example, according to this approach the age-related differences could be attributed either to (1) *increased in non-decision time* (i.e., the time for motor execution and stimulus encoding) (Owsley, Jackson, White, Feist and Edwards, 2001; Owsley, Stalvey, Wells, Sloane and McGwin, 2001), or (2) to the *slower information accumulation rate* (Thapar, Ratcliff, & McKoon, 2003). It is clear why the effect of non-decision time cannot be identified by calculating RG, which is characterized by an RT difference measure (i.e., RT(faster single-target) – RT(redundant-target)).[1,2] In contrast, the information accumulation rate can be used to explain the age differences in the RG effect, considering that the accumulation rates for the RT(faster single-target) and RT(redundant-target) may change as a result of aging.

Another line of research has suggested that age-related slowing in some experiments might be associated with other cognitive factors, such as (3) a *more cautious response criterion* (i.e., speed–accuracy trade-off settings), that should be distinguished from the changes in information accumulation rate (Dirk et al., 2017; Ratcliff, Spieler and McKoon, 2004). In a series of studies, the evidence supported the idea that age-related differences can be explained by assuming that older participants adopted a higher, and thus, more conservative response criteria, than younger participants. Within a framework of a sequential sampling approach to describe cognitive operations, a more conservative criterion implies a time–accuracy tradeoff, in which a higher criteria value is associated with longer decision time, but improves overall accuracy (Ratcliff, Thapar, & McKoon, 2001; Ratcliff, Thapar, & Mckoon, 2003). Older participants may adopt more conservative criteria to improve the quality of their decision making, but they can also use it to offset the decline in the accumulation rate due to age impairment in the information extraction (Thapar et al., 2003), which would be also consistent with the general slowing hypothesis.

Recently, an increasing number of studies showed the evidence in favor of (4) *the inhibition of distractor account* (Allen, Groth, Weber, & Madden, 1993; Allen et al., 1992; Ben-David, Eidels, & Donkin, 2014; Hasher & Zacks, 1988; Kane, Hasher, Stoltzfus, Zacks, & Connelly, 1994; Lustig, Hasher, & Zacks, 2007). This hypothesis assumes that older adults are less able to overcome dominant responses or ignore distracting information than younger adults, implying the declined ability of distractor inhibition processing and conflict resolution (Diaz, Johnson, Burke, Truong, & Madden, 2018; Hasher & Zacks, 1988; but see Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Kramer & Madden, 2008). Due to the less efficiency in inhibiting distractors, processing for a single target is easily interfered by distractors, which results in a relative benefit for the redundant targets. However, in the current RG literature, the results are quite mixed. The presence of a distractor may produce the age-related effect (i.e., Allen et al., 1992; Ben-David et al., 2014), reduce the age-related effect (Allen et al., 1993), or have no impact at all (Allen, Weber, & Madden, 1994).

Ben-David et al. (2014) adopted two types of redundant-target tasks: one redundant-target task was tested with the presence of a distractor in the single-target condition (i.e., XO or OX) and the other task was tested without the presence of a distractor (i.e., X_ or _X). They found that older adults had slightly higher accuracy than younger adults (old: 99.1%; young: 98.6%). More importantly, although older adults responded slower than younger adults across all conditions, they exhibited a larger RG and workload capacity only when the task was tested with the presence of distractors in the single-target condition. In contrast, when the task was tested without the presence of distractors in the single-target condition, the RG and workload capacity differences across age groups were eliminated. Moreover, Ben-David et al. conducted a linear ballistic accumulator model (LBA, Brown & Heathcote, 2008), which assumes that two channels accumulate information independently and in parallel to the decision criteria and enables the decomposition of the RT into the decision component and non-decision component, which is related to sensory and motor factors. The LBA results suggest that motor slowing or sensory degradation cannot explain the age-related differences in workload capacity. It is the older adults' inability to inhibit the distractor that leads to the less efficient processing for the identification of a target when the distracting information is concurrently presented, which, in turn, results in a relative benefit for the redundant targets (i.e., a larger RG and workload capacity).

In a more recent study, Yamani, McCarley, and Kramer (2015) conducted a similar redundant-target task with several modifications. Participants were required to judge whether the red targets were X or O with or without the presentation of distracting clutter information. The red targets could be two Xs, two Os, one X, or one O. The results showed that older and younger adults performed the redundant-target task with equivalent levels of accuracy. More importantly, older adults exhibited a larger RG and a higher workload capacity than younger adults particularly when the clutter information was simultaneously presented, although both groups of participants adopted limited-capacity processing. The larger RG and workload capacity in the clutter-present condition than in the clutter-absent condition provides additional empirical support for the inhibition of distractor account. Furthermore, the results may suggest another possibility that to take advantage of the redundancy, older adults would process the redundant targets in a way that involves higher degrees of facilitatory interchannel crosstalk than younger adults

[1] In the RG equation, all component RTs are assumed to have the same non-decision RT part, thus the RG effect is not affected by the cancellation law of addition.

[2] It is notable that the ratio-based RG (i.e., RT(faster single-target)/RT(redundant-target)) or the log-transformed RG would remain unchanged by age-related slowing.

(Yamani et al., 2015, p. 69). However, this explanation contrasts with the common expectations that parallel models with facilitatory interactions would predict supercapacity processing rather than limited-capacity processing (Eidels, Houpt, Altieri, Pei, & Townsend, 2011; Townsend & Nozawa, 1995).

In the present paper, we applied *Systems Factorial Technology* (SFT, Little, Altieri, Fifić, & Yang, 2017; Townsend & Nozawa, 1995) to investigate the age-related differences in workload capacity. We followed the logic of Ben-David et al.'s (2014) study and designed two types of redundant-target tasks: the discrimination-type redundant-target task (Experiments 1–3) and the detection-type redundant-target task (Experiment 4). In the former task context, which is similar to the context used in Ben-David et al.'s (2014) distractor-present condition, distracting information is presented in the single-target condition; therefore, participants must address the interfering information when making decisions. In contrast, in the latter task context, which is exactly the same redundant-target detection task adopted by Townsend and Nozawa (1995) and a variant of Ben-David et al.'s (2014) distractor-absent condition, there is no distracting information in the single-target condition. Notably, the order of the four experiments presented in the paper was not the original order of how we tested the participants. Experiments 1 and 3 shared the same participants, and Experiments 2 and 4 also shared the same participants.

Through the four experiments, the results enable us to better understand the age-related differences in redundant-target signal processing and further tease apart the influence of several possible cognitive mechanisms, such as the (1) non-decision time, (2) information accumulation rate, (3) decision criteria, and the (4) distractor-inhibition processing. For example, if the differences in (1) non-decision time can explain the age differences under the general slowing framework, we would expect similar patterns of results in both the discrimination-type and detection-type redundant-target tasks. In other words, older adults respond slower than younger adults, while the age-related differences in RG and workload capacity would be consistent across the two types of tasks. Alternatively, if the effect of (4) distractor inhibition processing can explain the age differences, we would expect that older adults show a larger RG and workload capacity than younger adults only in the discrimination-type redundant-target task, whereas in the detection-type redundant-target task without presenting the distracting information, the differences across age groups would be eliminated. In the later computational modeling section, we will examine to what extent the various factors (1 to 4) can be used to explain age-related differences.

It is also notable that the present study is not merely a replication of Ben-David et al.'s (2014) findings as we aimed to extend a Poisson interactive parallel model developed by Johnson, Blaha, Houpt, and Townsend (2010) to provide a processing account for the age-related differences in workload capacity (please refer to the *Computational Modeling* section for the model descriptions). Using this model, we can test several parameters (e.g., information accumulation rate, decision criteria, interchannel crosstalk, and violation of context invariance) and explore which combination of parameters can well recover the empirical results (please refer to the following section for the introduction to each parameter). Thus, it enables us to infer whether the age-related differences are a result of a qualitative change in the way of redundant-target signal processing or a quantitative change in the information processing properties.

Therefore, the current findings can be used to challenge the limiting conditions of the previous studies and provide advancement in the diagnosis of underlying processing properties. For example, although Ben-David et al.'s (2014) application of the LBA model enables a detailed examination of the age effect on each decision-making parameter (e.g., base time, drift rate, decision boundary, and starting point), they assumed channel independence, which did not enable the test of interchannel crosstalk. The interactive parallel model allows for the test of the interaction between parallel channels. In addition, whether it is a facilitatory or inhibitory interchannel crosstalk during information accumulation can be diagnosed. More importantly, we included a novel and diagnostic parameter that might be sensitive to the ability of distractor inhibition processing, that is, the *violation of context invariance* (Otto & Mamassian, 2012),[3] which assumes that the processing times for a channel have the same distribution as the marginal processing times for the channel when redundant targets are presented jointly (please refer to the following section for more details). If older adults are more easily affected by the presence of a distractor than younger adults because of the age-related decline in attentional control for distractor inhibition, the processing time for a single target would be slower when the distracting information is presented than when it is presented as a part of the redundant targets. This would result in a larger violation of context invariance. Via the current simulation, we propose a model that integrates several processing properties to recover the capacity profile that underlies the age-related differences.

2. Systems factorial technology

Systems factorial technology (SFT, Little et al., 2017; Townsend & Nozawa, 1995) is a useful and diagnostic tool for making inferences regarding several important properties of cognitive operations, such as the mental architecture, stopping rule, processing dependency, and processing capacity (also termed workload capacity). In the context of redundant-target signal processing, we can diagnose all relevant properties. First, the *mental architecture* denotes the order of redundant-target signal processing. Redundant signals may be processed in a sequential and serial fashion without overlap between the processing times of each channel or in a parallel fashion with all channels processed simultaneously and in parallel. The coactive model is a special case of the parallel models with redundant signals processed in parallel and then pooled together into a single accumulator prior to decision-making. Second, the *stopping rule* denotes the way of how a decision is terminated. A self-terminating stopping rule is adopted when a decision is made based on the completion of one of the redundant-target signals; in contrast, an exhaustive stopping rule is adopted when a decision requires participants to exhaustively process all redundant-target information sources. Third, the *processing dependency* denotes the degrees of how different channels interact with each other during the information accumulation stage. Different channels may be independent of each other or interact with each other with interchannel crosstalk. Notably, the coactive model is a special case in which the two channels completely interchange information prior to decision-making. Finally, the *processing capacity* denotes a change in the processing efficiency as the workload (i.e., the number of channels to be processed) increases. If the individual-channel processing time is not affected by an increase in the workload, the decision system is defined as an unlimited-capacity system. In contrast, if the individual-channel processing time speeds up or slows down because of an increase in the workload, the decision system is defined as a supercapacity or limited-capacity system, respectively.

[3] We thank Dr. Daniel R. Little for providing the insightful suggestion on the test for the violation of context invariance.

The four properties are logically separable from each other; however, certain mental architectures have been associated with a certain range of capacity. For example, a standard serial model is assumed to be of limited capacity; a coactive model is of supercapacity; and a standard parallel model is unlimited in capacity. The unlimited-capacity, independent, parallel (UCIP) model is considered a baseline model that provides the capacity reference value to which other mental architectures are compared, which is central to the development of capacity measures in SFT (Townsend & Eidels, 2011; Townsend & Nozawa, 1995; Wenger & Townsend, 2000).

Recent simulations by Eidels et al. (2011) have shown that parallel models may possess a wide range of capacities, which range from limited capacity to supercapacity. In the first case, there is an interaction between two parallel channels during information accumulation. This is the case in which two channels are not independent of each other (referred to as a violation of *stochastic independence*, Ashby & Townsend, 1986; Colonius, 1986, 1990; Colonius & Townsend, 1997). The processing capacity would become limited when the two channels inhibit with each other (inhibitory interaction) or supercapacity when one channel processing facilitates the processing of another channel (facilitatory interaction) (Eidels et al., 2011). Note that the stochastic independence assumes that the distribution of the redundant-target processing time is equal to the product of the two single-target distributions of the processing time. Thus, $P\left(T_{1,2} \leq t|X_{1,2}\right) = P(T_1 \leq t|X_1) \times P(T_2 \leq t|X_2)$. In the second case, a parallel cognitive system can achieve a supercapacity due to the violation of context invariance (Otto & Mamassian, 2012; Yang, Altieri, & Little, 2018). The violation of context invariance may also cause a parallel model to violate the race-model inequality (Miller, 1982), a routine test for RT data in a redundant-target task, which further suggests that separate processing cannot explain the redundancy gain and supercapacity coactive processing is more likely. The context invariance assumes that the processing times for a channel have the same distribution as the marginal processing times for the channel when redundant targets are presented jointly. That is, $P\left(T_1 \leq t|X_{1,2}\right) = P(T_1 \leq t|X_1)$ and $P\left(T_2 \leq t|X_{1,2}\right) = P(T_2 \leq t|X_2)$. If the mean RT of a channel decreases or the variance of a channel increases when presented as part of a redundant target, a parallel model may violate the race-model inequality (Otto & Mamassian, 2016). Overall, this evidence indicates that the supercapacity measure may be achieved as the result of the influence of several separate cognitive mechanisms.

To improve the diagnostic limitations of capacity function analysis and provide a processing account for the age-related differences, we extended Johnson et al.'s (2010) Poisson interactive parallel model for simulation (please refer to the *Computational Modeling* section for the model descriptions). Several factors were considered in the simulation, including: (1) the processing speed of a channel (i.e., information accumulation rate): it is assumed that older adults may have a lower accumulation rate than younger adults. Several studies have corroborated this idea using the drift-rate diffusion model to show age-related differences in the drift rate (Thapar et al., 2003; but see Ratcliff, Thapar, Gomez and McKoon, 2004); (2) the criterion for the evidence accumulation termination for each channel (i.e., decision threshold): it is assumed that older adults are more conservative with a higher decision criterion (threshold) than younger adults (Raghuram, Lakshminarayanan, & Khanna, 2005). Previous studies have demonstrated that older adults are more *cautious* in making decisions (i.e., higher response threshold settings) to increase their response accuracies (Forstmann et al., 2011; Ratcliff, Thapar and McKoon, 2004). In a lexical decision task, the decision threshold was higher for older adults than younger adults, which can explain the mean RT differences across age groups (Ratcliff, Thapar, Gomez et al., 2004); (3) the crosstalk between the two parallel channels during information accumulation (i.e., inhibitory interaction): it is assumed that two processes compete for limited-capacity attentional resources (van der Heijden, 1975); therefore, the accumulation of a channel would inhibit the accumulation of another channel and vice versa, which results in limited-capacity processing (Eidels et al., 2011); (4) the variation of information processing speed across contexts (i.e., the violation of context invariance): it is assumed that older adults are more sensitive to the stimulus presentation context than younger adults because of less effectiveness and efficiency in attentional control for distractor inhibition (Andrés, Guerrini, Phillips, & Perfect, 2008; Braver et al., 2001; Colcombe, Kramer, Erickson, & Scalf, 2005; Lustig et al., 2007; Rey-Mermet & Gade, 2018). The information accumulation rate for a channel with a concurrent presentation of distracting information would become lower than the rate of the channel when it is presented as a part of redundant targets, thus resulting in a violation of context invariance. In the *Computational Modeling* section, we will test the effect of each parameter independently to recover the capacity functions and ultimately propose an integrative account to explain the age-related differences.

3. SFT and workload capacity

By definition, workload capacity denotes the variation of the processing efficiency as a function of workload (Townsend & Eidels, 2011; Townsend & Nozawa, 1995). Townsend and Nozawa (1995) used the integral of the hazard function, *H(t)*, to represent the processing efficiency, which is interpreted as the amount of work performed in units of the to-be-completed processes at a certain time point t where the hazard function, *h(t)*, provides the instantaneous rate of completion at any time t, given that the process has not yet completed. That is, $H(t) = \int h(t)\,dt$, where $h(t) = \frac{f(t)}{P(T>t)}$ and $f(t)$ is the probability density at time t. Assuming statistical independence, the workload capacity is defined by dividing the integrated hazard function of the redundant-target condition by the predicted performance from the UCIP model, which is the sum of the integrated hazard functions of the two single-target conditions. Thus, workload capacity is expressed as:

$$C(t) = \frac{H_{1,2}(t)}{H_1(t) + H_2(t)}, \tag{1}$$

where $t > 0$. A value of $C(t) = 1$ suggests an unlimited-capacity processing: the processing efficiency of an individual channel is *not* affected by the change in workload. $C(t) > 1$ suggests supercapacity processing: increasing the number of the to-be-processed channels speeds up the processing time of an individual channel. $C(t) < 1$ indicates limited-capacity processing: increasing the workload slows down the processing time of an individual channel.

However, the standard approach to measure the workload capacity, previously outlined, cannot be used to estimate a system's capacity when distracting information is simultaneously presented. Little, Eidels, Fific, and Wang (2015) proposed the resilience coefficient, which is used to reflect the efficiency of an information processing system when the single target conditions (A and B) contain distracting information (AY and XB) and can be expressed as

$$R(t) = \frac{H_{AB}(t)}{H_{AY}(t) + H_{XB}(t)}, \tag{2}$$

where the subscripts A and B denote the target information sources (i.e., task-relevant information that can be used to make a correct decision) and the subscripts X and Y denote the distracting information. Assuming parallel processing,[4] the inferences of *R(t)* are the same as the inferences of *C(t)*.

To provide a statistical basis of the test of capacity, the raw capacity scores are transformed to the statistic Cz (Houpt & Townsend, 2012), which provides a summary measure of the entire capacity function, aggregated over time. Values are distributed as a standard normal distribution such that we can apply z test to Cz. A value of 0 indicates unlimited capacity, a negative value indicates limited capacity, and a positive value indicates supercapacity.

Workload capacity is regarded as a sensitive measure to investigate age-related cognitive individual differences, which may provide more information than traditional accuracy and mean RT measures. Individual differences in workload capacity have been demonstrated in various task contexts (e.g., Ben-David et al., 2014; Chang, Little, & Yang, 2016; Chang & Yang, 2014; Gottlob, 2007; Yamani et al., 2015; Yu, Chang, & Yang, 2014). These individual differences may be attributed to several factors, such as cognitive aging, cognitive ability (e.g., working memory capacity), and personality traits (e.g., Zhong–Yong tendency, a Chinese cultivated cognitive style of middle-way thinking). Thus, we took the advantages of the workload capacity measures combined with a simulation approach to investigate the age-related differences in information processing.

4. Experiment 1

In Experiment 1, we aimed to replicate Ben-David et al.'s (2014) distractor-present condition. An X/O discrimination task was conducted in which participants were required to identify the target X among the distractor O with a manipulation of the number of targets (0/1/2). We expect to observe that older adults would show slower mean RTs, a larger RG, and a larger resilience capacity coefficient than younger adults.

4.1. Methods

4.1.1. Participants

Fourteen younger (7 males and 7 females, mean age = 20.29 ± 2.95) and eleven older (5 males and 6 females, mean age = 66.73 ± 4.67) adults[5] participated in this experiment (please refer to Table 1 for the demographic information for each group and each experiment). Participants recruited were right-handed, free of neurological and psychological disorders, and had normal or corrected-to-normal vision through Internet advertisements in this study. The Montreal Cognitive Assessment (MoCA) was used to screen participants for cognitive impairment based on the Taiwanese standard (< 24 were mild cognitive impairment) (Tsai et al., 2012). They signed a written informed consent prior to the experiment, and they received NTD 200 per hour after they completed the experiment. The ethics approval for the study was obtained from the Ethics Committee of Department of Psychology at National Cheng Kung University, and the experiment was conducted in accordance with the approved guidelines and regulations.

4.1.2. Equipment

All stimuli were presented on a 19-in. CRT monitor (CTX) with a refresh rate of 85 Hz and a display resolution of 1024 × 768 pixels. The viewing distance was 60 cm. The experiment was programmed with E-prime 1.1 (Schneider, Eschman, & Zuccolotto, 2002).

[4] Note that the inferences of R(t) and C(t) may be different given serial processing.

[5] All the participants in the four experiments are familiar with Latin alphabets.

Table 1
Demographic information of the participants for Experiments 1–4.

Experiments	Younger	Older
Experiments 1 and 3		
n (male/female)	14 (7/7)	11 (5/6)
Mean age (*SD*)	20.29 (2.95)	66.73 (4.67)
Range	18–30	61–75
Experiments 2 and 4		
n (male/female)	15 (7/8)	13 (7/6)
Mean age (*SD*)	20.80 (1.82)	69.38 (2.93)
Range	19–24	65–76

SD denotes standard deviation.

4.1.3. Stimuli, design, and procedure

In the X/O discrimination task (Fig. 1), participants were required to discriminate target X from distractor O. The test display consisted of two letters (X, O), which were 1° (horizontal) × 1° (vertical). In the redundant-target condition, the test display consisted of two Xs that were presented at the locations above and below the central fixation point with a distance of 6°. In the single-target condition, the test displayed consisted of an X and an O, in which the X was pressed above or below the fixation point. In the target-absent condition, the test display consisted of two Os. Each condition was equally probable and randomly intermixed within a block. After the participants practiced for 20 trials, they performed 4 blocks of 80 formal test trials.

Each trial was initiated with a 500 ms fixation point (see Fig. 1 for an illustration). Following a uniformly distributed random foreperiod that ranged from 50 ms to 850 ms, a test display was presented until the participants responded or until 1500 ms elapsed. The participants had to make a two-alternative-forced-choice (2AFC) response as accurately and rapidly as possible when they detected an X. If *either* or *both* Xs were detected, the participants were required to press the key (/) on the keyboard; if *no* X was detected, they had to press the key (z) on the keyboard. The inter-trial interval (ITI) was 500 ms.

4.2. Results

Data from the practice trials were excluded from the analysis, and correct RTs were included for the analysis at the mean and distribution level. Table 2 shows the mean performance.

4.2.1. Accuracy

The accuracy was analyzed with a mixed-design two-way analysis of variance (ANOVA). The results showed that there was a significant main effect of the test condition [$F(3, 69) = 5.10$, $p = .003$, $\eta_p^2 = .181$]. Post hoc comparisons showed that the accuracy was higher for the redundant-target condition (0.99 ± 0.02) and top-X (0.99 ± 0.02) than the target-absent condition (0.98 ± 0.02) (*ps* <.05). The main effects of group and the interaction between the test condition and group did not reach the significance level (*ps* = .26 and.79, respectively).

4.2.2. RT

The mean RTs of the correct trials were analyzed with a mixed-design two-way ANOVA. The results showed that the main effect of the test condition was significant [$F(3, 69) = 48.48$, $p < .001$, $\eta_p^2 = .678$]. Post hoc comparisons showed that the mean RT of the redundant-target condition (483.11 ± 86.67 ms) was the fastest, and the mean RT of the target-absent condition (557.65 ± 95.99 ms) was the slowest, whereas the mean RTs of the two single-target conditions (top-X: 494.05 ± 98.46 ms; bottom-X: 521.50 ± 111.76 ms) were in-between (*ps* <.05 for all comparisons). The main effect of group was significant [$F(1, 23) = 70.26$, $p < .001$, $\eta_p^2 = .75$], which suggests that the older adults

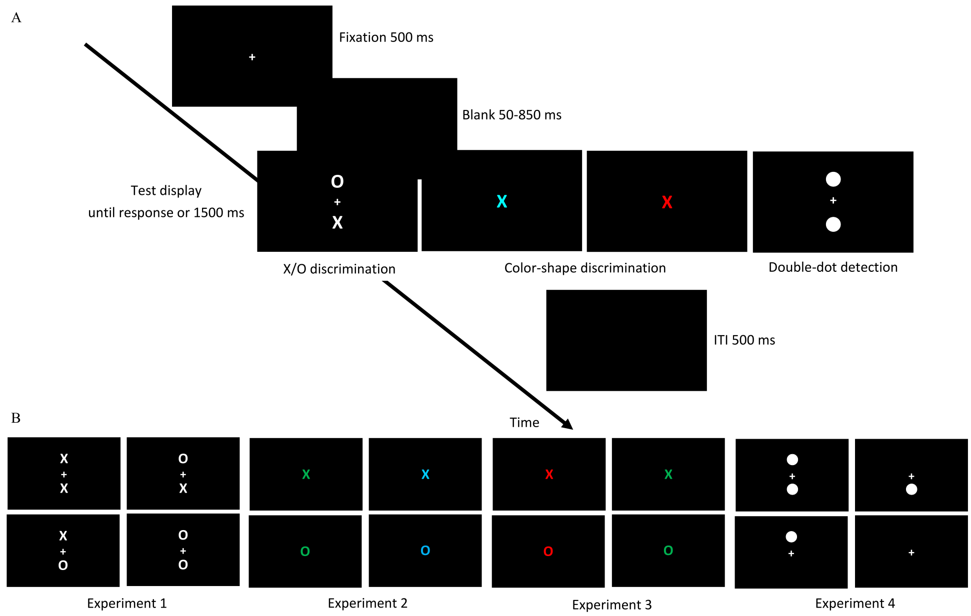

Fig. 1. (A) An illustration of the experimental procedure and (B) all the possible test conditions in Experiments 1–4 . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Mean RT, RG, log-transformed RG, and accuracy for the younger and older adults in Experiments 1–4.

	Experiment 1		Experiment 2		Experiment 3		Experiment 4	
	Younger ($n = 14$)	Older ($n = 11$)	Younger ($n = 15$)	Older ($n = 13$)	Younger ($n = 14$)	Older ($n = 11$)	Younge ($n = 15$)	Older ($n = 13$)
RT								
Target-absent	487.05 (45.47)	647.50 (59.74)	532.38 (92.69)	708.09 (128.42)	466.90 (48.66)	684.74 (70.90)	726.96 (76.58)	872.40 (113.20)
Redundant-Target	419.27 (41.29)	564.35 (53.33)	415.42 (80.83)	549.59 (60.01)	390.87 (45.00)	548.88 (72.50)	424.66 (75.99)	494.34 (44.11)
Single-target 1	439.04 (45.57)	626.45 (75.11)	475.48 (85.34)	674.33 (82.56)	420.45 (45.38)	635.26 (91.68)	449.85 (74.65)	528.50 (46.49)
Single-target 2	420.84 (38.63)	587.22 (65.38)	463.88 (99.66)	616.06 (78.74)	445.87 (48.03)	620.11 (81.17)	433.36 (75.48)	494.96 (35.35)
RG	−1.61 (18.49)	21.65 (27.81)	37.03 (20.64)	65.26 (38.66)	24.13 (12.56)	62.88 (24.45)	5.74 (17.59)	0.61 (13.77)
log RG	0.001 (0.017)	0.017 (0.02)	0.033 (0.02)	0.041 (0.024)	0.024 (0.012)	0.044 (0.013)	0.007 (0.017)	0.000 (0.01)
Accuracy								
Target-absent	0.98 (0.02)	0.97 (0.02)	0.95 (0.04)	0.96 (0.04)	0.97 (0.02)	0.97 (0.02)	0.95 (0.04)	0.92 (0.05)
Redundant-Target	1.00 (0.01)	0.99 (0.03)	1.00 (0.00)	1.00 (0.01)	1.00 (0.00)	1.00 (0.00)	0.96 (0.03)	0.97 (0.03)
Single-target 1	0.99 (0.02)	0.98 (0.02)	0.98 (0.04)	0.95 (0.10)	0.99 (0.01)	0.99 (0.02)	0.95 (0.03)	0.95 (0.04)
Single-target 2	1.00 (0.01)	0.98 (0.03)	0.99 (0.02)	0.98 (0.03)	0.99 (0.01)	0.99 (0.02)	0.96 (0.05)	0.97 (0.03)

1. Values in parentheses represent standard deviation.
2. The single-target 1 condition represents the bottom-X (Experiment 1), green O (Experiment 2), red O (Experiment 3), and bottom-dot (Experiment 4) condition, respectively. The single-target 2 condition represents the top-X (Experiment 1), cyan X (Experiment 2), green X (Experiment 3), and top-dot (Experiment 4) condition, respectively.

(606.38 ± 69.85 ms) responded slower than the younger adults (441.55 ± 49.99 ms). Moreover, the interaction also reached the significance level [$F(3, 69) = 3.30$, $p = .040$, $\eta_p{}^2 = .125$]. The significant interaction indicated a critical RT difference between the test conditions across age groups, which showed that there was a significant RT difference between the two single-target conditions for the older adults (top-X: 587.22 ± 65.38 ms vs. bottom-X: 626.45 ± 75.11 ms) ($p = .020$); however, this difference was not identified for the younger adults (top-X: 420.84 ± 38.63 ms vs. bottom-X: 439.04 ± 45.57 ms) ($p = .106$).

4.2.3. RG

We subsequently computed the log-transformed RG[6] by subtracting the mean log-transformed RT of the redundant-target condition from the minimum of the mean log-transformed RTs of the two single-target conditions. An independent samples t test was conducted to compare the RG between the two groups. The results showed that the log-transformed RG were significantly different across age groups [old: 0.017 ± 0.020, young: 0.001 ± 0.017, $t(23) = 2.19$, $p = .039$, Cohen's $d = 0.86$], and the log-transformed RG was significantly greater than 0 only for the older adults [old: $t(10) = 2.911$, $p = .016$; young: $t(13) = 0.273$, $p = .789$]. Similar results have been observed in the raw RG without any log-transformation [old: 21.65 ± 27.81, young: −1.61 ± 18.49, $t(23) = 2.51$, $p = .020$, Cohen's $d = 0.98$], and RG was significantly greater than zero only for the older adults [old: $t(10) = 2.582$, $p = .027$; young: $t(13) = -0.326$, $p = .750$].

4.2.4. Workload capacity

Fig. 2 plots the resilience capacity coefficient functions for each group. From our visual inspection, the older adults had a larger workload capacity than the younger adults. To verify the results, we conducted an independent t test to compare the z transformed capacity scores across the age groups, i.e., Houpt–Townsend statistics (Houpt & Townsend, 2012). The results showed that the older adults (−2.25 ± 1.50) had a larger Cz than the younger adults (−4.17 ± 1.59) [$t(23) = 3.07$, $p =$

6 We also present the results of the raw RG without any log-transformation in Table 2.

.005, Cohen's $d = 1.24$], and the mean *Cz*s for both groups were significantly smaller than zero [old: $t(10) = -4.96$, $p = .001$; young: $t(13) = -9.83$, $p < .001$], which suggests limited-capacity processing.

4.3. Discussion

In Experiment 1, we conducted an X/O discrimination task as employed in Ben-David et al. (2014). The current results replicated their findings. Older adults and younger adults had similar levels of accuracy in making a discrimination decision. More importantly, although older adults responded slower than younger adults with longer mean RTs, they had a larger RG and workload capacity than the younger adults. How should the results be interpreted? Note that in the current task settings, participants had to simultaneously monitor two spatial channels for a correct decision. One reasonable explanation is that it is possible that older adults are less efficient in simultaneously monitoring two far-separated spatial locations than younger adults as previous studies have suggested that older adults appear to be impaired in the "useful field of view", which reduced the ability to rapidly detect and localize targets (Ball, Beard, Roenker, Miller, & Griggs, 1988; Cosman, Lees, Lee, Rizzo, & Vecera, 2012; Owsley, Ball, & Keeton, 1995; Wood & Owsley, 2014), or older adults have a smaller "functional visual field" than younger adults such that older adults are forced to serially scan for a large part of the display, whereas younger adults could process a large area in parallel (Tanja, Frans, Wiebo, & Aart, 2004). The decline in spatial attention may force old adults to rely on the processing of the redundant targets. We further test the possibility of the age related declined spatial attention span in Experiments 2 and 3.

5. Experiment 2

To examine the role of a possible decreased spatial attention span account, we examined the workload capacity when processing requires discrimination on two independent visual features (color and shape) jointly presented at the same spatial location. If the age-related differences are associated with the narrowing of the spatial attention span, we would expect that when two features are presented at the same location, older adults would show similar levels of capacity to younger adults. Alternatively, if the age-related differences are associated with the level of attentional control in inhibiting distractors and resolving the response conflict, we would expect to observe a similar pattern of results as obtained in Experiment 1.

5.1. Methods

5.1.1. Participants

Fifteen younger (7 males and 8 females, mean age = 20.80 ± 1.82) and thirteen older (7 males and 6 females, mean age = 69.38 ± 2.93) adults participated in this experiment. Participants recruited were right-handed, free of neurological and psychological disorders, and had normal or corrected-to-normal vision through Internet advertisements in this study. The Montreal Cognitive Assessment (MoCA) was used to screen participants for cognitive impairment based on the Taiwanese standard (< 24 were mild cognitive impairment) (Tsai et al., 2012). They received NTD 200 per hour after they completed the experiment. They signed a written informed consent prior to the experiment.

5.1.2. Stimuli, design, and procedure

In the color-shape discrimination task (Fig. 1), a test display consisted of a letter that was an O or an X in shape, green (RGB: 0,167,0) or cyan (RGB: 0,178,177) in color, and 1° (horizontal) $\times$1°(vertical). In the redundant-target condition, the test stimuli consisted of both the target color and target shape (green X). In the single-target condition, the test stimuli consisted of the target color or the target shape (green O, cyan X). In the target-absent condition, neither the target color nor target shape was presented (cyan O). Each condition was equally probable and randomly intermixed within a block. After the participants practiced for 20 trials, they performed 4 blocks of 80 test trials.

The procedure was exactly the same as that used in Experiment 1. The participants had to make a 2AFC response as accurately and rapidly as possible. If the participants detected the target color, target shape, or both, the participants were required to press the key (/) on the keyboard; if *neither* the target color *nor* the target shape was detected, they had to press the key (z) on the keyboard.

5.2. Results

Data from the practice trials were excluded from the analysis, and correct RTs were included for further analysis. Table 2 shows the mean performance.

5.2.1. Accuracy

The accuracy was analyzed with a mixed-design two-way ANOVA. The results showed that there was a significant main effect of the test condition [$F(3, 78) = 6.91$, $p < .001$, $\eta_p^2 = .21$]. Post hoc comparisons showed that the accuracy was higher for the redundant-target condition (1.00 ± 0.01) than the target-absent condition (0.95 ± 0.04) ($p < .05$). The main effects of group and the interaction did not reach the significance level (*ps* = .38 and.33, respectively).

5.2.2. RT

The mean RTs of the correct trials were analyzed with a mixed-design two-way ANOVA. The results indicated that there was a main effect of test condition [$F(3, 78) = 61.32$, $p < .001$, $\eta_p^2 = .70$]. The RTs were the fastest for the redundant-target condition (477.71 ± 98.14 ms) and the slowest for the target-absent condition (613.96 ± 140.52 ms), and the two single-target conditions (cyan X: 534.54 ± 117.81 ms; green O: 567.80 ± 130.41 ms) were in-between (*ps* <.05 for all comparisons). The main effect of group was significant [$F(1, 26) = 27.07$, $p < .001$, $\eta_p^2 = .51$], which suggests that the older adults (637.02 ± 107.21 ms) responded slower than the younger adults (471.79 ± 97.13 ms). Moreover, the interaction also reached the significance level [$F(3, 78) = 3.59$, $p = .017$, $\eta_p^2 = .12$]. The significant interaction indicated a critical RT difference between the test conditions across age groups, which showed that there was a significant RT difference between the two single-target conditions for the older adults (cyan X: 616.06 ± 78.74 ms vs. green O: 674.33 ± 82.56 ms) ($p = .009$); however, this difference was not identified for the younger adults (cyan X: 463.88 ± 99.66 ms vs. green O: 475.48 ± 85.34 ms) ($p = .35$). These results implied that the older adults found it more difficult to discriminate colors than shapes (Brewer & Barton, 2016; Habak, Wilkinson, & Wilson, 2009), whereas the discriminability of colors and shapes was similar for the younger adults.

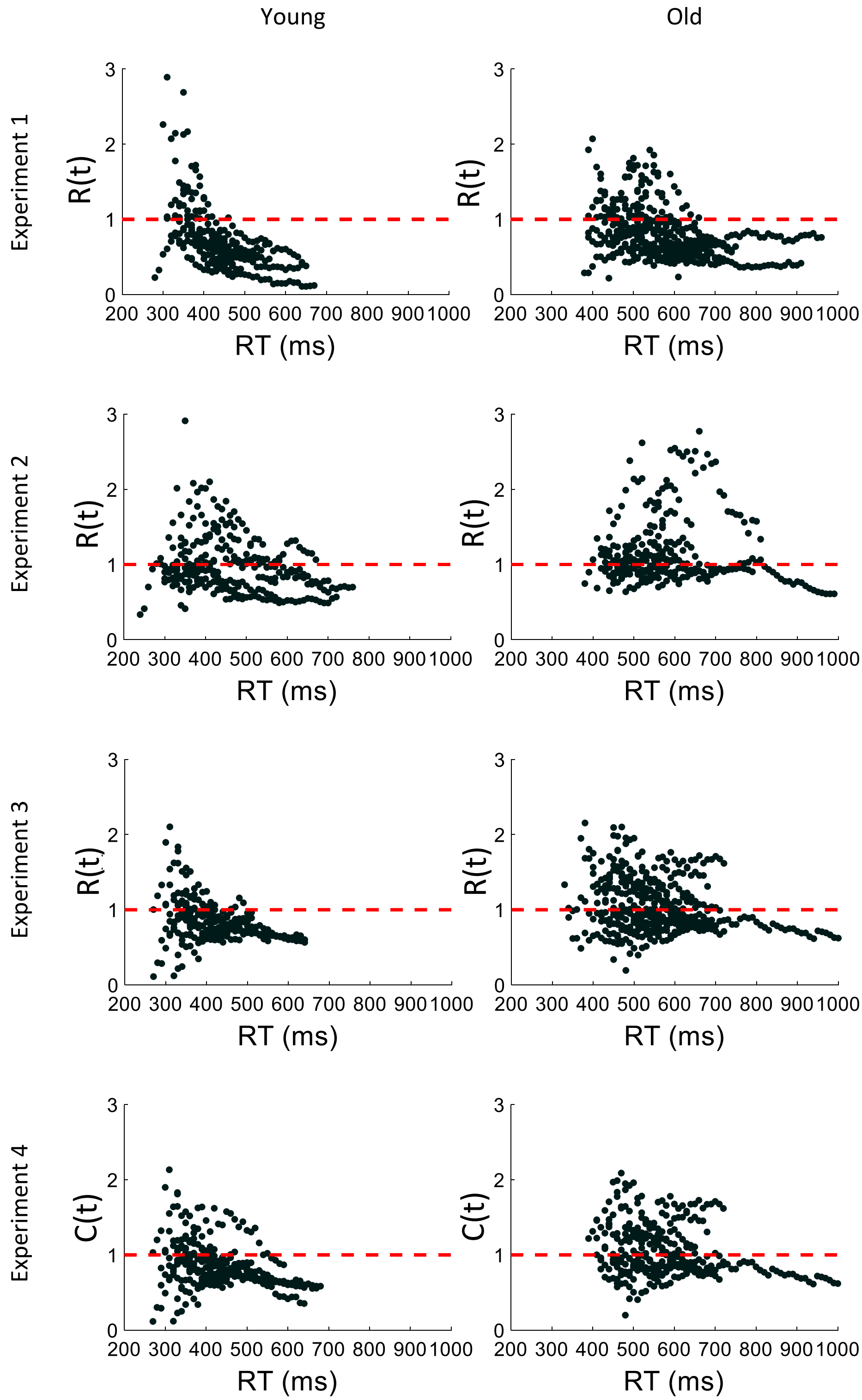

Fig. 2. Plots of the capacity coefficient *R(t) or C(t)* for the younger and older adults in Experiment 1–4.

5.2.3. RG

An independent samples t test was conducted to compare the log-transformed RG between the two groups. The results showed that there were no significant differences across age groups although there was a trend showing that older adults had a larger log-transformed RG than the younger adults [old: 0.041 ± 0.024, young: 0.033 ± 0.020, $t(26) = 1.05$, $p = .305$]. The log-transformed RGs for both groups were significantly greater than zero [old: $t(12) = 6.214$, $p < .001$; young: $t(14) = 6.226$, $p < .001$]. However, there was a significance difference in the raw RG across age groups [old: 65.26 ± 38.66, young: 37.03 ± 20.64, $t(26) = 2.46$, $p = .021$, Cohen's $d = 0.91$], and the RGs for both groups were significantly greater than zero [old: $t(12) = 6.087$, $p < .001$; young: $t(14) = 6.949$, $p < .001$].

5.2.4. Workload capacity analyses

Fig. 2 shows the plots of the resilience capacity coefficient function for each group. From our visual inspection, the older adults had a larger capacity than the younger adults. In addition, the results showed that the older adults (0.92 ± 1.72) had a larger Cz than the younger adults (-0.69 ± 2.04) [$t(26) = 2.239$, $p = .034$, Cohen's $d = 0.85$], whereas the mean Czs for the two groups were not significantly different from zero [older: $t(12) = 1.92$, $p = 0.08$; younger: $t(14) = -1.32$, $p = 0.21$], which suggests unlimited-capacity processing.

5.3. Discussion

In Experiment 2, the participants were required to discriminate colors and shapes that were jointly presented at the same spatial location. Similar to Experiment 1, we identified similar accuracy levels for the different age groups. More importantly, the older adults had a larger workload capacity than the younger adults, although the older adults responded slower than the younger adults. Note that there was a trend showing that older adults had a larger log-transformed RG than younger adults, but it did not reach the significance level. These findings suggested that the age-related differences were not a result of the decline of spatial attention functioning. Instead, the age-related differences may have occurred because both tasks in Experiments 1 and 2 involved the processes of distractor inhibition. Older adults may have less resources of controlled attention such that the information accumulation process might be easily affected by the distracting information. Therefore, the individual-channel processing time was easily affected by the stimulus presentation context, thereby leading to a violation of the context invariance, which, in turn, results in the capacity differences across age groups. We will test the account of the violation of context invariance in the latter simulation.

6. Experiment 3

In Experiment 2, several older adults reported that they had difficulty in discriminating green from cyan, and this self-report was verified by showing that the older adults had significantly larger RT differences in discrimination between colors and shapes than the younger adults. Previous literature has shown that as age increases, the colors seen by elderly people become darker due to the yellowing of the human lens, which may decrease their sensitivity in discriminating cyan from green color (Hassan, Kugimiya, Tanaka, Tanaka, & Paramesran, 2015). Furthermore, as suggested by Monge and Madden (2016), some age-related cognitive decline may be simply due to color perception deficiencies as predicted by the information degradation hypothesis (Lindenberger & Baltes, 1994). We suspected that the relative difficulty in color discrimination would make the older participants rely more on the shape-target or redundant-target signals for decision-making. The unequal weighting processing between two channels might result in an artifact of a larger capacity. Therefore, in Experiment 3, we adjusted the color discrimination difficulty using red as the target color and green as the distractor color. According to the Red–Green–Blue (RGB) color wheel, green and cyan are close to each other, whereas red and green are more distinct; therefore, with increasing age, it may become more difficult for older adults to discriminate similar RGB colors. Prior to the experiment, all participants were administered a prescreening test to ensure that they did not have red–green color blindness. If the results of Experiment 2 resulted from the unequal weighting of the two channels, we expect the older adults and younger adults would show similar levels of workload capacity when the color and shape discriminability are well controlled. Otherwise, we would expect to observe the same findings obtained in Experiment 2.

6.1. Methods

6.1.1. Participants

The participants were individuals who had participated in Experiment 1. Prior to the formal experiment, all participants completed a screening test to ensure that they were able to easily discriminate red from green.

6.1.2. Stimuli, design, and procedure

The stimuli, design, and procedure were exactly the same as those used in Experiment 2 with the exception of the color of the test stimuli. The target color was defined as red (RGB: 255,0,0) and the distractor color was defined as green (RGB: 0,167,0).

6.2. Results

6.2.1. Accuracy

The accuracy was analyzed with a mixed-design two-way ANOVA. The results showed that there was a significant main effect of the test condition [$F(3, 69) = 21.76$, $p < .001$, $\eta_p^2 = .49$]. Post hoc comparisons showed that the accuracy was higher for the redundant-target condition (1.00 ± 0.00) than the target-absent condition (0.97 ± 0.02) ($p < .001$). The main effects of group and the interaction did not reach the significance level ($ps = .45$ and.81, respectively).

6.2.2. RT

The mean RTs of the correct trials were analyzed with a mixed-design two-way ANOVA. The results indicated that there was a main effect of the test condition [$F(3, 69) = 77.94$, $p < .001$, $\eta_p^2 = .77$]. The mean RTs were the fastest for the redundant-target condition (460.39 ± 98.47 ms) and the slowest for the target-absent condition (562.75 ± 124.73 ms) ($p < .001$), and the two single-target conditions were in-between (green X: 522.54 ± 108.57 ms; red O: 514.97 ± 128.30 ms). The main effect of group was significant [$F(1, 23) = 63.70$, $p < .001$, $\eta_p^2 = .74$], which suggests that the older adults (622.25 ± 91.10 ms) responded slower than the younger adults (431.02 ± 53.79 ms). Moreover, the interaction also reached the significance level [$F(3, 69) = 9.11$, $p < .001$, $\eta_p^2 = .28$]. The significant interaction indicated a critical RT difference between the test conditions across age groups, which showed that the RT difference between the two single-target conditions was not significant for the older adults (green X: 620.11 ± 81.17 ms vs. red O: 635.26 ± 91.68 ms) ($p = 1.00$), thereby validating the manipulation of relative discriminability between two features. In contrast, there was a significant RT difference between the two single-target conditions for the younger adults (green X: 445.87 ± 48.03 ms vs. red O: 420.45 ± 45.38 ms) ($p = .011$), which suggests that the younger adults may have been able to take advantage of the color information when color discrimination became relatively easy.

6.2.3. RG

An independent samples t test was conducted to compare the log-transformed RG between the two groups. The results showed that the older adults (0.044 ± 0.013) had a larger log-transformed RG than the younger adults (0.024 ± 0.012) [$t(23) = 3.96$, $p = .001$, Cohen's $d = 1.60$], and the log-transformed RGs for both groups were significantly greater than zero [old: $t(10) = 10.83$, $p < .001$; young: $t(13) = 7.739$, $p < .001$]. Similarly, there was a significant difference in the raw RG across age groups [old: 62.88 ± 24.45, young: 24.13 ± 12.56, $t(23) = 5.15$, $p < .001$, Cohen's $d = 1.99$], and the RGs for both groups were significantly greater than zero [old: $t(10) = 8.530$, $p < .001$; young: $t(13) = 7.190$, $p < .001$].

6.2.4. Workload capacity

Fig. 2 shows the plots of the resilience capacity coefficient function for each group. From our visual inspection, the older adults had a larger capacity than the younger adults. In addition, the results showed that the older adults (0.00 ± 1.77) had a larger *Cz* than the younger adults (-1.75 ± 1.21) [$t(23) = 2.94$, $p = .007$, Cohen's $d = 1.15$]; the mean *Cz* was not significantly different from 0 for the older adults [$t(10) = 0.00$, $p = 1.00$], whereas it was significantly different from 0 for the younger adults [$t(13) = -5.41$, $p < 0.001$], which suggests unlimited-capacity processing for the older adults and limited-capacity processing for the younger adults.

6.3. Discussion

The results of Experiment 3 replicated the findings of Experiment 2. Although the difficulty in color discrimination was adjusted, we identified a larger RG and workload capacity for the older adults than the younger adults. Therefore, the present results ruled out the possibility that unequal weighting of the two channels (color and shape) would result in an artifact of a larger workload capacity. Our results further supported that it may be the discrimination process involving the distractor inhibition that explains the age-related differences in the workload capacity.

7. Experiment 4

In contrast to the first three experiments, Experiment 4 tested the redundant-target signal processing using a simple detection task without presenting distracting information. We used a typical detection-type redundant-target task employed in many previous studies (e.g., Townsend & Nozawa, 1995) to assess the workload capacity. By comparing the results of the present experiment and the first three experiments, we can understand whether presenting the distracting information in the single-target condition where the participants were required to discriminate the target from the distractor is a critical factor that explains the age-related differences in the workload capacity. If the inhibition of distractor account is valid, we would expect that older adults would show a larger capacity than younger adults only in the discrimination-type redundant-target tasks (Experiments 1–3), whereas in the detection-type redundant-type task (Experiment 4) without the presentation of distracting information, the capacity differences would be eliminated.

7.1. Methods

7.1.1. Participants

The participants were individuals who had participated in Experiment 2.

7.1.2. Stimuli, design, and procedure

The design and procedure were the same as those used in the first three experiments, with the exception of the test stimuli. A $1^\circ \times 1^\circ$ light dot (luminance $= 0.031$ cd/m^2) was presented 6° above and/or below the fixation point. In the redundant-target condition, both locations contained a light dot. In the single-target condition, either top or bottom location contained a light dot. In the target-absent condition, neither location contained a light dot. If participants detected a dot, they were required to press the key (/) on the keyboard; otherwise, they had to press the key (z) on the keyboard.

7.2. Results

7.2.1. Accuracy

The accuracy was analyzed with a mixed-design two-way ANOVA. The results showed that there was a significant main effect of test condition [$F(3, 78) = 3.75$, $p = .014$, ${\eta_p}^2 = .13$]. However, the post hoc comparisons showed that the accuracy was similar across all conditions (all $ps > .05$). The main effects of group and the interaction did not reach the significance level ($ps = .94$ and.10, respectively).

7.2.2. RT

The mean RTs of the correct trials were analyzed with a mixed-design two-way ANOVA. The results indicated that there was a main effect of the test condition [$F(3, 78) = 309.11$, $p < .001$, ${\eta_p}^2 = .92$]. The mean RTs were the fastest for the redundant-target condition (457.01 ± 71.49 ms) and the slowest for the target-absent condition (794.49 ± 119.13 ms), and the two single-target conditions (top-dot: 461.96 ± 67.00 ms; bottom-dot: 486.37 ± 73.79 ms) were in between ($ps < .05$). There were no significant differences between the two single-target conditions ($p = 0.24$). The main effect of group was significant [$F(1, 26) = 16.44$, $p < .001$, ${\eta_p}^2 = .39$], which suggests that the older adults (597.55 ± 173.62 ms) responded slower than the younger adults (508.71 ± 147.20 ms). Moreover, the interaction reached the significance level [$F(3, 78) = 4.18$, $p = .008$, ${\eta_p}^2 = .14$]. The significant interaction indicated that the RT differences between the target-present and target-absent conditions were larger for the older adults than the younger adults.

7.2.3. RG

An independent samples t test was conducted to compare the log-transformed RG between the two groups. The results showed that there were no significant differences across age groups [old: 0.000 ± 0.010, young: 0.007 ± 0.017, $t(26) = -1.30$, $p = .205$], and the log-transformed RGs for both groups were not significantly different from zero [old: $t(12) = 0.022$, $p = 0.983$; young: $t(14) = 1.621$, $p = 0.127$]. Similar result has been shown in the raw RG [old: 0.61 ± 13.77, young: 5.74 ± 17.59, $t(26) = -.850$, $p = .403$], and the RGs for both groups were not significantly different from zero [old: $t(12) = 0.159$, $p = 0.877$; young: $t(14) = 1.264$, $p = 0.227$].

7.2.4. Workload capacity analyses

Fig. 2 shows the plots of the capacity coefficient function for each group. From our visual inspection, the older adults had similar levels of capacity as the younger adults. In addition, the results showed that there were no significant differences in the mean *Cz* across age groups [old: -3.61 ± 1.13, young: -3.65 ± 1.45; $t(26) = 0.08$, $p = 0.94$], with a Cz less than 0 for both groups, thus suggesting limited-capacity processing [old: $t(12) = -11.57$, $p < .001$; young: $t(14) = -9.76$, $p < .001$].

7.3. Discussion

Experiment 4 adopted a detection-type redundant-target task employed in many previous studies (e.g., Townsend & Nozawa, 1995). The detection-type redundant-target task does not require participants to discriminate targets from distractors such that no response conflict existed in the single-target condition. In this task context, we observed that the older adults still responded slower than younger adults; however, most importantly, the older adults and younger adults had similar levels of workload capacity without statistical difference. By comparing the present results and the findings of Experiments 1–3, we suggest that it is the inhibition of distractor process that explains the age-related differences in the workload capacity identified in the first three experiments and previous studies.

8. Computational modeling

We found that the age-related differences in the workload capacity varied across tasks. We identified three key findings: older adults always showed: (1) slower RTs than younger adults, (2) a larger workload capacity than younger adults in a discrimination-type redundant-target task (Experiments 1–3) and a similar level of limited capacity in a detection-type redundant-target task (Experiment 4), and (3) a larger (Experiments 1 and 3) or similar log-transformed RG (Experiments 2 and 4) than younger adults.

To propose a processing account to explain the age-related differences, we conducted a simulation study. We extended Johnson et al.'s (2010) framework of the Poisson parallel interactive model to test which combinations of the model's parameters can best recover the capacity profiles in the discrimination-type and detection-type redundant-target tasks for different age groups, respectively. Johnson et al.'s (2010) original model enabled exploration of the effect of the information accumulation rate, the decision criteria, and the interaction between two parallel channels on the redundant-signal processing. However, this model can only explain the redundant-signal processing in a detection-type redundant-target task in which no distracting information is presented. In the present simulation, we first introduced a new parameter that controls for the violation of context invariance and is associated with the distractor inhibition process. Second, to model the target-distractor processing in the discrimination-type redundant-target tasks, we adjusted the decision criterion for each channel, which consisted of two thresholds: the upper threshold is associated with the target response and the lower threshold is associated with the distractor response. The detailed formal description of the Poisson parallel interactive model is available in Johnson et al. (2010) and the detailed derivation of our modified model is presented in Appendix. In the following section, we briefly describe the model with a focus on the model's properties relevant to our study.

8.1. Poisson parallel interactive model in a discrimination-type redundant-target task

We modeled interactive parallel processing of redundant targets and target-distractor with two channels acting as simultaneous Poisson accumulators. The accumulators could exchange processing information determined by the probability of information passing between the two channels (Fig. 3). Let U_i, $i = 1$, 2, be the random variable for the number of counts accumulated with a single channel *i operating alone*, and let U_i be distributed as a Poisson random variable with an accumulation rate parameter λ_i, $i = 1, 2$, given by

$$P\left(U_i\left(t\right) = u_i\right) = f\left(u_i, \lambda_i, t\right) = \begin{cases} \dfrac{(\lambda_i t)^{u_i} e^{-\lambda_i t}}{u_i!}, \lambda_i, t \geq 0, u_i = 0, 1, 2\ldots \\ 0, \text{otherwise.} \end{cases}$$

Channels accumulate information through time from a zero-activation state to a completion state in which channel i has reached a criterion number of counts γ_i or $-\gamma_i$ ($i = 1, 2$). If *any* channel reaches the criterion γ_i, a target response is made. A distractor response is made when *both* channels reach the decision criterion $-\gamma_i$.

Let $K_{j,i}$, $i, j = 1, 2$, $i \neq j$ be the random variable that denotes the total amount of information shared from channel j to channel i. The probability that a single count is shared from channel j to channel i is distributed as a Bernoulli random variable, and the total amount of shared information $K_{j,i}$ is distributed as a binomial distribution, which is expressed as:

$$P\left(K_{j,i} = k_{j,i} | U_j = u_j\right) = \binom{u_j}{k_{j,i}} p_{j,i}^{k_{j,i}} (1 - p_{j,i})^{u_j - k_{j,i}}$$

where $k_{j,i}$ is the count shared from channel j to channel i and $p_{j,i}$ is its probability.

To enable model flexibility, we allowed that a single channel accumulation rate λ_i depends on the presence or absence of another channel. Thus, we generally define the single channel accumulation rate as $\lambda_{1|1,2} = \mathrm{m}\lambda_{1|1}$ and $\lambda_{2|1,2} = \mathrm{m}\lambda_{2|2}$, where m is the multiplicative factor that represents the violation of context invariance, $\lambda_{i|1,2}$ represents a single channel accumulation rate for channel i when both channels are active and $\lambda_{i|i}$ represents a single channel accumulation rate for channel i when only channel i is active. The parameter m indicates the extent to which a single channel accumulation rate is affected by the presence/absence of another channel. When m equals 1, it indicates that the accumulation rate of a channel is the same under both the single-target condition and the redundant-target condition, which suggests that there is no violation of context invariance. Any value for m different than one ($\mathrm{m} \neq 1$) indicates a violation of context invariance. It is important to note that the violation of context invariance does not imply channel dependencies in terms of a crosstalk. Rather, it implies an accumulation rate change as a result of a change in the processing context (addition of more processes) that may occur as a result of the shared resources between channels.

Let X_i, $i = 1, 2$, be the random variable that represents the total activation (total number of counts) in a single channel. Given that the target processing is activated, the channel i accumulates information toward the upper bound γ_i, whereas given that the distractor processing is activated, the channel i accumulates information toward the lower bound $-\gamma_i$. Therefore, $x_{i,target}\left(t + \Delta t\right) = x_i\left(t\right) + 1$ and $x_{i,distractor}\left(t + \Delta t\right) = x_i\left(t\right) - 1$. Assuming that an inhibitory inter-channel interaction exists, given that information is shared from target-processing channel j to another channel i, $k_{j,i}$ is subtracted: $X_i = U_i - K_{j,i}$. The inhibitory inter-channel interaction indicates that a single channel activation is reduced because of the activation of another target-processing channel, such that the following holds: $-\gamma_i \leq u_i\ (t) - k_{j,i}\ (t) \leq \gamma_i$. Alternatively, given that information is shared from distractor-processing channel j to another channel i, $k_{j,i}$ is added: $X_i = U_i + K_{j,i}$.[7] The inhibitory inter-channel interaction indicates that a single channel activation is increased because of the activation of another distractor channel, such that the following holds: $-\gamma_i \leq u_i\ (t) + k_{j,i}\ (t) \leq \gamma_i$.

8.2. Poisson parallel interactive model in a detection-type redundant -target task

In the detection-type redundant-target task, there is no need to model the distractor processing. Therefore, the critical model differences between the two tasks are as follows: (1) the completion state is defined as the channel i having the number of counts that reach the criterion γ_i ($i = 1, 2$). (2) The total activation in a single channel is represented as $X_i = U_i - K_{j,j}$ with the following holds: $0 \leq u_i\ (t) - k_{j,i}\ (t) \leq \gamma_i$.

8.3. Selective manipulation of the model's properties and the model's predictions (Experiments 1–3)

We ran several simulations to explore whether the Poisson parallel interactive model provides an adequate qualitative match to the observed age-related differences in data patterns. In Experiments 1–3, we used our modified model to simulate the redundant-target processing and target-distractor processing, and in Experiment 4, we adopted Johnson et al.'s original model for simulation. First, we tested each of the parameters, assuming that the distractor is presented in the single-target condition.

[7] Given that the distractor channel j is activated, the accumulator i should accumulate information toward $-\gamma_i$. However, assuming that it is an inhibitory interaction, $k_{j,i}$ is added because two negatives make a positive.

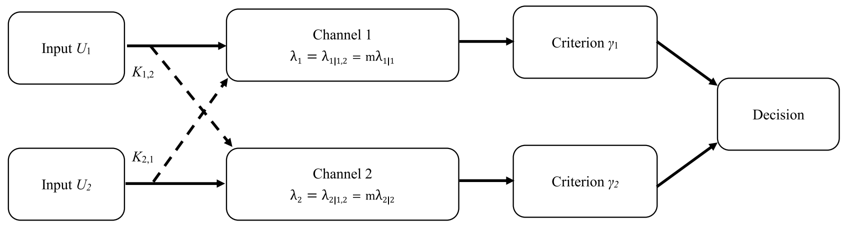

Fig. 3. A schematic illustration of the Poisson parallel interactive model with two channels.

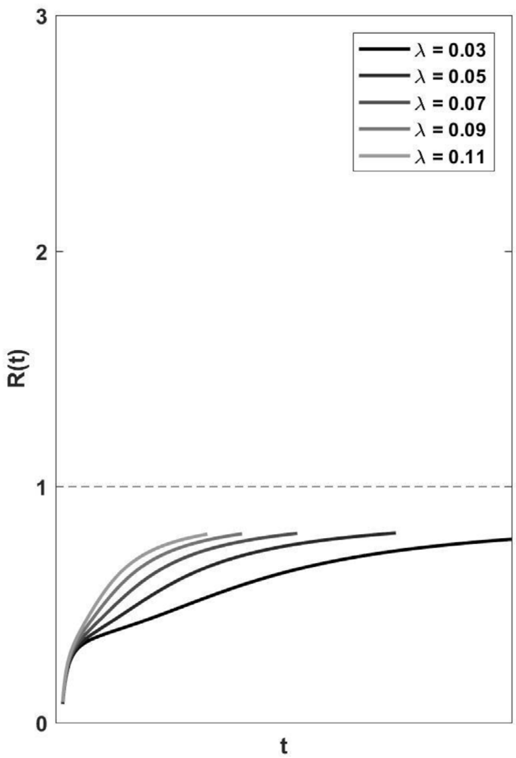

Fig. 4. Capacity simulation results when λ, the parameter that represents the information accumulation rate, varied from 0.03 to 0.11 for the discrimination-type redundant-target task.

8.3.1. Effect of information accumulation rate

We tested the effect of the information accumulation rate on the workload capacity, overall RTs, and log-transformed RG by varying the accumulation rate parameter (λ_i). Let $\gamma_1 = \gamma_2 = 10$, $k_{j,i} = 0.1$ (i.e., mild inhibitory interaction), and $m = 1$ (i.e., no violation of context invariance). We then systematically varied λ_i from 0.03 to 0.11. Please refer to Fig. 4 and Table 3 for the results. The simulated results showed that varying the information accumulation rate had a small effect on the change in workload capacity, in which a lower accumulation rate led to a weak capacity function decrease at the faster RTs. It also led to the overall RTs slowing down. All capacity functions were monotonically increasing functions and reached an asymptote of 0.8. In addition, the log-transformed RG was not significantly affected by the change in the information accumulation rate. Assuming that the older adults have a slower accumulation rate than the younger adults, these results only match one of the three key findings (i.e., overall RTs) in age-related differences. However, the results failed to reproduce the capacity differences we identified. Therefore, our simulation results suggest that the change in the information accumulation rate alone is unlikely to explain the age-related differences in workload capacity.

Table 3
Simulated results for the discrimination-type redundant-target task. Results consist of values of the parameters and the corresponding simulated mean RTs for the redundant-target condition, average mean RTs of the two single-target conditions, and log-transformed RG.

	λ	γ	k	m	$RT_{1,2}$	Mean (RT_1, RT_2)	RG	Log-RG
Varying λ								
	0.03	10	0.1	1	294	307	13	0.014
	0.05	10	0.1	1	176	184	8	0.013
	0.07	10	0.1	1	126	131	5	0.012
	0.09	10	0.1	1	98	102	4	0.011
	0.11	10	0.1	1	81	83	2	0.01
Varying γ								
	0.03	6	0.1	1	164	185	21	0.045
	0.03	8	0.1	1	228	246	18	0.027
	0.03	10	0.1	1	294	307	13	0.014
	0.03	12	0.1	1	360	368	8	0.005
	0.03	14	0.1	1	427	429	2	−0.002
	0.03	16	0.1	1	495	490	−5	−0.007
Varying k								
	0.03	10	0	1	275	333	58	0.078
	0.03	10	0.1	1	294	307	13	0.014
	0.03	10	0.3	1	345	266	−79	−0.117
	0.03	10	0.5	1	427	233	−194	−0.263
	0.03	10	0.7	1	578	205	−373	−0.438
	0.03	10	0.9	1	976	181	−795	−0.689
Varying m								
	0.03	10	0.1	0.5	587	307	−280	−0.286
	0.03	10	0.1	0.6	489	307	−182	−0.207
	0.03	10	0.1	0.7	419	307	−112	−0.14
	0.03	10	0.1	0.8	367	307	−60	−0.082
	0.03	10	0.1	0.9	326	307	−19	−0.031
	0.03	10	0.1	1	294	307	13	0.014
	0.03	10	0.1	1.1	267	307	40	0.056
	0.03	10	0.1	1.2	245	307	62	0.093
	0.03	10	0.1	1.3	226	307	81	0.128
	0.03	10	0.1	1.4	210	307	97	0.16
	0.03	10	0.1	1.5	196	307	111	0.19
Case								
Younger	0.04	15	0.25	1.4	282	308	26	0.035
Older	0.04	17	0.25	1.5	302	348	46	0.058

8.3.2. Effect of decision criteria

We tested the effect of decision criteria on the workload capacity, overall RTs, and log-transformed RG by varying γ_i. Let $\lambda_1 = \lambda_2 = 0.03$, $k_{j,i} = 0.1$ (i.e., mild inhibitory interaction), and $m = 1$ (i.e., no violation of context invariance). We then systematically varied γ_i from 6 to 16. Please refer to Fig. 5 and Table 3 for the results. The simulated results showed that increasing the decision criterion decreases the capacity values, increases the overall RTs, and decreases the log-transformed RG values. The observed results did not qualitatively match the key age-related findings. Assuming that the older adults are more conservative than the younger adults and adopt a higher criterion value, the observed capacity will show their lower capacity values and lower log-transformed RG than the younger adults despite slower RTs across all conditions for older adults than younger adults. Therefore, our simulation results suggest that the change

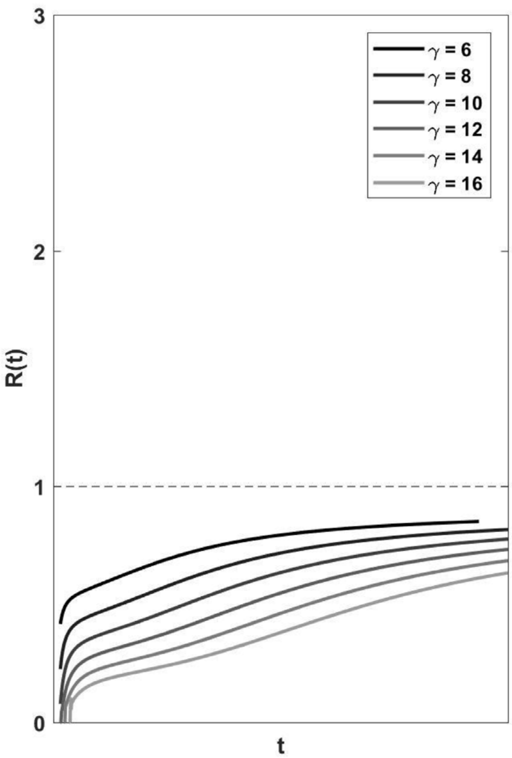

Fig. 5. Capacity simulation results when γ, the parameter that represents the decision threshold, varied from 6 to 16 for the discrimination-type redundant-target task.

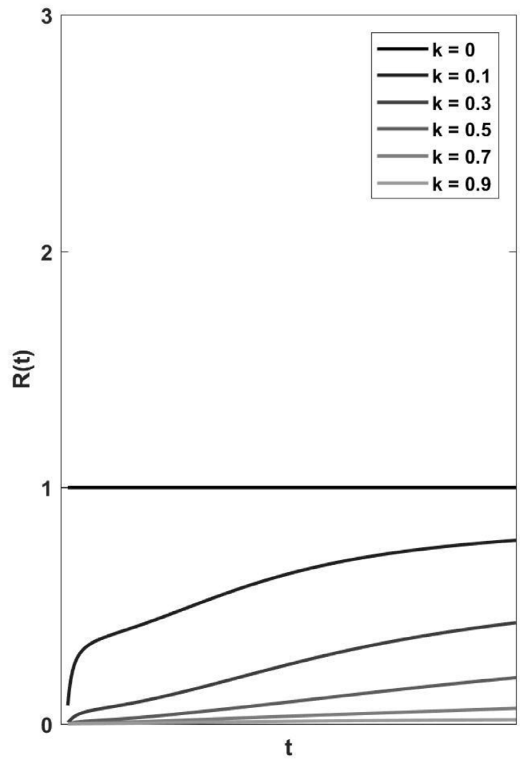

Fig. 6. Capacity simulation results when k, the parameter that represents the inhibitory interaction, varied from 0 to 0.9 for the discrimination-type redundant-target task.

in the decision criteria alone is unlikely to explain the age-related differences in workload capacity.

8.3.3. Effect of inhibitory interaction

We tested the effect of inhibitory interaction on the workload capacity, overall RTs, and log-transformed RG by varying $k_{j,i}$. Let $\lambda_1 = \lambda_2 = 0.03$, $\gamma_1 = \gamma_2 = 10$, and $m = 1$ (i.e., no violation of context invariance). We then systematically varied k_{ji} from 0 to 0.9. Please refer to Fig. 6 and Table 3 for the results. The simulated results showed that increasing the inhibitory interaction between two parallel channels decreases the capacity values and log-transformed RG. It also increases the mean RTs of the redundant-target condition and decreases the mean RTs of the single-target condition. If the older adults exhibit more inhibition between processing channels than the younger adults, the observed results do not qualitatively match the key age-related findings. Therefore, our simulation results suggest that the change in inhibitory interaction alone is unlikely to explain the age-related differences in workload capacity.

8.3.4. Effect of a violation of context invariance

We tested the effect of the violation of context invariance on the workload capacity, overall RTs, and log-transformed RG by varying m. Let $\lambda_1 = \lambda_2 = 0.03$, $\gamma_1 = \gamma_2 = 10$, and $k_{j,i} = 0.1$ (i.e., mild inhibitory interaction). We then systematically varied m from 0.5 to 1.5. Please refer to Fig. 7 and Table 3 for the results. The simulated results showed that as m increases, the capacity and log-transformed RG also increase, whereas the overall RTs decrease. Although the simulated data did not match the observed overall RT data, the manipulation of the violation of context invariance is the only manipulation thus far that led to increasing both the capacity function and log-transformed RG values, which could be expected to occur with the older adults compared to the younger adults. Assuming that the older adults have less ability of controlled attention, the processing would be more easily affected by the stimulus presentation context, particularly when distracting information is simultaneously presented, thus resulting in a violation of context invariance. In conclusion, a change in m may explain the relative differences in workload capacity across age groups.

8.4. Selective manipulation of the model's properties and the model's predictions (Experiment 4)

We tested each of the parameters in the detection-type redundant-target task (Experiment 4). In this simulation, we did not test the effect of m parameter on the workload capacity because we assume that there is no violation of context invariance due to the absence of a distractor.

8.4.1. Effect of information accumulation rate

We tested the effect of the information accumulation rate on the workload capacity, overall RTs, and log-transformed RG by varying the accumulation rate parameter (λ_i). Let $\gamma_1 = \gamma_2 = 12$, $k_{j,i} = 0.25$ (i.e., mild inhibitory interaction), and $m = 1$ (i.e., no violation of context invariance). We then systematically varied λ_i from 0.03 to 0.11. Please refer to Fig. 8 and Table 4 for the results. The simulated results showed that varying the information accumulation rate had a small effect on the change in the workload capacity, in which a lower accumulation rate led to a lower capacity values across all times t. All capacity functions were monotonically increasing functions and reached an asymptote of 0.7. It also led to the overall RTs slowing down; by contrast, there were no effects on the log-transformed RG. Assuming that the older adults have a slower accumulation rate than the younger adults, these results match two of the three

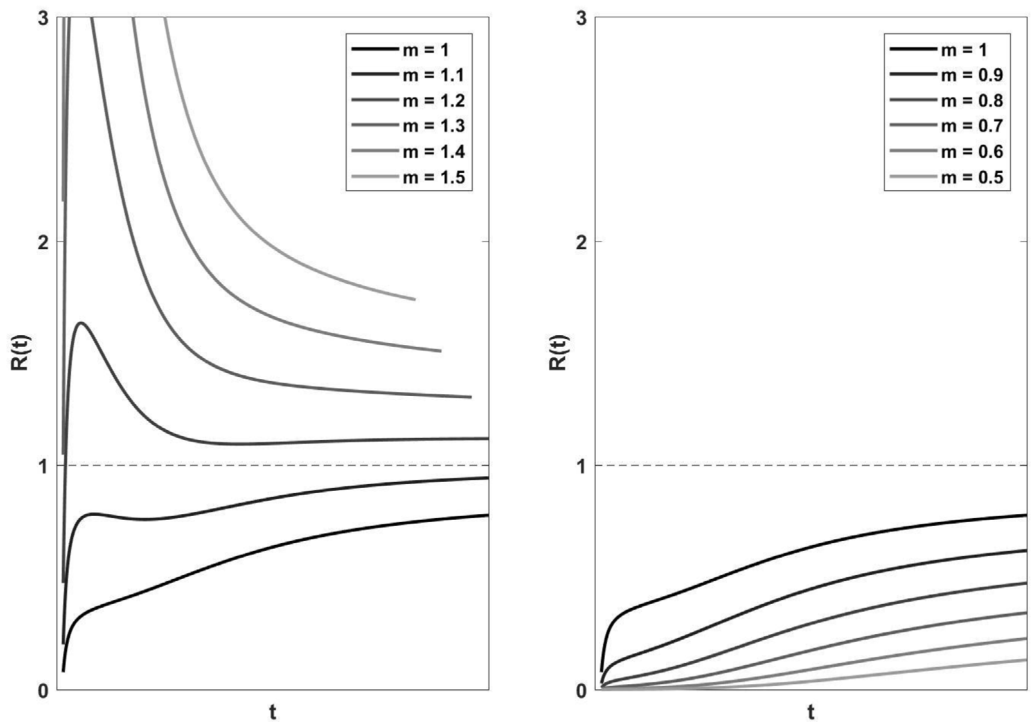

Fig. 7. Capacity simulation results when m, the parameter that represents the violation of context invariance, varied from 1 to 1.5 (left panel) and 0.5 to 1 (right panel) for the discrimination-type redundant-target task.

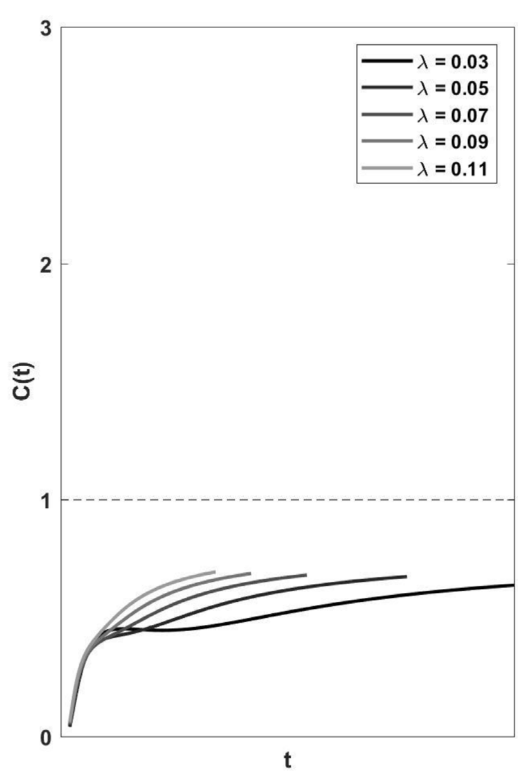

Fig. 8. Capacity simulation results when λ, the parameter that represents the information accumulation rate, varied from 0.03 to 0.11 for the detection-type redundant-target task.

key findings (i.e., overall RTs and log-transformed RG) in age-related differences. However, the simulated capacity functions are all monotonically increasing, which are inconsistent with what we have observed empirically.

8.4.2. Effect of decision criteria

We tested the effect of decision criteria on the workload capacity, overall RTs, and log-transformed RG by varying γ_i. Let $\lambda_1 = \lambda_2 = 0.03$, $k_{j,i} = 0.25$ (i.e., mild inhibitory interaction), and $m = 1$ (i.e., no violation of context invariance). We then systematically varied γ_i from 6 to 14. Please refer to Fig. 9 and Table 4 for the results. The simulated results showed that increasing the decision criterion had a small effect on the capacity values and log-transformed RG value (i.e., slight decrease). By contrast, it indeed increases the overall RTs. Assuming that the older adults are more conservative than the younger adults and adopt a higher criterion value, older adults will show age slowing in the overall RTs but they will have similar or smaller levels of capacity values and log-transformed RG than the younger adults. Therefore, our simulation results suggest that the change in the decision criteria alone is able to explain the results what we have observed empirically.

8.4.3. Effect of inhibitory interaction

We tested the effect of inhibitory interaction on the workload capacity, overall RTs, and log-transformed RG by varying $k_{j,i}$. Let $\lambda_1 = \lambda_2 = 0.03$, $\gamma_1 = \gamma_2 = 12$, and $m = 1$ (i.e., no violation of context invariance). We then systematically varied k_{ji} from 0 to 1. Please refer to Fig. 10 and Table 4 for the results. The simulated results showed that increasing the inhibitory interaction between two parallel channels decreases the capacity values and log-transformed RG and increases the overall RTs. If the older adults exhibit more inhibition between processing channels than the younger adults, the observed results do not qualitatively match two of the three key age-related findings (i.e., capacity values and log-transformed RG). Therefore, our simulation results suggest that the change in inhibitory interaction alone is unlikely to explain the results what we have observed empirically.

Table 4
Simulated results for the detection-type redundant-target task. Results consist of values of the parameters and the corresponding simulated mean RTs for the redundant-target condition, average mean RTs of the two single-target conditions, and log-RG.

	λ	γ	k	m	$RT_{1,2}$	Mean (RT_1, RT_2)	RG	Log-RG
Varying λ								
	0.03	12	0.25	1	399	400	1	−0.001
	0.05	12	0.25	1	239	240	1	−0.001
	0.07	12	0.25	1	171	171	0	−0.002
	0.09	12	0.25	1	133	133	0	−0.002
	0.11	12	0.25	1	109	109	0	−0.003
Varying γ								
	0.03	6	0.25	1	174	200	26	0.055
	0.03	8	0.25	1	247	267	20	0.03
	0.03	10	0.25	1	322	333	11	0.012
	0.03	12	0.25	1	399	400	1	−0.001
	0.03	14	0.25	1	476	467	−9	−0.011
Varying k								
	0.03	12	0	1	335	400	65	0.072
	0.03	12	0.25	1	399	400	1	−0.001
	0.03	12	0.5	1	505	400	−105	−0.098
	0.03	12	0.75	1	712	400	−312	−0.238
	0.03	12	1	1	1333	400	−933	−0.472
Varying m								
	0.03	12	0.25	0.5	797	400	−397	−0.301
	0.03	12	0.25	0.6	664	400	−264	−0.222
	0.03	12	0.25	0.7	569	400	−169	−0.155
	0.03	12	0.25	0.8	498	400	−98	−0.097
	0.03	12	0.25	0.9	443	400	−43	−0.046
	0.03	12	0.25	1	399	400	1	0.001
	0.03	12	0.25	1.1	362	400	38	0.041
	0.03	12	0.25	1.2	332	400	68	0.078
	0.03	12	0.25	1.3	307	400	93	0.113
	0.03	12	0.25	1.4	285	400	115	0.145
	0.03	12	0.25	1.5	266	400	134	0.175
Case								
Younger	0.03	10	0.25	1	321	332	11	0.012
Older	0.03	12	0.25	1	398	399	1	−0.001

8.5. Integrative account via the parallel interactive model

As we have demonstrated in the previous simulations, varying a single parameter alone cannot capture the age-related differences in the workload capacity identified in Experiments 1–3; varying the parameter of decision criteria alone can explain the results identified in Experiment 4. Thus, we gained insights from these simulations. First, we determined that only one of the four model properties, which is a *violation of context invariance,* led to sensible changes in the capacity function and differences in log-transformed RG, which would be emended later by other parameters. Moreover, three of four manipulations led to expected data patterns for the overall RTs (*accumulation rate, decision criteria, and inhibitory interaction).* Thus, it is reasonable, at this stage, to attempt to explore how joint manipulations of these model properties may affect the observed qualitative age-related differences. As a preview, we will examine how a combination of the parameters will lead to a satisfactory prediction outcome that matches the three key findings, as well as the overall shape of the observed capacity functions.

First, we will use the m parameter, which is important to explain the relative differences in processing efficiency between redundant targets and single targets, particularly when distracting information is provided in the single-target condition. We postulated that the older adults would violate the context invariance with a larger m parameter in a discrimination-type redundant-target task where the single-target condition requires the participants to inhibit the distractor and resolve the response conflict rather than in a detection-type redundant-target task where there is no distracting information presented in the single-target condition.

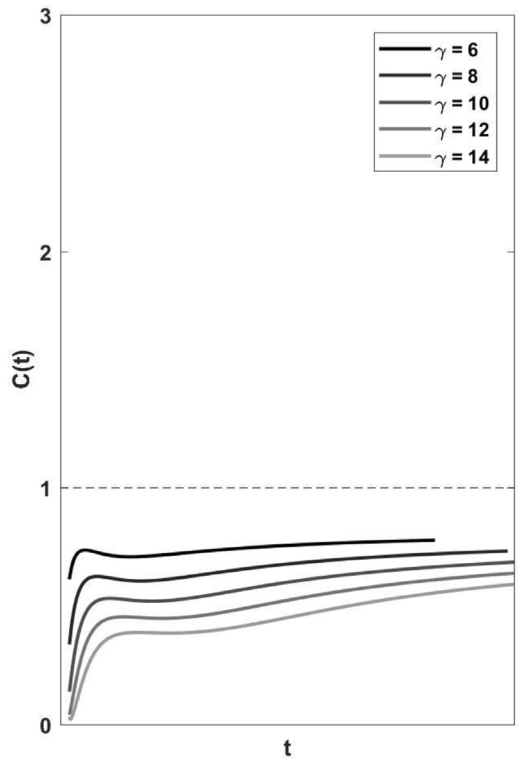

Fig. 9. Capacity simulation results when γ, the parameter that represents the decision threshold, varied from 6 to 14 for the detection-type redundant-target task.

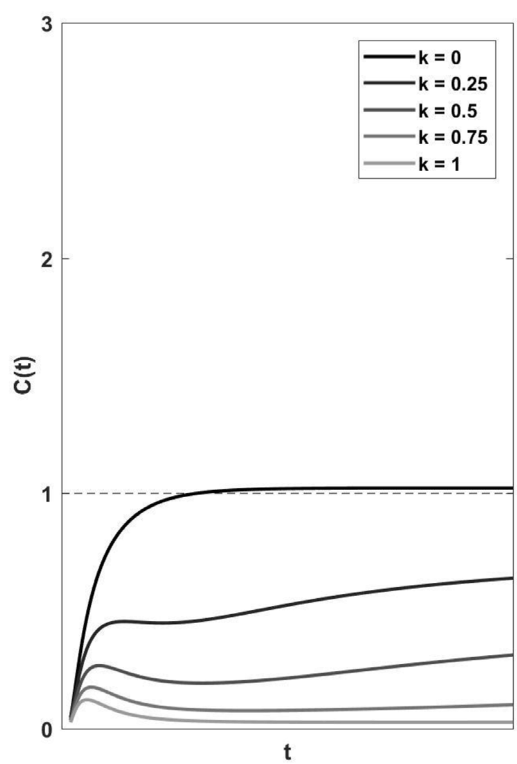

Fig. 10. Capacity simulation results when k, the parameter that represents the inhibitory interaction, varied from 0 to 1 for the detection-type redundant-target task.

Second, we will use the decision criterion parameter γ_i, accumulation rate λ_i, and inhibitory interaction $k_{j,i}$ to account for the overall RTs in age-related differences. Among these, the decision criterion is one of the most important and robust parameters that has been considered to explain the mean RT differences across age groups in the cognitive aging literature (Raghuram et al., 2005; Ratcliff, Thapar, Gomez et al., 2004). Thus, we postulated that the decision criterion parameter could be used to explain the age slowing effect. Note that the decision criterion alone cannot be used to explain the age-related differences in workload capacity in the simulation used for the discrimination-type redundant-target task.

To apply this integrative account, we simulate a case to explain the results in a discrimination-type redundant-target task (Experiments 1–3). In the first case using our modified model, let $\lambda_{old} = \lambda_{young} = 0.04$, $\gamma_{old} = 17$, $\gamma_{young} = 15$, $k_{old} = k_{young} = 0.25$ (i.e., mild inhibitory interaction), and $m_{old} = 1.5$, $m_{young} = 1.4$, which suggests that older and younger adults have equal information accumulation rates (assuming that aging does not affect the information accumulation rate) and equal levels of inhibitory interactions between the two parallel channels (assuming limited capacity in attentional processing), whereas older adults have a higher decision criterion and a larger violation of context invariance. Please refer to Fig. 11a and Table 3 for the results. The simulated results well explain the findings of Experiments 1–3: the older adults responded slower, while at the same time, they had a larger workload capacity and log-transformed RG values. More importantly, for both age groups, we identified a decreasing shape of the capacity functions, which suggests that we successfully captured the capacity profiles for different age groups.

In an attempt to simulate the results of the detection-type redundant-target task (Experiment 4), we conducted a second simulation. We used Johnson et al.'s original model, let $\lambda_{old} = \lambda_{young} = 0.03$, $\gamma_{old} = 12$, $\gamma_{young} = 10$, $k_{old} = k_{young} = 0.25$ (i.e., mild inhibitory interaction), and $m_{old} = m_{young} = 1$. The m parameter was maintained at 1 for both groups, which suggests that both older adults and younger adults do not violate the context invariance because there is no need to inhibit the distractor and resolve the response conflict. Please refer to Fig. 11b and Table 4 for the results. The simulated results well explain the findings of Experiment 4: the older adults responded slower; however, they had similar levels of capacity and log-transformed RG. The capacities were very limited across all times t, which was consistent with our findings.

9. General discussion

In this study, we investigated age-related differences in redundant-target signal processing. In discrimination-type redundant-target tasks (Experiments 1–3) with distracting information presented in the single-target condition, we replicated Ben-David et al.'s (2014, distractor-present condition) findings: older adults responded slower and had a larger workload capacity and a larger or similar level of log-transformed RG effect than younger adults. In contrast, in a detection-type redundant-target task (Experiment 4), in which no distracting information was presented in the single-target condition, we obtained similar findings as Ben-David et al. (2014, distractor-absent condition): older adults responded slower than younger adults; more importantly, the age-related differences in the workload capacity were eliminated.

With an increase in age, there is a progressive and generalized slowing effect of information processing (Birren, 1974; Cerella, 1990; Salthouse, 1992). It is worth mentioning that the present study allowed for validation/falsification of a possible mechanistic explanation regarding the cognitive processing characteristics underlying the general slowing effect.

We analyzed the effect of several factors that could be used to explain the overall slower RTs for older adults than younger adults. The age-related slowing may be a result of the increased non-decision times (e.g., slower perceptual or motor processes) (Owsley, Jackson et al., 2001; Owsley, Stalvey et al., 2001). In contrast, the age slowing effect may be a result of the increased decision time in terms of the slower information accumulation rate and/or greater caution in making decisions (known as general slowing theory or processing-speed theory by Salthouse, 1996; Thapar et al., 2003).

Questions may subsequently be raised: can the age-related differences in workload capacity be simply attributed to the slow-down in non-decision time? We ruled out the effect of non-decision time by showing different patterns of log-transformed RG and workload capacity results in the discrimination-type and detection-type redundant-target tasks. In addition, we can draw conclusions from Ben-David et al.'s (2014) findings. In the LBA model, the parameter t_0 represents the non-decision time. If the slowing in the non-decision time can explain the age-related differences in workload capacity, we should expect older adults to have a larger t_0 than younger adults only in the distractor-present condition rather than in the distractor-absent condition. However, they identified similar t_0 differences across the two conditions, thus ruling out the possibility.

Can the age-related differences in workload capacity be simply attributed to the slow-down in the decision time? The results of the exploratory analysis using the parallel interaction model revealed very important findings: although a decrease in the drift rate, an increase in the decision criteria, and an increase in inhibitory interaction can result in a slower overall RT, a single cognitive component alone cannot recover the age-related differences in the workload capacity what we have observed in the discrimination-type redundant-target tasks. Thus, we rule out the possibility that the slow-down in decision time itself could be used as a sufficient factor to explain the observed age-related differences.

To account for the observed data patterns, based on the computational simulation results we proposed an integrative processing account by assuming that the older adults were more conservative in making decisions (i.e., a higher decision threshold) and the capacity differences occurred because the older adults were less effective and efficient in inhibiting distractors (i.e., a larger violation of context invariance).

9.1. Inhibition of distractors

With an increase in age, the functional capacity of working memory is reduced because less efficient inhibitory processes fail to prevent irrelevant information from entering or being maintained in working memory (Diaz et al., 2018; Hasher & Zacks, 1988; Lustig et al., 2007). Specifically, inefficient inhibition may result in an increased processing time and reductions in the identification and recognition of relevant information. In a Stroop task, numerous studies have shown that older adults produce a larger RT difference between congruent conditions and incongruent conditions than younger adults (Cohn, Dustman, & Bradford, 1984; Comalli, Wapner, & Werner, 1962; Fisk & Rogers, 1991; Houx, Jolles, & Vreeling, 1993), which suggests an increased susceptibility to interference from irrelevant information.[8] Similarly,

[8] Please note, alternative hypothesis regarding age-related changes in Stroop effects suggests that the changes may not reflect inhibition per se, but reflect changes in speed of processing (Verhaeghen & De Meersman, 1998b), in sensory (Ben-David & Schneider, 2009, 2010), or in the discriminability of the two dimensions (see the work by Eidels, Townsend, & Algom, 2010).

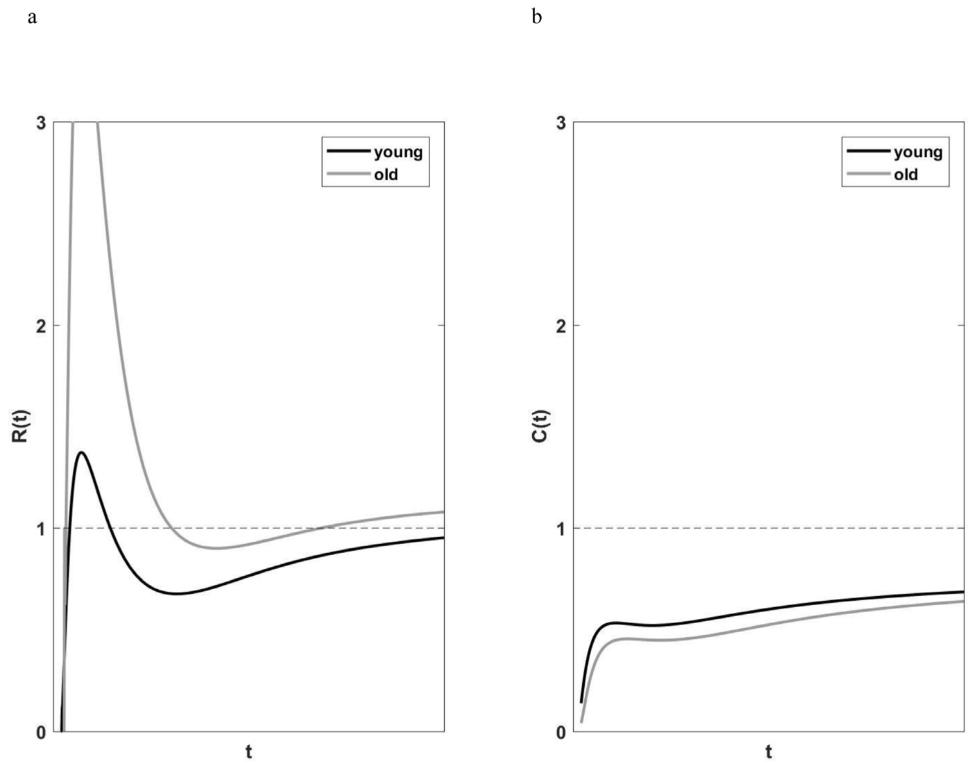

Fig. 11. Two simulated cases and the corresponding capacity results. (a) Case 1: assuming inhibitory interaction, older adults had higher decision criterion and larger violation of context invariance than the younger adults (old: $\gamma = 17$, $m = 1.5$; young: $\gamma = 15$, $m = 1.4$). (b) Case 2: assuming inhibitory interaction, older adults had higher decision criterion than the younger adults (old: $\gamma = 12$; young: $\gamma = 10$), but they do not violate the context invariance ($m = 1$).

in a negative priming task, older adults failed to show a negative priming effect, whereas younger adults exhibited negative priming, thus suggesting age deficits in inhibitory processes, which may lead to decreased performance on selective attention tasks (McDowd & Oseas-kreger, 1991).[9]

Our current findings were in favor of the inhibition of distractor account, which assumes that the ability to inhibit distractors deteriorates with age (Hasher & Zacks, 1988; Kane et al., 1994). Thus, it is the deficiency in distractor inhibition for the older adults such that they were less efficient in processing the single target when the distractor was presented than when the distractor was absent. The slower processing time for the single target when it is presented concurrently with a distractor than when it is presented as a part of redundant targets would result in a violation of context invariance, which, in turn, would increase the workload capacity. Younger adults are more efficient than older adults in exerting their attentional control to inhibit the distractors, such that their processing time for a single target was less affected by the presentation context. To support this argument, our simulation showed only the parameter m can mimic the relative difference in the processing efficiency between the redundant-target and single-target conditions. Therefore, it is not because the older adults process the redundant targets more efficiently with more interchannel facilitatory crosstalk, but rather the less efficiency in processing single targets where processing requires the inhibition of distractors.

[9] Please note, as Stoop effects, Verhaeghen and De Meersman (1998a) have suggested that age-related effects in negative priming may also reflect slowing but not only inhibition. Frings, Schneider, and Fox (2015) provided an updated view that there might be no age-related difference in the negative priming effect (Frings et al., 2015).

9.2. Interactions between the parallel channels

One would argue that the age-related differences might be explained by the interchannel interaction between the parallel channels. For example, it might be expected that the increase in workload capacity would be the consequence of a facilitatory interchannel crosstalk. The cross-channel facilitation can, under general conditions, improve perception when redundant targets are presented. In such a case, the facilitation can increase the rate of evidence accumulation through a mutual exchange of evidence across simultaneously processed targets. This possibility is ruled out because the observed limited capacity results would indicate that an inhibitory interchannel crosstalk exists.

Alternatively, one might argue that the increased inhibition between parallel channels would explain the age differences. Assuming that older adults possess less attentional resource than the younger adults that led to a greater inhibitory interaction, when we increase the inhibitory interaction (parameter k) in our simulation, we should observe a increase in both the workload capacity and log-transformed RG. However, the simulated results did not match our observed findings except for the slower overall RTs. Therefore, we concluded that aging did not change the level of the inhibitory interaction. Both younger and older adults were of limited capacity in their attentional resources, which led to multiple channels compete with each other with a mutual exchange of inhibitory signals.

9.3. Redundancy gain vs workload capacity

Many aging studies have relied on the measure of RG to demonstrate the age-related differences in redundant-target signal processing, showing that older adults exhibited a larger RG effect than younger adults (Allen et al., 1992; Linnet & Roser, 2012). Although RG is typically considered a processing advantage because it indicates improved speed performance, with advancing ages, it is considered to be an indicator of a potential cognitive impairment. However, it is lack of mechanistic explanation to explain the increased RG with advancing ages. In addition, it is notable that in the literature, the RG results are quite mixed: the presence of a distractor may produce the age-related effect (i.e., Allen et al., 1992; Ben-David et al., 2014), reduce the age-related effect (Allen et al., 1993), or have no impact at all (Allen et al., 1994). In our current study, we also found that in Experiments 1–3 the log-transformed RG s were not consistently larger for the older adults than for the younger adults.

We considered that workload capacity is a more sensitive measure to reveal the age-related differences in cognitive processing. The workload capacity measure enables us to provide a mechanistic explanation for the age differences. A larger workload capacity can be used to indicate an increase in the overall system's processing efficiency when performing cognitive operations. On the other hand, it is important to note that a higher workload capacity measure can also be achieved by the process of distractor inhibition. The resilience capacity function depends on the relative efficiency of processing of the redundant-target condition to the processing efficiency of a target plus distractor condition Eq. (2). According to the *distractor inhibition account*, the presence of the distractors could decrease the efficiency in the single-target condition (the denominator in Eq. (2)), which, in turn, can inflate the value of the measured capacity. Thus, in a similar fashion as the RG effect, the capacity function can show the capacity increase for older adults as the result of the decreased ability to inhibit distractors.

In addition to distractor inhibition, the workload capacity can be influenced by other properties of cognitive processes, such as the information accumulation rate (drift rate), the decision criteria, inhibitory interaction, and the processing order (serial, parallel). To provide a differential analysis, as previously described, complete theoretical assessments of the capacity results were conducted to isolate a likely source of the observed age-related difference in capacity measures. The results via the computational simulation demonstrated that the parameter that governed the level of violation of context invariance produced all joint data patterns and provided the best overall qualitative fit to the data. The violation of context invariance is consistent with the *distractor inhibition account* and provided a single systematic mechanistic explanation for age-related differences across the four experiments.

In conclusion, the present findings suggest that the workload capacity assessment is potentially a more robust measure of age-related differences than the RG measure. One reason for a limitation of the RG measure could be that the RG effect is confined to the use of a parallel processing architecture, which simultaneously processes all sources of information. This is not the case with the resilience workload capacity function, which can provide assessment for different types of mental architectures (Little et al., 2015). Note that the robustness of the measure of workload capacity, compared to RG, comes with a price. The full assessment of the possible causes of changes in the workload capacity measure would require more elaborate modeling. In the current paper, we demonstrated a qualitative approach to model properties tested via extensive simulation work. The current work demonstrated how it is possible to selectively test each cognitive component in the simulation procedure, while using the qualitative model fitting criteria. Stronger conclusions could be achieved by employing parametric model testing (e.g. Fific, Little, & Nosofsky, 2010). It is also worth noting that we can more closely examine the profile of the capacity functions by applying advanced analysis techniques (e.g., functional principal component analysis: Burns, Houpt, Townsend, and Endres (2013); or RT modeling: Fific et al. (2010)) to demonstrate the age-related differences. Future studies are encouraged to explore the capacity differences in detail.

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Appendix

A.1. Target-distractor processing

Similar to Johnson et al.'s (2010) Poisson parallel interactive model, we utilize the Markov chain to model the target-distractor processing. Let $U_i, K_{j,i}, X_i, \gamma_i,$ *and* $\lambda_i, i, j = 1, 2, i \neq j$, be defined in the text, and let Δt be a sufficiently small increment of time. Let $P[m, n]$ denote the transition probability such that, at time $t + \Delta t$, x_i has changed by m and x_j has changed by n. Assuming channel i represents the target-processing channel and channel j represents the distractor-processing channel, the transition probability for all possible transitions of the inhibitory Markov chain are defined, for $i, j = 1, 2, i \neq j$, by

$$P[0,0] = P\left[x_i(t+\Delta t) = x_i(t)\, AND\, x_j(t+\Delta t) = x_j(t)\right]$$
$$= (1-\lambda_i \Delta t)(1-\lambda_j \Delta t)$$
$$P[1,0] = P\left[x_i(t+\Delta t) = x_i(t)+1\, AND\, x_j(t+\Delta t) = x_j(t)\right]$$
$$= \lambda_i \Delta t(1-\lambda_j \Delta t)(1-p_{i,j})$$
$$P[0,-1] = P\left[x_i(t+\Delta t) = x_i(t)\; AND\, x_j(t+\Delta t) = x_j(t)-1\right]$$
$$= (1-\lambda_i \Delta t)\lambda_j \Delta t(1-p_{j,i})$$
$$P[1,-1] = P\left[x_i(t+\Delta t) = x_i(t)+1\, AND\, x_j(t+\Delta t) = x_j(t)-1\right]$$
$$= \lambda_i \Delta t\left(1-\lambda_j \Delta t\right)p_{i,j} + \lambda_i\lambda_j(\Delta t)^2\left(1-p_{i,j}\right)\left(1-p_{j,i}\right)$$
$$+ (1-\lambda_i \Delta t)\lambda_j \Delta t p_{j,i}$$
$$P[1,-2] = P\left[x_i(t+\Delta t) = x_i(t)+1\, AND\, x_j(t+\Delta t)\right.$$
$$\left.= x_j(t)-2\right] = \lambda_i\lambda_j(\Delta t)^2 p_{i,j}(1-p_{j,i})$$
$$P[2,-1] = P\left[x_i(t+\Delta t) = x_i(t)+2\, AND\, x_j(t+\Delta t) = x_j(t)-1\right]$$
$$= \lambda_i\lambda_j(\Delta t)^2(1-p_{i,j})p_{j,i}$$
$$P[2,-2] = P\left[x_i(t+\Delta t) = x_i(t)+2\, AND\, x_j(t+\Delta t) = x_j(t)-2\right]$$
$$= \lambda_i\lambda_j(\Delta t)^2 p_{i,j}p_{j,i}$$

We assume $-\gamma_i \leq \mathrm{x_i}(t) \leq \gamma_i$, $i = 1, 2$ for all t and if at time t_γ, $\mathrm{x_i}\left(\mathrm{t}_\gamma\right) = \pm\gamma_\mathrm{i}$, $\mathrm{i} = 1, 2$, then for all $\mathrm{t} > \mathrm{t}_\gamma$, $x_i(t) = x\left(t_\gamma\right)$. It follows that for all remaining time steps, $k_{i,j}(t+\Delta t) = 0$.

With the previously defined transition probabilities and the absorbing state ($\pm\gamma_1$ *and* $\pm\gamma_2$), we can state the model in terms of its transition matrix. Table A.1 provides an example for a system where $\gamma_1 = \gamma_2 = 2$.

Table A.1
Transition matrix for the inhibitory target-distractor processing, $\gamma 1 = \gamma 2 = 2$.

	Activation state at time $t + \Delta t$																								
Activation state at time t	(−2, −2)	(−2, −1)	(−2, 0)	(−2, 1)	(−2, 2)	(−1, −2)	(−1, −1)	(−1, 0)	(−1, 1)	(−1, 2)	(0, −2)	(0, −1)	(0, 0)	(0, 1)	(0, 2)	(1, −2)	(1, −1)	(1, 0)	(1, 1)	(1, 2)	(2, −2)	(2, −1)	(2, 0)	(2, 1)	(2, 2)
(−2, −2)	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(−2, −1)	a	b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(−2, 0)	0	a	b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(−2, 1)	0	0	a	b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(−2, 2)	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(−1, −2)	0	0	0	0	0	c	0	0	0	0	d	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(−1, −1)	0	0	0	0	0	e	f	0	0	0	l	i	0	0	0	m	0	0	0	0	0	0	0	0	0
(−1, 0)	0	0	0	0	0	0	e	f	0	0	g	h	i	0	0	j	k	0	0	0	0	0	0	0	0
(−1, 1)	0	0	0	0	0	0	0	e	f	0	0	g	h	i	0	0	j	k	0	0	0	0	0	0	0
(−1, 2)	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(0, −2)	0	0	0	0	0	0	0	0	0	0	c	0	0	0	0	d	0	0	0	0	0	0	0	0	0
(0, −1)	0	0	0	0	0	0	0	0	0	0	e	f	0	0	0	l	i	0	0	0	m	0	0	0	0
(0, 0)	0	0	0	0	0	0	0	0	0	0	0	e	f	0	0	g	h	i	0	0	j	k	0	0	0
(0, 1)	0	0	0	0	0	0	0	0	0	0	0	0	e	f	0	0	g	h	i	0	0	j	k	0	0
(0, 2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
(1, −2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	c	0	0	0	0	d	0	0	0	0
(1, −1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	e	f	0	0	0	n	i	0	0	0
(1, 0)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	e	f	0	0	o	p	i	0	0
(1, 1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	e	f	0	0	o	p	i	0
(1, 2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
(2, −2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
(2, −1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
(2, 0)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
(2, 1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
(2, 2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

a $= \lambda_2 \Delta t$, b $= (1 - \lambda_2 \Delta t)$, c $= (1 - \lambda_1 \Delta t)$, d $= \lambda_1 \Delta t$, e $= P[0, -1]$, f $= P[0, 0]$, g $= P[1, -2]$, h $= P[1, -1]$, i $= P[1, 0]$, j $= P[2, -2]$, k $= P[2, -1]$, l $= P[1, -1] + P[1, -2]$, m $= P[2, -1] + P[2, -2]$, n $= P[1, -1] + P[1, -2] + P[2, -1] + P[2, -2]$, o $= P[1, -2] + P[2, -2]$, p $= P[1, -1] + P[2, -1]$

Table A.2
Transition matrix for the inhibitory redundant-target processing, $\gamma 1 = \gamma 2 = 1$.

		Activation state at time $t + \Delta t$								
		(−1, −1)	(−1, 0)	(−1, 1)	(0, −1)	(0, 0)	(0, 1)	(1, −1)	(1, 0)	(1, 1)
Activation state at time t	(−1, −1)	1	0	0	0	0	0	0	0	0
	(−1, 0)	0	P[0, 0]	P[0, 1]+P[−1, 1]	P[1, −1]	P[1, 0]	P[1, 1]	0	0	0
	(−1, 1)	0	0	1	0	0	0	0	0	0
	(0, −1)	0	P[−1, 1]	0	P[0, 0]	P[0, 1]	0	P[1, 0]+ P[1, −1]	P[1, 1]	0
	(0, 0)	0	0	p[−1, 1]	0	P[0, 0]	P[0, 1]	P[1, −1]	P[1, 0]	P[1, 1]
	(0, 1)	0	0	0	0	0	1	0	0	0
	(1, −1)	0	0	0	0	0	0	1	0	0
	(1, 0)	0	0	0	0	0	0	0	1	0
	(1, 1)	0	0	0	0	0	0	0	0	1

A.2. Redundant-target processing

Given that both channels contain the targets, we modified Johnson et al.'s original transition matrix to let the upper bound be γ_i and the lower bound be $-\gamma_i$. Moreover, the transition matrix should follow that, if at time t_γ, $\mathrm{x}_i\left(\mathrm{t}_\gamma\right)=\gamma_i$, i = 1, 2, then for all $\mathrm{t}>\mathrm{t}_\gamma$, $x_i\left(t\right)=x\left(t_\gamma\right)$. Table A.2 provides an example for a system where $\gamma_1=\gamma_2=1$.

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