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Dual-task interference: Bottleneck constraint or capacity sharing? Evidence from automatic and controlled processes

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Abstract
This study investigated whether the interference between two tasks in dual-task processing stems from bottleneck limitations or insufficient cognitive resources due to resource sharing. Experiment 1 used tone discrimination as Task 1 and word or pseudoword classification as Task 2 to evaluate the effect of automatic versus controlled processing on dual-task interference under different SOA conditions. Experiment 2 reversed the task order. The results showed that dual-task interference persisted regardless of task type or order. Neither experiment found evidence that automatic tasks could eliminate interference. This suggests that resource limitations, rather than bottlenecks, may better explain dual-task costs. Specifically, when tasks compete for limited resources, the processing efficiency of both tasks is significantly reduced. Future research should explore how cognitive resources are dynamically allocated between tasks to better account for dual-task interference effects.

Keywords Dual-task processing · Psychological refractory period · Cognitive resource · Response selection

Introduction

In real-life situations, people are often faced with simultaneously processing two or more stimuli, such as talking to someone while driving. Although the human brain can flexibly process multiple pieces of information, there is a significant reduction in the ability to process the second stimulus when multiple stimuli are processed simultaneously. The psychological refractory period (PRP) paradigm has been widely used in laboratory settings to explore this issue (Pashler, 1994). In this paradigm, two tasks are presented rapidly in succession, with Task 1 (T1) and Task 2 (T2) initiated at stimulus onset asynchrony (SOA), typically requiring participants to complete their responses to T1 before responding to T2 or giving relatively more priority to T1 responses than to T2 responses. The response time to T2 (RT2) was strongly affected by the duration of the SOA. Under the condition of shorter SOAs, the participants' processing time for T1 and T2 had a high overlap, and RT2 was significantly delayed (Pashler, 1994; Pashler et al., 2008; Schubert & Strobach, 2018; Telford, 1931). The shorter the SOAs between T1 and T2, the more RT2s are delayed; the phenomenon of RT2s being delayed under shorter SOA conditions is known as the *PRP effect* (Leonhard et al., 2011; Strobach et al., 2018). The PRP effect is highly robust (Levy et al., 2006; Pashler, 1994; Pashler et al., 2008; Schubert & Strobach, 2018).

The most influential models in the explanation of the PRP effect are the response selection bottleneck (RSB) model proposed by Pashler (1994) and the central capacity sharing (CCS) model proposed by Tombu and Jolicœur (2003). The RSB model postulates that the processing of a task is divided into three stages: perceptual processing, central processing, and response execution processing. Perceptual (A) and response execution (C) belong to the non-bottleneck processing stage, but central processing (response selection, B) belongs to the bottleneck processing stage. In overlapping dual-task processing, the non-bottleneck stages of both tasks can be processed in parallel. The non-bottleneck stage of one task and the bottleneck stage of the other task can also be processed in parallel, but the bottleneck stages of both tasks cannot be processed simultaneously because human processing of the bottleneck stages is discrete and serial (Pashler, 1994; Wu & Liu, 2008). When the central processing of T1

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starts, the central processing of T2 cannot start and can only queue outside the bottleneck until T1 releases the bottleneck. Therefore, a bottleneck-like structural restriction mechanism emerges in the shorter SOA condition.

According to the predictions of the RSB model, RT2 is highly dependent on the variation in SOA duration (long or short SOA change); the shorter the SOA, the longer the T2 central processing delay and the longer RT2 will be. However, RT2 does not vary with different difficulty levels of T2 because both easy T2 and hard T2 perceptual processing is completed during the cognitive slack period of waiting for T1 to release the central bottleneck; thus, there will be no significant difference between RT2 in the easy T2 condition and RT2 in the hard T2 condition in the shorter SOA condition (see row 2 and 3 in Fig. 1). However, under longer SOA conditions, because central processing for T1 is completed before T2 enters the bottleneck, an easy T2 requires short perceptual processing and a difficult T2 requires long perceptual processing; thus, RT2 under easy T2 conditions is significantly shorter than RT2 under difficult T2 conditions (rows 4 and 5 in Fig. 1).

However, RT1 (response time to T1) is not affected by the duration of SOA and the difficulty of T2 because regardless of how difficult SOA and T2 are, when central processing of T1 begins, the central processing of T2 has no choice but to wait. When T2 enters the bottleneck to start its central processing, T1 has already started its response execution. At this time, the bottleneck stage of T2 and the non-bottleneck stage of T1 can be processed simultaneously, and central processing of T2 will not cause backward crosstalk to T1. Therefore, RT1 is always independent of changes in SOA duration and T2 difficulty.

The CCS model suggests that there is no "all-or-none" bottleneck-limiting mechanism in dual-task processing and that the central processing stage of T1 and T2 can be processed in parallel; however, because the total amount of central cognitive resources is limited, when the central processing of the two tasks overlaps, the limited cognitive resources are shared between the two tasks at the same time, and then the efficiency of both tasks is significantly reduced due to insufficient cognitive resources (Katus, & Eimer, 2019; Tombu & Jolicœur, 2005).

According to the hypothesis of the CCS model, in the shorter SOAs, if the experimental instruction emphasizes priority processing for T1, then the participants will allocate the vast majority of cognitive resources to T1 for central-response selection; if 90% of cognitive resources are allocated to T1, T2 can only obtain 10% of cognitive resources for central processing. Because T2 obtains very few cognitive resources, the processing speed of T2 will be prolonged, and RT2 will be significantly delayed. However, because T2 shares some of the cognitive resources from T1, RT1 will also be delayed, and a difficult T2 will share more cognitive resources from T1; thus, the more difficult T2 is, the more RT1 will be delayed, such that RT1 will be affected by the duration of the SOA as well as by changes in the difficulty of T2 when T1 and T2 share limited central resources; both RT1 and RT2 will be longer. Moreover, perceptually processing difficult T2 will be prolonged by the T2 central processing prestage 2A. However, prolongation of 2A will not prolong RT1 (row 7 in Fig. 2), and increasing the duration of any processing stage of T1 will increase RT1.

The RSB model seems to provide the most concise explanation when the experiment requires the participant to prioritize processing on T1. The CCS model assumes that it is more flexible and elastic. For example, when subjects strategically allocate 100% of their cognitive resources to T1 for central processing, T2 will only obtain 0% of their cognitive resources. Under this allocation condition, the CCS model is a special case of the RSB model.

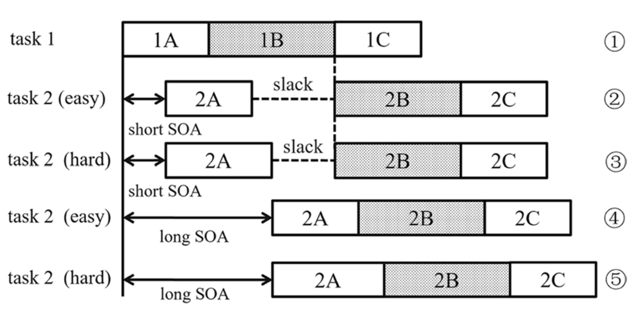


Fig. 1 Schematic diagram of the response selection bottleneck (RSB) model processing: response selection of the Task 2 (T2) process must wait for the response selection process of Task 1 (T1) to finish before it can start, i.e., T2 can only wait outside the central bottleneck when T1 occupies it, and only after central processing of T1 has finished and the bottleneck is released is T2 allowed to enter the bottleneck to start its response selection

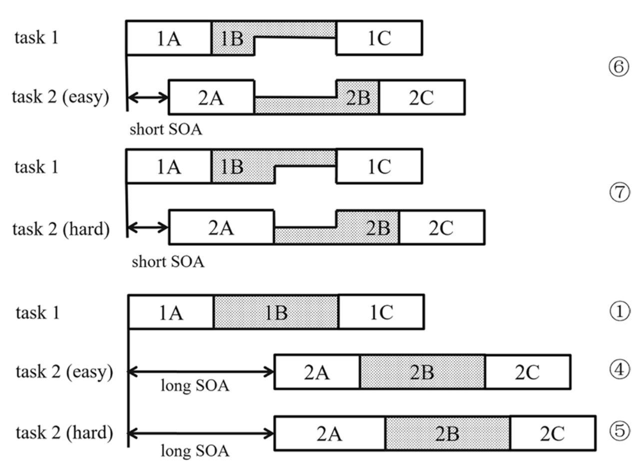


Fig. 2 Schematic representations of the central capacity sharing (CCS) model processing: Task 1 (T1) and Task 2 (T2) will share limited central cognitive resources when their response selection overlaps in the short stimulus onset asynchrony (SOA) condition

The focus of the debate between the two models primarily revolves around whether the central processing stage can simultaneously handle two or more stimuli. The criteria for evaluation mainly center on two aspects: (1) whether changes in the duration of the SOA affect the response time and error rate of T1, and (2) whether changes in T2 affect the response time and error rate of T1. Both models are currently supported by a large body of experimental evidence (Klapp et al., 2019; Miller & Durst, 2015; Pashler et al., 2008; Töllner et al., 2012; White & Besner, 2018), and a series of studies performed by Pashler et al. found that T1 was unaffected by changes in SOA duration and T2 difficulty (Pashler, 1994; Pashler et al., 2008), thus favoring serial processing of T1 and T2 during the central processing stage. However, in recent years, an increasing number of research results have emerged that indicate that T1 is influenced by different SOA durations or T2 information (Lehle et al., 2009; Lien et al., 2011; Miller et al., 2009; Pannebakker et al., 2011; Piai & Roelofs, 2013; Tombu & Jolicœur, 2002, 2003, 2005). Koch et al. (2018) provided a comprehensive summary of previous findings in dual-task research. They pointed out that prior studies have indicated that factors such as SOA duration, the occurrence of T2, the predictability of the order of T1 and T2, and changes in the order of T1 and T2 may all impact the performance of T1. However, they also noted that the research on how changes in T2 affect the performance of T1 is not systematic and comprehensive. While some studies have suggested that changes in T2 can affect the performance of T1, further research is needed to fully understand the underlying mechanisms of this impact and the patterns of change in T1 under different conditions. Therefore, the authors suggest this issue requires further in-depth investigation and exploration. Watter and Logan (2006) noted that T1 was affected by T2 information, which showed that T2 also entered the central bottleneck when T1 was processing the central-response selection. The response selections of T1 and T2 were effectively processed in parallel.

Integrating the differences between the two models' viewpoints is still tricky. Previously, most research on the PRP effect has focused on relatively simple perceptual judgment tasks. However, some scholars have extended the PRP effect to fields such as psycholinguistics, using tasks such as picture naming (Piai & Roelofs, 2013), lexical processing variations (Paucke et al., 2015), bilingual switching (Hirsch et al., 2015), etc. to explore the PRP effect. Despite the extensive research conducted on experimental materials, there has been a lack of in-depth exploration of materials that require semantic processing. These prior explorations have not adequately controlled the difficulty of T1 or T2, investigated the backward crosstalk effects of T2 on T1, or examined the mutual influences between T1 and T2 and other related issues. To further expand the scope of the PRP effect produced by the bottleneck mechanism, this study chose a different type of experimental material: Chinese characters (words) and pseudo-Chinese characters (pseudowords). By using words and pseudowords, not only could the difficulty of tasks in the dual-task paradigm be precisely controlled, but the core assumptions in dual-task processing could also be precisely tested:

First, it is possible to test whether automatic processing tasks can bypass the limitations of the bottleneck mechanism. From a theoretical perspective, for words, given that they have established corresponding representations in the mental lexicon, the retrieval of words only requires a very short time to find matching results and quickly make decision responses (Prinzmetal et al., 1991). The process of word recognition is considered an unconscious automatic process (Marcel, 1983). The orthographic information of Chinese words affects their perception and recognition, and Chinese words can be automatically activated (Zou et al., 2012; Chen & Chen, 2013), indicating that the processing of words falls under automatic processing (Chen & Chen, 2013). According to the theory of automatic processing, automatic processing does not require cognitive resource investment, is not under conscious control, has a fast processing speed, and is difficult to inhibit (Kiefer, 2012; Kiefer & Martens, 2010; Schneider & Shiffrin, 1977). In the design of dual-task experiments, the use of automatic tasks aims to evaluate whether they can achieve parallel processing with another task, avoiding resource competition between tasks (Maquestiaux et al., 2018). Ruthruff et al. (2006) also proposed that in overlapping dual-task processing, if one of the tasks is automatic, the processing of these two tasks will not lead to central resource conflicts, nor will it encounter processing bottlenecks.

For pseudowords, given that they have not formed corresponding representations in the mental lexicon, the recognition process requires more time to determine the presence of matching results (Schneider & Shiffrin, 1977). At the same time, pseudowords lack orthographic information, leading to significantly longer processing times for participants when gazing at and recognizing pseudowords compared to words (Gu et al., 2015; Prinzmetal et al., 1991), indicating that the processing of pseudowords falls under controlled processing (Chen & Chen, 2013). Recognizing pseudowords requires more cognitive resources. Therefore, using words and pseudowords as T2 and T1 can effectively test whether automatic processing tasks can bypass the bottleneck-limitation mechanism.

Second, it is possible to test whether the difficulty in information of T2 can produce backward crosstalk effects on T1. Traditional PRP studies have rarely examined the interference effects on T1 by manipulating the difficulty of T2, which has limited our understanding of the underlying mechanisms of the PRP effect. Although many early dual-task studies have focused on backward crosstalk effects (Hommel, 1998; Janczyk et al., 2014; Miller, 2006; Paucke et al., 2015; Piai & Roelofs, 2013), they have not reported or analyzed the performance of T1 in detail, overlooking the potential impact on T1. Backward crosstalk effects indicate that task-processing channels may not be wholly isolated during parallel processing, and there may be some interaction between tasks (Koch et al., 2018). Therefore, examining the backward crosstalk effects of T2 on T1 under different SOA conditions can verify whether the response selection of the two tasks is carried out in parallel and whether the processing of the two tasks is entirely independent. Therefore, this study adopted a crossover design where in Experiment 1, T1 was a tone-discrimination task, and T2 was a word-pseudoword classification task. Longtin and Meunier (2005) found that participants had significantly more difficulty recognizing pseudowords than words. Therefore, in Experiment 1, we focused on whether the different difficulty levels of T2 information would map onto T1, producing similar difficulty effects on T1. In Experiment 2, we reversed the order of T1 and T2 to observe whether the difficulty difference in T1, which initially had difficulty differences between the two levels of T2 (words simple, pseudowords difficult), would disappear when the two levels of T2 had the same difficulty. This design allows us to comprehensively and reliably examine whether the difficulty information of T2 can produce backward crosstalk effects on T1 from different perspectives, providing a more in-depth observation for understanding the processing mechanism of dual tasks.

Experiment 1

Experiment 1 employed the standard PRP paradigm, with T1 being the discrimination of high or low tones and T2 being the classification of words or pseudowords. The aim was to assess whether dual-task interference stems from bottleneck-limitation mechanisms or the constraints caused by insufficient cognitive resources due to sharing limited cognitive resources between the two tasks. To investigate this issue, Experiment 1 focused on two observation points: The first is whether the reaction time and error rate of T1 are affected by the variations in the duration of the SOA. According to the predictions of the RSB model, changes in the duration of SOA should not cause corresponding changes in the reaction time and error rate of T1. However, according to the assumptions of the CCS model, changes in the duration of SOA would lead to corresponding changes in the reaction time and error rate of T1 (Mittelstädt & Miller, 2017; Strobach et al., 2015). Under conditions of a short SOA, the response selection for T1 and T2 would overlap earlier. This extension of time during which T1 and T2 share limited central resources would significantly reduce the information processing speed at the response selection stage for both T1 and T2. Consequently, this would cause a significant slowdown in the reaction time for T1 and a noticeable increase in the error rate. Hence, in the experiment, the reaction time for T1 under short SOA conditions should be significantly slower than under long SOA conditions, and the error rate for T1 under short SOA conditions should be significantly lower than under long SOA conditions.

The second aspect concerns whether the difficulty of T2 influences T1. The RSB model also posits that T1 does not vary with variations in T2 difficulty. According to the CCS model and the viewpoint of Ruthruff et al. (2006) regarding the absence of cognitive resource conflicts in automatic tasks, this study hypothesizes that when T2 involves words, automatic processing should not be subject to bottleneck limitations. Thus, the PRP effect should be minimal or even disappear. As tasks with automatic features are not expected to compete for limited cognitive resources with T1, this condition should result in faster response times and lower error rates for T1, serving as a comparative baseline. However, when T2 involves pseudowords, controlled processing is expected to significantly constrain T2 due to the bottleneck mechanism, leading to a significant PRP effect. Additionally, as T2 and T1 compete for limited cognitive resources, participants will likely reallocate more cognitive resources from T1 to accurately process T2, resulting in slower response times and higher error rates for T1 under this condition.

Method

Participants

Forty-six undergraduate students (31 females) were recruited to participate in this experiment. All participants had normal or corrected-to-normal vision and normal hearing. Additionally, they had not participated in any similar experiments before. Before beginning the experiment, all participants provided informed consent. The research protocol, including Experiment 2 in this study, was approved by the Medical Ethics Committee of Tianshui Normal University.

Apparatus and stimuli

All visual stimuli were presented in the center of a 19-in. monitor with a resolution of 1,280 × 1,024 and a refresh rate of 60 Hz. The auditory stimuli consisted of low (300 Hz) or high (1000 Hz) tones lasting for 150 ms, with a bit rate of 1,144 Kbps, an audio sample size of 16 bits, and an audio sample level of 44 kHz in stereo. The participants were asked to listen carefully and clearly distinguish the difference between the two tones before participating in the experiment. There were 16 words and 16 pseudowords in the visual stimuli, with the words being used at high frequencies (> 30 times per million): eight in the left–right structures and eight in the upper–lower structures (see

Appendix); the number of strokes ranged from 8 to 13, with an average of 9.81 strokes. The pseudowords were created using the TrueType character-building program that comes with Windows XP, eight in the left-right structures and eight in the upper-lower structures.

The appearance features of pseudowords conform to orthographic rules, but they do not exist in Chinese dictionaries and are meaningless. This study matched the shelf structure and the number of strokes of pseudowords and words, and the production process was mainly divided into two types: for the left–right structures, pseudowords were obtained by keeping the right component of the corresponding words unchanged while replacing the left component with other components; for example, the left component of the word "核" is "木", and the component "木" was replaced with "火" to make the corresponding pseudoword "烗". For the upper–lower structures, the production of pseudowords involved keeping the larger components of the words unchanged and replacing the smaller components with other parts. For example, the smaller component of the word "袁" is "土". Therefore, the component "土" was changed to "十" to create the corresponding pseudoword "袁". The number of strokes in the words ranged from 8 to 13, with the average number of strokes being 9.81. The mean number of strokes for the pseudowords ranged from 8 to 13, with the mean number of strokes being 9.69. An independent-samples *t*-test of the number of strokes for the words and pseudowords revealed that the difference was not significant, $t(30) = 0.28$, $p = 0.78$, Cohen′s $d = 0.50$. All visual stimuli were made as .bmp images of 54 × 54 pixels in size, with black text on a white background and all fonts in Song.

Based on the theory of automatic processing and current research findings on lexical processing, it is known that the processing of words can occur automatically without the need for additional cognitive resources, a process that is not consciously controlled, has a fast processing speed, and is difficult to inhibit (Kiefer, 2012; Kiefer & Martens, 2010; Schneider & Shiffrin, 1977). Furthermore, studies have shown that Chinese character processing also exhibits automatic properties (Chen & Chen, 2013; Zou et al., 2012). Therefore, in this paper, the concept of "automaticity" specifically refers to the relative advantage participants demonstrate in terms of faster processing speed and lower degree of control when processing words compared to more resource-demanding controlled processes. However, this does not mean that automatic processing is not influenced by other tasks.

Procedures

The experimental program was conducted using E-prime 1.1 software. At the beginning of each trial, a fixation point "+" appeared in the center of the screen for a duration of 500 ms, followed by an empty screen for 300 ms. Then, a high or low tone appeared at random for 150 ms. Next, a visual stimulus was randomly presented after 50 ms, 100 ms, 300 ms, 500 ms, or 800 ms, lasting for 200 ms. After the visual stimulus disappeared, an empty screen of 2,300 ms appeared until the participants made an actual response. After the subject responded, an empty screen appeared for 1,000 ms. For T1, the participants were instructed to press the "Z" key with the left middle finger when hearing the low tone and the "X" key with the left index finger when hearing the high tone. For T2, the participants were asked to press "1" on the keypad with the right index finger when seeing a word and "2" on the keypad with the right middle finger when seeing a pseudoword. Participants responded on a standard QWERTZ computer keyboard. The instructions informed the participants that both tasks were very important, and that they should respond quickly and accurately to both tasks, but they must give priority to T1. When no response was made to the tones or visual stimuli within 2,500 ms, the response time data for that experiment were not recorded and counted as one incorrect response. The participants were given 32 practice trials before the formal experiment. Only those who achieved a correct rate of 90% or more were allowed to enter the formal experiment, and those who failed to reach the standard started a new session until the standard was reached. To eliminate the possibility of different response times between the high and low tones, the probability of their occurrence under each stimulus combination was the same, and the total number of trials in the formal experiment was 16 × 5 (SOA) × 2 (words or pseudowords) × 2 (high or low tone) = 320. All stimuli were presented on a white background. There were four breaks in between, the duration of which was determined by the participants, and the whole experiment lasted approximately 40 min.

Design

Both T1 and T2 adopted a 5 (SOA: 50 ms, 150 ms, 300 ms, 500 ms, and 800 ms) × 2 (word type: words and pseudowords) within-subject design. Dependent variables included RTs and the error rate of T1 and T2. To test the effect of T2 on T1, the data from T1 were also examined in a 5 × 2 within-subject design.

Results

Response times that deviated more than 2.5 standard deviations from the average were excluded for each treatment condition. Following the method proposed by Ulrich and Miller (2008) to eliminate response grouping strategy, the inter-response time (IRT) for each participant in each trial was calculated as IRT = RT2 + SOA - RT1. IRT data less than 100 ms were excluded. Upon observation, it was discovered that approximately half of the IRT values for three participants were less than 100 ms, indicating the presence of a significant response-grouping strategy. As a result, the data from these three participants were excluded in Experiment 1. Figures 3 and 4 display the results of RT1 and RT2 for each condition, respectively. In addition, Table 1 presents the error rates for T1 and T2 in the treatment conditions.

T1 response times (RT1s)

The ANOVA on RT1s revealed a significant main effect of SOAs, F (4,168) = 7.88, $p < 0.001$, $\eta^2_p = 0.16$. The RT1s recorded were as follows: 833 ms, 828 ms, 816 ms, 843 ms, and 877 ms for the 50-ms, 150-ms, 300-ms, 500-ms, and 800-ms SOAs, respectively. Pairwise comparisons indicated that RT1 at SOA of 800 ms was significantly slower than other SOA conditions. Furthermore, RT1 at an SOA of 500 ms was significantly slower than RT1 at an SOA of 300 ms, while the remaining differences between the two comparisons were not statistically significant. Overall, there was a trend of increasing RT1 with the extension of SOA under longer conditions (500 ms and 800 ms). The main effect of tone discrimination was significant, F (1, 42) = 29.59, $p < 0.001$, $\eta^2_p = 0.41$. When T2 involved the easier task of classifying words, the response time for T1 was faster (903 ms). In contrast, when T2 involved the more difficult task of classifying pseudowords, the response time for T1 (926 ms) significantly slowed down. The interaction between SOAs and tone discrimination was not significant, F (4,168) = 1.16, $p = 0.33$, $\eta^2\text{p} = 0.03$.

T2 response times (RT2s)

The ANOVA on RT2s found a significant main effect of SOAs, F (4,168) = 228.63, $p < 0.001$, $\eta^2\text{p} = 0.85$. As the SOAs increased, RT2s decreased linearly; the RT2s were 1,042 ms, 941 ms, 815 ms, 731 ms, and 668 ms for the 50-ms, 150-ms, 300-ms, 500-ms, and 800-ms SOAs, respectively, and pairwise comparisons revealed that the differences in RT2s between the two comparisons under different SOA conditions were significant ($p < 0.001$). The main effect of word type was significant, F (1, 42) = 95.58, $p < 0.001$, $\eta^2\text{p} = 0.70$, and the response speed of participants to pseudowords (879 ms) was significantly slower than that of words (800 ms). The interaction between SOAs and word type was not significant, F (4,168) = 0.97, $p = 0.43$, $\eta^2\text{p} = 0.02$.

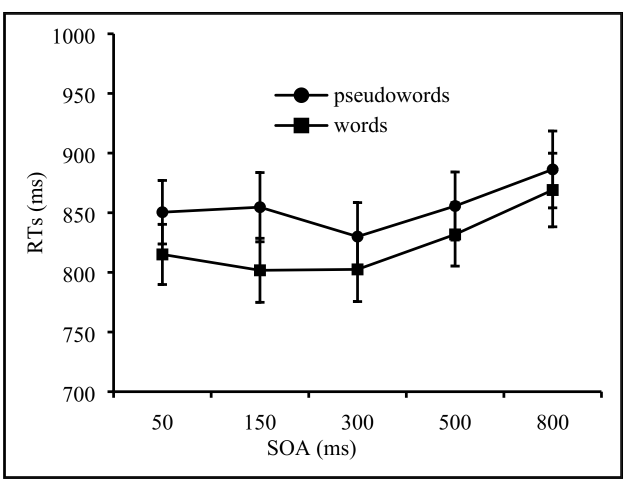


Fig. 3 Relationship between stimulus onset asynchronies (SOAs) and response times to Task 1 (RT1s) in Experiment 1. The results show a significant SOA effect and a word type effect, and error lines represent standard errors

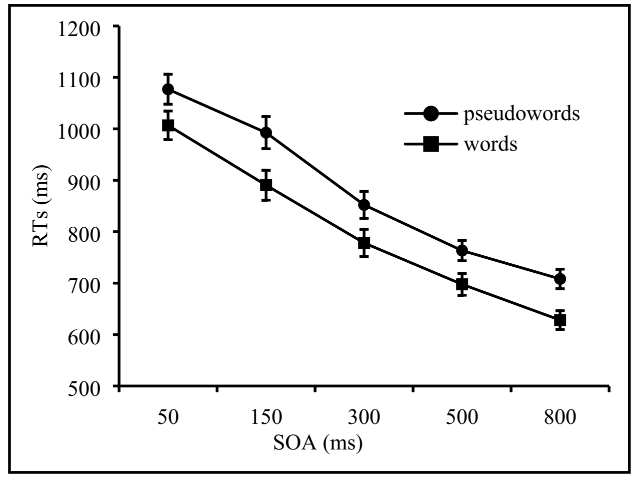


Fig. 4 Relationship between stimulus onset asynchronies (SOAs) and response times to Task 2 (RT2s) in Experiment 1. The results show a significant psychological refractory period (PRP) effect, and error lines represent standard errors

T1 error rates

The ANOVA on T1 error rates found that the main effect of SOAs was not significant, F (4,168) = 1.36, $p = 0.25$, $\eta^2_p = 0.03$. The main effect of tone discrimination was not significant, F (1, 42) = 0.37, $p = 0.55$, $\eta^2\text{p} = 0.01$. The interaction between SOAs and tone discrimination was not significant, F (4,168) = 2.24, $p = 0.81$, $\eta^2\text{p} = 0.05$.

Table 1 Error rates for each condition in Experiment 1 for Tasks 1 and 2 (T1 and T2) (standard deviations in brackets)

SOA	T1		T2	
	Words	Pseudowords	Words	Pseudowords
50 ms	0.06 (0.09)	0.04 (0.05)	0.04 (0.04)	0.09 (0.08)
150 ms	0.03 (0.04)	0.05 (0.07)	0.04 (0.04)	0.10 (0.06)
300 ms	0.03 (0.04)	0.05 (0.05)	0.04 (0.05)	0.10 (0.08)
500 ms	0.03 (0.04)	0.04 (0.04)	0.04 (0.04)	0.08 (0.07)
800 ms	0.03 (0.06)	0.03 (0.04)	0.06 (0.06)	0.08 (0.06)

SOA stimulus onset asynchrony

T2 error rates

An ANOVA on T2 error rates found that the main effect of SOAs was not significant, F (4,168) = 0.59, p = 0.65, η^2p = 0.01. The main effect for word type was significant, F (1, 42) = 55.16, p < 0.001, η^2p = 0.57, and the error rate of words (0.034) was significantly lower than that of pseudowords (0.087). The interaction between SOAs and word type was not significant, F (4,168) = 2.31, p = 0.08, η^2p = 0.19.

Discussion

The results of Experiment 1 showed that, in the T2 task, as the SOA decreased, RT2 increased linearly, and the PRP effect was significant, indicating that under shorter SOA conditions, the cognitive processing of T2 was significantly delayed. Participants' response speed to pseudowords was significantly slower than their response speed to words, and the error rate for pseudowords was also significantly higher than that for words, indicating that participants found processing pseudowords to be significantly more difficult than processing words. The interaction effect between SOAs and word type was not significant, suggesting that the degree of bottleneck restriction for words and pseudowords was the same. This finding is consistent with the assumptions of both the RSB model and the CCS model. However, Experiment 1 also found a significant main effect of SOAs on RT1, indicating that the response selection of T2 had a significant impact on that of T1, which does not support the prediction of the RSB model. Similarly, in RT1, it was also found that participants' response speed to pseudowords was significantly slower than their response speed to words, suggesting that the difficulty information from T2 was mapped onto the processing of T1.

Experiment 2

Experiment 1 found that automatic T2 failed to eliminate T2 seizing limited cognitive resources from T1. Thus, if T1 was an automatic processing task, could it avoid the competition for limited cognitive resources between two tasks, thus avoiding the constraint mechanism of a bottleneck like that on T2? To test this question, Experiment 2 reversed the order of T1 and T2 in Experiment 1 (that is, T1 involved word or pseudoword classification, and T2 involved high- or low-tone discrimination). According to the theory of automatic processing, the reason for the faster speed of automatic processing is that it can be completed automatically in both perceptual recognition and response selection stages; thus, the duration of 1A + 1B in automatic processing is significantly shorter than that of 1A + 1B in controlled processing. According to $RT2_{\text{(short SOA)}} = A1 + B1 + B2 + C2 - SOA$, in shorter SOA conditions, the processing time of the words 1A + 1B is significantly shorter than the processing time of the pseudowords 1A + 1B; thus, RT2 under the words T1 condition should be significantly smaller than RT2 under the pseudowords T1 condition. According to the formula of the PRP effect (Ruthruff et al., 2006), $PRP_{\text{effect}} = 1A + 1B - 2A - SOA$, and then the PRP effect under the condition of words T1 should be significantly smaller than that under the condition of pseudowords T1; that is, when the words are taken as the priority processing T1, the PRP effect should be very small or even disappear.

To test whether dual-task interference is based on bottleneck constraints or resource sharing, Experiment 2 still focused on two observation points: First, whether RT1 changes with the duration of SOA, which has the same theoretical assumption as Experiment 1. Second, whether T2 information will be mapped to T1 should be significantly different from Experiment 1. In Experiment 2, T2 involves the high-tone or low-tone task, which has the same cognitive processing difficulty. According to the RSB model, T1 is not affected by T2, so the duration of RT1 is only related to its own difficulty. Since the processing difficulty of pseudowords is significantly higher than that of words, the response speed for pseudowords RT1 should be significantly slower than that for words RT1. On the other hand, according to the CCS model, the difficulty information of T2 is directly mapped onto T1. Since the cognitive processing difficulty of the tone discrimination task is the same, similar response times for both pseudowords RT1 and words RT1 of the same size will be observed in Experiment 2.

Method

Participants

Forty-one undergraduate students (25 females) were recruited to participate in this experiment. All participants had normal or corrected-to-normal vision and normal hearing and had not participated in similar experiments.

Materials and apparatus

The same as in Experiment 1.

Procedure

The whole experimental procedure was the same as that used in Experiment 1. The difference was that T1 and T2 were reversed, i.e., T1 was a word or pseudoword classification task, and T2 was a high- or low-tone discrimination task. For T1, participants were asked to press "Z" with the left middle finger for words and "X" with the left index finger for pseudowords; for T2, participants were asked to press "1" on the keypad with the right index finger for low tones and "2" on the keypad with the right middle finger for high tones. Words or pseudowords had the same probability of appearing in each stimulus combination condition.

Design

Both T1 and T2 adopted a 5 (SOA: 50 ms, 150 ms, 300 ms, 500 ms, and 800 ms) × 2 (tone discrimination: high or low tone) within-subject design. Dependent variables include response time and the error rate of T1 and T2. To test the effect of T2 on T1, the data from T1 were also examined in a 5 × 2 within-subject design.

Results

Response times that deviated more than 2.5 standard deviations were excluded for each treatment condition. We excluded the data from one participant who exhibited a distinct response-grouping strategy. In addition, IRT data less than 100 ms were also excluded from the analysis. The results of RT1 and RT2 for each condition can be observed in Figs. 5 and 6, respectively. Table 2 presents the error rates for T1 and T2 in the treatment conditions.

T1 response times

A paired *t*-test was conducted on the data of the participants under the conditions of words (mean response time and standard deviation: 1,066 ± 318; mean error rate and standard deviation: 0.030 ± 0.029) and pseudowords (1,101 ± 316; 0.050 ± 0.066) in advance, and the results showed a significant difference in response time between the words and pseudowords [t (39) = -3.87, p < 0.001, Cohen′s d = 0.10] and an equally significant error rate [t (39) = 2.21, p = 0.033, Cohen′s d = 0.40], which indicated that the processing difficulty of pseudowords is significantly higher than that of words. Theoretically, under relatively shorter SOA conditions, word RT1s should be significantly shorter than pseudoword RT1s, and the error rate of word T1s should be significantly lower than that of pseudoword T1s. If this difficulty effect does not occur for response times and error rates for word and pseudoword T1s, then it can only be attributed to the same difficulty of T2 tone discrimination.

The ANOVA on RT1s found a significant main effect of SOAs, F (4,156) = 21.65, p < 0.001, η^2_p = 0.36. The RT1s were 1,038 ms, 1,032 ms, 1,051 ms, 1,099 ms, and 1,185 ms for the 50 ms, 150 ms, 300 ms, 500 ms, and 800 ms SOAs, respectively. Pairwise comparisons revealed that RT1 at an SOA of 800 ms was significantly slower than RT1s at all other SOA conditions, RT1 at an SOA of 500 ms was significantly slower than RT1 at SOAs of 50 ms, 150 ms,

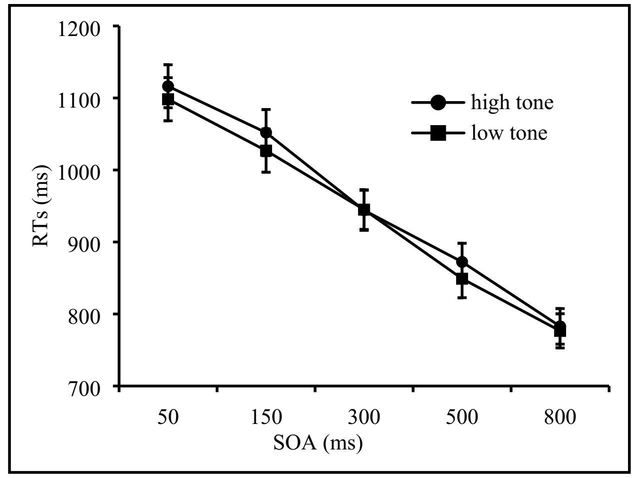


Fig. 6 Relationship between stimulus onset asynchronies (SOAs) and response times to Task 2 (RT2s) in Experiment 2. The results show a significant psychological refractory period (PRP) effect, and error lines represent standard errors

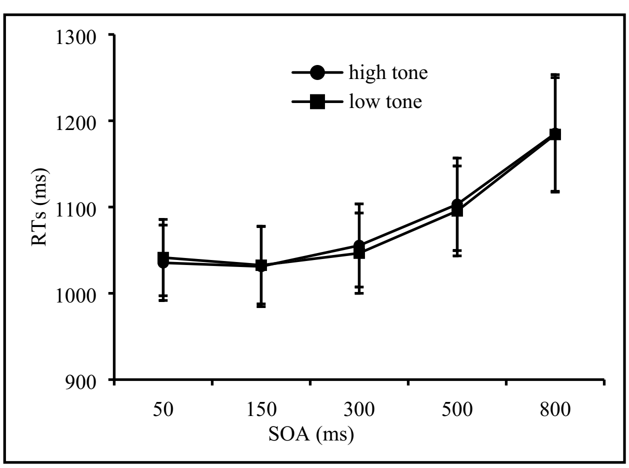


Fig. 5 Relationship between stimulus onset asynchronies (SOAs) and response times to Task 1 (RT1s) in Experiment 2. The results show a significant SOA effect, and error lines represent standard errors

Table 2 Error rates for each condition in Experiment 2 for Tasks 1 and 2 (T1 and T2) (standard deviations in brackets)

SOA	T1		T2	
	Low tone	High tone	Low tone	High tone
50 ms	0.04 (0.05)	0.04 (0.05)	0.03 (0.04)	0.04 (0.05)
150 ms	0.05 (0.05)	0.07 (0.06)	0.04(0.04)	0.05 (0.05)
300 ms	0.07 (0.06)	0.06 (0.06)	0.04 (0.04)	0.05 (0.05)
500 ms	0.06 (0.06)	0.06 (0.06)	0.05(0.05)	0.05 (0.05)
800 ms	0.06 (0.07)	0.06 (0.05)	0.05 (0.05)	0.05 (0.06)

SOA stimulus onset asynchrony

and 300 ms, and the remaining differences between the two comparisons were not significant, consistent with the findings of Experiment 1; under longer SOA conditions, there was an overall trend of increasing RT1 with the extension of SOA. The main effect of word type was not significant, F (1, 39) = 0.08, $p = 0.78$, $\eta^2_p = 0.002$. When T2 was the tone-discrimination task, the response-time difference between words and pseudowords that originally exhibited a difficulty difference disappeared. The interaction between SOAs and word type was not significant, F (4, 156) = 0.25, $p = 0.89$, $\eta^2_p = 0.006$.

T2 response times

The ANOVA on RT2s found a significant main effect of SOAs, F (4, 156) = 125.74, $p < 0.001$, η^2p = 0.76, with a linear increase in RT2s with shorter SOAs. The RT2s were 1,107 ms, 1,039 ms, 944 ms, 861 ms, and 780 ms for the 50 ms, 150 ms, 300 ms, 500 ms, and 800 ms SOAs, respectively, and pairwise comparisons revealed that the differences in RT2s between the two comparisons under different SOA conditions were significant ($p < 0.001$). The main effect of tone discrimination was not significant, F (1, 39) = 2.63, $p = 0.11$, η^2p = 0.06. The interaction between SOAs and tone discrimination was not significant, F (4, 156) = 0.55, $p = 0.70$ η^2p = 0.01.

T1 error rates

The ANOVA on the T1 error rates found a nonsignificant main effect for SOAs, F (4, 156) = 2.54, $p = 0.06$, η^2p = 0.22. There was a nonsignificant main effect for word type, F (1, 39) = 0.04, $p = 0.85$, η^2p = 0.001. The interaction between SOAs and word type was not significant, F (4, 156) = 1.84, $p = 0.14$, η^2p = 0.17.

T2 error rates

The ANOVA on the T2 error rates found a nonsignificant main effect for SOAs, F (4, 156) = 2.29, $p = 0.08$, η^2p = 0.02. There was a nonsignificant main effect for tone discrimination, F (1, 39) = 0.80, $p = 0.38$, η^2p = 0.02, and a nonsignificant interaction was found between SOAs and tone discrimination, F (4, 156) = 0.87, $p = 0.49$, η^2p = 0.09.

Discussion

In Experiment 2, we observed that as the SOA decreased, the RT2 increased linearly, and the PRP effect was significant. This indicates that even when T1 is an automatic processing task requiring minimal or no cognitive resources, it cannot eliminate the constraining mechanism that similarly affects T2 akin to a bottleneck. The study noted a significant impact of the SOA on the response time for T1, underscoring how T2's response selection influences a specific processing stage of T1 under varying SOA conditions. This contradicts the predictions of the RSB model. The preliminary examination of the T1 data in Experiment 2 revealed that participants responded faster and made fewer errors in classifying words, indicating that the difficulty of classifying words was significantly lower than that of pseudowords. However, the test results in the dual-task situation found that there were no difficulty effects observed on either T1 or T2. There is sufficient reason to explain that due to the absence of differentiation in the difficulty of discriminating between high and low tones in T2, the inherent difficulty contrast in the classification tasks of words and pseudowords in T1 disappeared. This finding was consistent with the results of Experiment 1, demonstrating that T1 and T2 exhibited fundamentally similar response patterns and clearly illustrated the complete mapping of T2's information onto T1. This suggests that the processing of the two tasks mutually influences and constrains each other.

General discussion

Our study utilized words and pseudowords as experimental materials and employed a crossover design to investigate the impact of task-order variation on experimental results. This approach allowed us to control task difficulty precisely and discover the unique characteristics of automatic and controlled processing. We also examined whether automatic processing tasks could bypass cognitive processing bottleneck constraints. Additionally, applying the crossover design enabled us to comprehensively assess whether information from the T2 produces backward crosstalk effects on the T1.

According to the assumptions of the RSB model, under longer SOA conditions, the response selection stages of T1 and T2 do not overlap. When T2 enters the bottleneck to start response-selection processing, T1 has already completed its response-selection processing. Therefore, in this scenario, the response-selection processing of T2 is not delayed, resulting in RT1 and RT2 being close to the response times of these two tasks in single-task conditions.

However, under shorter SOA conditions, partial (or even complete, e.g., when the SOA is 0 ms) response selections of both T1 and T2 overlap. Since response-selection processing occurs sequentially within the bottleneck, when T1 occupies the bottleneck for response-selection processing, T2's response selection can only proceed after T1 has completed its response selection. Therefore, as the SOA becomes shorter, the overlap between the response selections of the two tasks increases, resulting in longer waiting times for T2 to be released from the bottleneck and, consequently, longer

RT2. Theoretically, a decrease in SOA by 10 ms corresponds to a 10-ms increase in RT2, indicating a direct relationship between the duration of SOA and RT2.

Although different, the processing principles of the CCS and RSB models result in the exact predictions for RT2. For instance, under sufficiently long SOA conditions where there is no overlap between the response-selection processing of T1 and T2, or if the duration of SOA exactly matches the time needed for T1 to complete central-response selection and T2 to conduct central-response selection, the processing of T2 will not be affected by T1. However, under short SOA conditions, the duration of T1's central-response selection heavily influences the duration of RT2. The shorter the SOA, the more time T1 and T2 need to process and share central cognitive resources and the longer it takes for T2 to obtain 100% of the cognitive resources. This limited allocation of resources directly results in a slower central processing speed for T2, and the time taken by this slower processing is directly added to RT2. Therefore, the duration of SOA directly impacts the duration of RT2.

In both experiments of this study, a significant SOA effect on RT2 was observed, indicating that as the SOA decreases, RT2 linearly increases, demonstrating a significant impact of T1's response selection on T2's response selection and a significant PRP effect. This result is consistent with previous research on the PRP effect (Hoffmann et al., 2020; Katus & Eimer, 2019; Pashler, 1994; Pashler et al., 2008; Strobach et al., 2018; Tombu & Jolicœur, 2005). It suggests that even Chinese words that are very familiar to participants and can be processed without or with minimal cognitive resources cannot avoid bottleneck limitations. The shorter the SOA between T1 and T2, the greater the interference of T1 on T2, and the more delayed RT2 becomes. Therefore, the results of this study once again confirm the robust nature of the PRP effect.

To investigate whether the central stages of two tasks can simultaneously process multiple stimuli, this study specifically focused on whether T1 is affected by the duration of SOA and whether T1 is affected by the change in difficulty of T2. Regarding the issue of whether T1 is affected by changes in the duration of SOA, both Experiment 1 and Experiment 2 found a significant main effect of SOAs on RT1, which the RSB model cannot reasonably explain. However, the CCS model can provide a reasonable explanation: Under short SOA conditions, the response selection stages of T1 and T2 overlap, leading to a sharing of limited cognitive resources between T1 and T2. As the SOA decreases, T2 shares cognitive resources from T1 earlier, resulting in a more significant delay in RT1. Due to the prioritized processing of T1, it occupies the vast majority of resources (e.g., 90%), while T2 receives a small amount of resources (e.g., 10%). Therefore, the impact of SOA on T1 is overall minimal, but the impact on T2 is significant, reflected in the data results where the SOA effect on RT1 is much smaller than the SOA effect on RT2. As the duration of SOA increases, when T1 completes its central processing, most resources are reallocated to T2, allowing T2 to have a large amount of resources to expedite the processing of the remaining stages. Consequently, the response speed of T2 increases, and the error rate significantly decreases. This fully demonstrates that in overlapping dual-task processing, individuals can process the central stages of two or more tasks in parallel, and reflects the dynamic allocation of cognitive resources between the two tasks (Mittelstädt et al., 2022).

Regarding the impact of T2 on T1, this study obtained new findings by reversing the order of the two tasks: the response of T1 changed with the variation of the difficulty level of T2. In Experiment 1, we observed that when T2 was words, the response time of T1 was shorter and the error rate was lower; when T2 was pseudowords, the response time of T1 was longer and the error rate was higher, indicating that the difficulty of pseudowords' classification for participants was significantly higher than words' classification. At the same time, the information on the T2 difficulty level also significantly affected the performance of T1: when T2 was pseudowords, the response time of T1 was longer; when T2 was words, the response time of T1 was shorter. These results support the hypothesis that T2 difficulty information was mapped to T1.

The observation results from Experiment 2 indicated that there were no significant differences in participants' response times and error rates, whether in the high-tone (T2) condition or the low-tone condition, suggesting that participants did not show a significant difference in identifying the two tones. However, the analysis of the results for T1 was surprising, as there were no significant differences in response times and error rates, whether in the pseudoword (T1) condition or the word (T1) condition. Nevertheless, through pre-conducted paired t-tests, it was found that participants had significantly longer response times in the pseudoword condition compared to the word condition, and the error rate for pseudoword was also significantly higher than that for word. This result confirmed that participants found the classification difficulty of pseudowords to be significantly higher than that of words. It is perplexing that in the absence of difficulty differences in the T2 condition, the difficulty differences that originally existed in T1 disappeared. The reason for this phenomenon can only be attributed to the influence of difficulty information in the T2 condition, indicating that the balanced difficulty of T2 dissolved the difficulty effect in T1. The results of these two experiments collectively indicate that the performance of T1 was significantly influenced by the difficulty differences in T2, revealing that T2 information can directly map and influence the processing stages of T1.

All of this evidence demonstrates the significant backward crosstalk effect of T2 on T1, indicating that in dual-task processing, there is mutual influence and constraint between the difficult information of the tasks. The innovative experimental design used in this study provides a new perspective and theoretical foundation for in-depth research into the processing mechanisms of dual tasks, particularly for the dynamic allocation of resources. Moreover, this approach allows for a more rigorous test of how T2 information may influence the T1 process, providing new evidence for understanding the nature of dual-task interference in the PRP paradigm and offering new insights into the dynamic allocation mechanism of cognitive resources in dual tasks.

In both experiments of this study, it was consistently observed that under longer SOA conditions (500 ms and 800 ms), there was an overall trend of increasing RT1 with the extension of SOA. The RSB model cannot explain this phenomenon and it cannot be reasonably explained by the CCS model. This study suggests that in dual tasks, the duration of SOA determines the time window for resource allocation. When the SOA is short, T1 occupies the vast majority of cognitive resources, and T2 quickly follows T1, resulting in participants having less attentional dispersion due to the less anticipated appearance of T2 after T1. Therefore, RT1 is faster under shorter SOA conditions. In longer SOA conditions, T1 similarly occupies the vast majority of cognitive resources, allowing these resources to remain concentrated on T1 for an extended period. This increases the depth of processing for T1 and heightens the difficulty of reallocating resources from T1 to T2, potentially leading to a prolonged RT1. Simultaneously, under long SOA conditions, participants must continuously anticipate the appearance of T2, leading to ongoing attentional dispersion, which could be a significant factor contributing to the elongation of RT1. Further investigation is warranted to understand this issue.

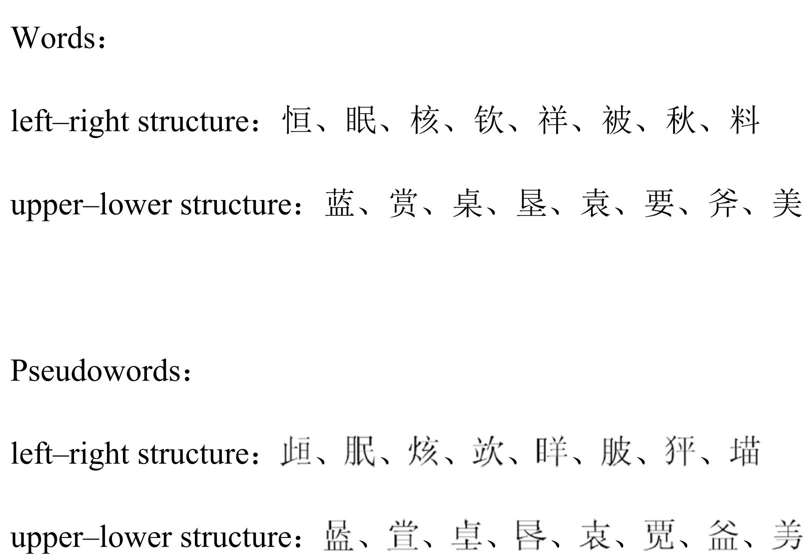
In this sense, in overlapping dual-task processing, the PRP effect cannot simply be attributed to bottleneck constraints but rather to the dynamic sharing of limited central cognitive resources by the two tasks. Insufficient total cognitive resources are the main reasons for the significant decrease in the operational efficiency of both tasks and the mutual interference between them.

Conclusions

The results of both experiments did not provide evidence that automatic processing tasks could eliminate dual-task interference. In overlapping dual-task situations, even with an emphasis on prioritizing processing for the automatic task, the first task was not prevented from creating a bottleneck-like limiting mechanism for the second task. As long as the response-selection processing of the two tasks overlaps, the comprehensive data results showed that the primary reason for the mutual interference of dual tasks was the lack of total central cognitive resources; when the two tasks competed for limited cognitive resources simultaneously, the operational efficiency of both tasks was significantly reduced. The shorter the SOA between the two tasks, the more pronounced the mutual interference. As the SOA decreases, the competition for limited cognitive resources between the two tasks becomes more intense. Therefore, the main reason for the mutual interference of dual tasks lies in the insufficient total central cognitive resources, leading to a significant decrease in the operational efficiency of both tasks when the two tasks compete for limited cognitive resources simultaneously.

Appendix

Visual stimulus materials in Experiments 1 and 2:



Data Availability Data and materials for this study reported here are available from the corresponding author on reasonable request.

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