An Assessment of Inhibition in The Simon Task

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by
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The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled

An Assessment of Inhibition in The Simon Task

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and hereby certify that, in their opinion, it is worthy of acceptance.

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ABSTRACT

Different from some other context tasks, the Simon task is featured with a congruency effect decreasing with increasing RT. Ridderinkhof proposed a two-route model to account for the negative slope of this congruencey effect and attributed it to selective inhibition. Two experiments were conducted to test this theory. In experiment 1, each participant's inhibition level was manipulated by taxing working memory capacity to different degrees, but no differentiation of congruency effect slope was found. In experiment 2, increased perceptual difficulty of stimuli resulted in an increasing congruency effect in time course, which is beyond prediction based on any available explanations of the Simon task. In sum, no support for Ridderinkhof's theory was found.

Introduction

Psychologists have long known that the context in which a stimulus is presented affects how the stimulus is perceived. Examples of these context effects (see also Kornblum & Lee, 1995) include the Simon tasks (Simon,1969), Stroop tasks (Stroop,1935), flanker tasks (Eriksen & Eriksen, 1974), priming tasks (Scarborough, Cortese, & Scarborough, 1977) and identification tasks with nested letters (Navon, 1977). How context affects processing has provided insight into human pattern processing including object recognition and reading.

In these context tasks, a stimulus has two attributes or components: a target attribute (component) which the participants are required to respond to, and a task-irrelevant one which triggers some prepotent response tendency. For example, in a classic Stroop task, a colored color word–e.g., either a "RED" in red ink, or a "Blue" in green ink–is presented, and participants respond to the color of the word. Here, the relevant attribute is the color of the ink and the irrelevant attribute the content of the word.

Apparently, the relevant and irrelevant features (components) could be either mutually facilitating or conflicting, and a central concept of context tasks, *congruency*, captures this dichotomy of their relationship. In context tasks, a trial is called congruent when the relevant and irrelevant attributes correspond to the same response, and incongruent otherwise. In a classic Stroop task, a congruent trial happens when the content and color of a color word matches, while mismatch of the color and the content leads to an incongruent trial. *Congruency effect*, the relative advantage of response speed of congruent trials compared with incongruent trials, measured by reaction time (RT), is the benchmark of the context effect. Researchers have proposed a variety of possible reasons for congruency effect, including spreading activation (Neely, 1991), selective attention (Spieler, Balota, & Faust, 2000), response inhibition (Ridderinkhof, 1997), and cognitive control (Botvinick, Braver, Brach, Carter, & Cohen, 2001). In this study, we focus on the characteristic congruency effect pattern of a single and perhaps the most studied context task, the Simon task.

Simon effect

Simon tasks refer to a family of tasks in which spatially differentiated responses are made to the identity of the stimulus. In its most classic paradigm, the participants are asked to indicate the color of either a red or green square presented on one side of the screen by pressing a left or a right key. In this task, the relevant attribute is the color while the irrelevant attribute the position of the square, their combination determines congruency or incongruency of each trial. For instance, when the response key corresponding to a green stimulus is on the left, a congruent trial happens when a green stimulus appears on the left, and an incongruent trial happens when the green stimulus appears on the right or a red stimulus appear on the left.

The unique lateralized nature of both the distracting stimulus attribute (location) and the response method (left vs. right key) of Simon tasks aroused interesting findings. It was surprising that, for example, the Simon effect was found to persist even when all possible stimuli and responses are limited to one side of the body (Umilta & Nicoletti, 1985), as well as when participants operated the right key using left hand and vise versa (Riggio, Gawryszewski, & Umilta, 1986; Simon, Hinrichs, & Craft, 1970), which means Simon effect can not be purely anatomical but should involve some code translation and mapping in higher levels. As will be discussed below, the Simon effect has some fundamental difference from some other context effects like the Stroop effect.

Before 1994, studies of Simon effect almost exclusively focused on comparing the accuracy and mean RT values in congruent and incongruent conditions, and most explanations concentrate on a single underlying mechanism(De Jong, Liang, & Lauber, 1994). Exemplar mechanisms include an automatic instantiation of the orienting reflex (Simon, 1969), automatic activation of spatial stimulus codes (Wallace, 1971), and automatic activation of the spatially corresponding response (Kornblum, Hasbroucq, & Osman, 1990).

However, it has long been noticed that Simon effect could be reversed in some situations, which defied explanation from many single-process accounts. An example is the reverse Simon effect discovered by Hedge and Marsh (1975), which occurs when participants were asked to press the key of alternate color to the stimulus instead of the key of the same color. Responses were faster when stimulus and response positions were incongruent. Motivated to solve this puzzle, De Jong, Liang and Lauber (1994) suggested a dual-process hypothesis for explaining Simon effect, in which the initial stimulus onset triggers an automatic tendency to orient or respond towards its location, which is then either enhanced or diminished by the following goal-dependent processing. In other words, in this model there are two components assumed to have different causes and time-course: a nonconditional component that becomes effective immediately after stimulus onset but dissipates rapidly, and a conditional component that arises once the transformation rule (identity or reversal) is applied to the relevant attribute as well as, unintentionally, the spatial code of stimulus.

A congruency effect time course analysis technique and the RT distribution in the Simon Effect

As part of their effort to glean evidence supporting their findings, De Jong and colleagues (De Jong, Liang, & Lauber, 1994; also see Zhang and Kornblum, 1997; Speckman, Rouder, Morey, & Pratte,in press) adopted transformation of probability density function plots (as illustrated in Figure **??**) to better examine the time couse of congruency effect and RT distribution in Simon task, which was named *delta plot*. To make a delta plot, RT data of congruent and incongruent conditions are ordered into percentiles respectively. For the RTs corresponding to each percentile point for congruent and incongruent conditions, their difference–which is the congruency effect at that point–is plotted on the y axis against their average which is plotted on the x axis. Thus, the whole curve represents the changing congruency effect along increasing mean RT.

In spite of losing some details, delta plots highlight two benchmark findings regarding the RT distribution in Simon task. First, the average RT of incongruent trials is longer than that of congruent trials; second, the congruency effect is largest for fastest responses and decreases with the increase of RT, i.e., for RT of higher percentiles, the advantage of RT in congruent trials over incongruent trials shrinks and even reverses. This corresponds to the negative slope going from a relative high value with smallest RT to small or even negative values for longest RTs, as shown in Figure **??**. This delta plot is typical of results in the literature about Simon tasks.

De Jong et.al's model was later questioned for its ability to explain the reverse Simon effect better than Hedge and Marsh's original effort and criticized for its inappropriate and unnecessary time-course assumptions (Zhang & Kornblum, 1997). However, the merit of its construct of two processes, one activation tendency triggered by the location feature and the other goal-oriented processing, has been largely appreciated and was adopted by other researchers in recent years. For example, Wascher, Schatz, Kuder and Verleger (2001) examined a variety of tasks under the Simon paradigm using natural hand, cross hand, visual and auditory stimuli, and claimed two processes could account for similar response time effects in these heterogeneous tasks. Specifically, they proposed a direct activation of motor functions by the spatial properties of visual stimuli through a visuomotor network, and an addi-

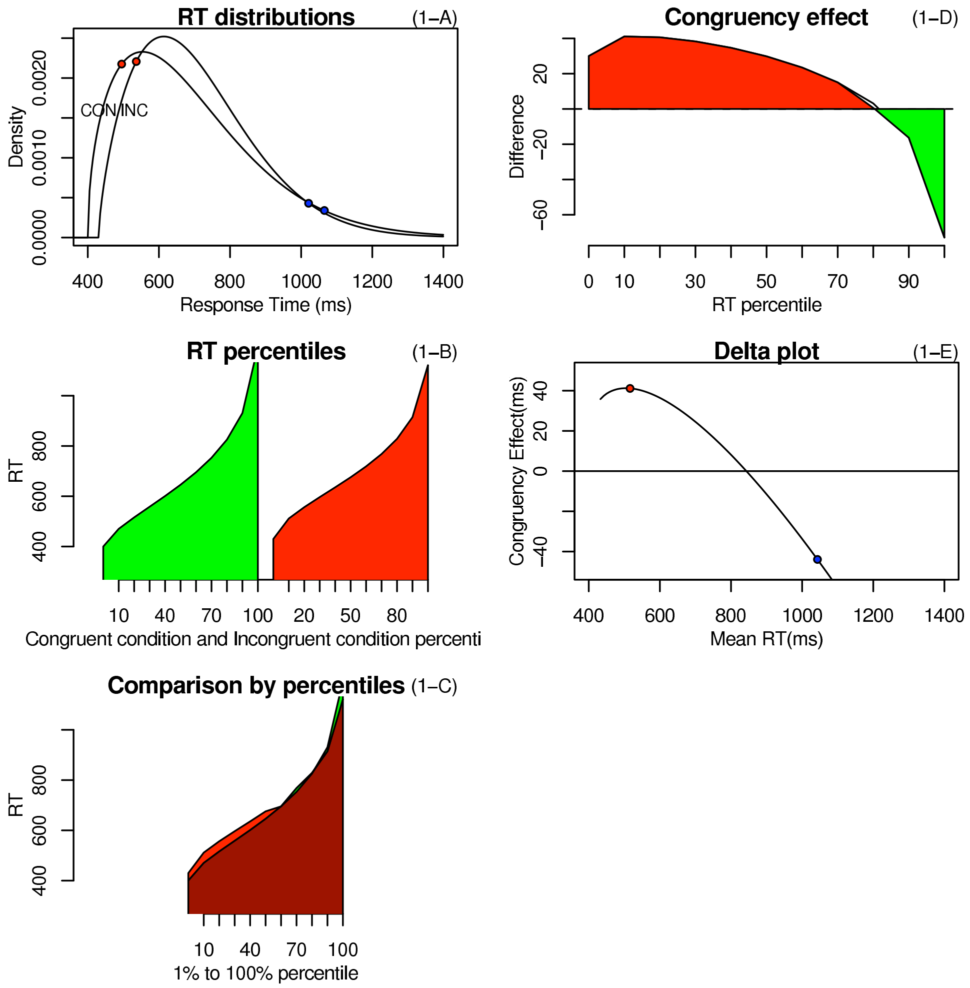

Figure 1. (1-A). The typical shape of RT distributions in the congruent (noted by 'CON') and the incongruent (noted by 'INC') conditions in a Simon experiment. Usually the congruent condition distribution starts earlier, but also has a fatter tail, and the incongruent condition has a slightly narrower shape. The two red dots are the 15 percentile points of the two conditions, and the blue dots indicate the 95 percentile points. (1-B). The rearrangement of RT data according to their percentile in the congruent condition (green on the left) and the incongruent condition (red on the right). (1-C). The comparison of RT between the two conditions from small to large percentiles.As typical in Simon tasks, the RT is longer in the incongruent condition than in the congruent condition for smaller percentiles (the red section), but turns longer in the congruent conditions for larger percentiles (the green section). (1-D).The RT difference between the incongruent and the congruent conditions, namely the congruency effect, along RT percentiles. (1-E). When the congruency effect is plotted along RT rather than RT percentiles, a delta plot is made. Specifically, each single point on the delta plot curve represent a percentile, its x value is the average of its corresponding RTs in the two conditions, and its y value is the difference between these two RTs. Again, the red dot stand for the 15 percentile and the blue dot stand for the 95 percentile.

tional process due to code conflict during stimuli response translation. Nonetheless, their expressed unique view concerning the activation process, distinct from De Jong's theory: "activation processes are not unconditional but controllable and that the two mechanisms may alternate rather than overlap with each other, both depending on task requirements."

Ridderinkhof's model

A dual-process model of Simon effect attracting growing attention in recent years was developed by Ridderinkhof (2002). Like in De Jong et.al.'s model, there are two routes: one is a slow, deliberate response decision process, which needs to be triggered by the target attribute of the stimulus; the other one, preceding the deliberate route, is fast and directly activated by the initial stimulus processing, often by the task-irrelevant attribute of the stimulus. In the classical Simon task, the color of the stimulus is the task-relevant attribute which triggers the slow and deliberate route, whereas the location of the stimulus is the task-irrelevant attribute which activates the fast route. Characteristic of this model is the existence of conscious inhibition manifested in the slow suppression of the initial direct activation by the deliberate processing, which begins at the onset of relevant feature, and accounts for the deceasing Simon effect for longer RT. This slow suppression is in similar ways described as prime discounting by Huber (2002) and overcompensation by Eimer (1999).

According to Ridderinkhof, if there is no inhibition of initial facilitation in congruent trials (for example, when it is knocked out with some manipulation), the processing stages in incongruent trials should be all the same as congruent trials except for an extended duration for responding to the stimuli color, and therefore the RT distribution of incongruent trials should have the same shape and scale as congruent trials with merely a positive shift; reflecting this shift, the congruency

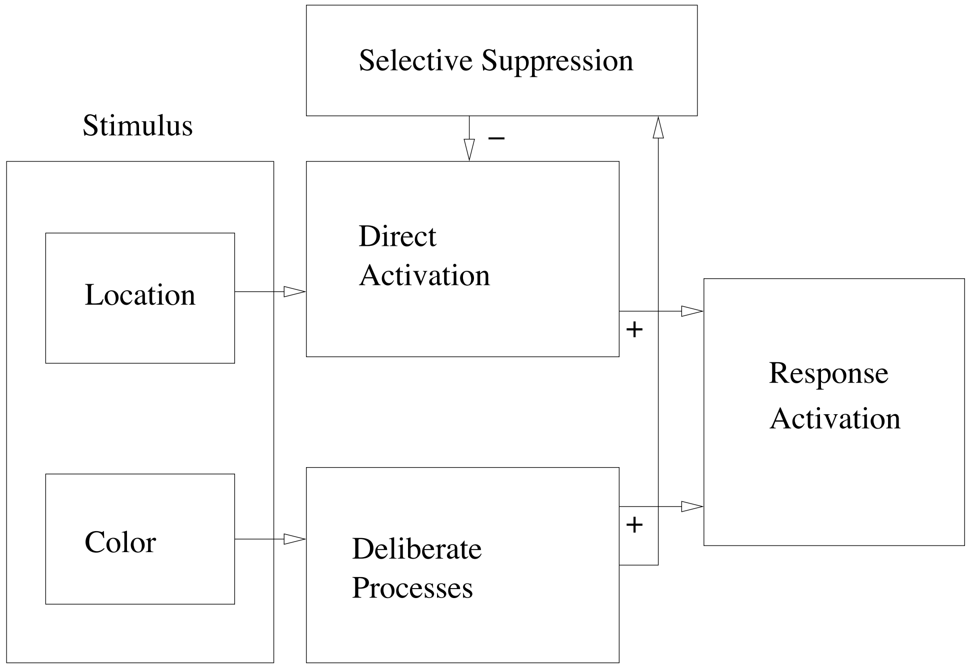

Figure 2. The Ridderinkhof model

effect should be a constant throughout all RT values. In this sense, Ridderinkhof's theory can be tested by comparing the slopes of Simon effects under different degrees of suppression manipulation.

Ridderinkhof's theory has gained support from some studies conducted by himself and other researchers. For example, Ridderingkhof et.al. (2005) found that, in a context where the need for suppression is weakened, the delta plot slopes became more positive. He used two experiments to demonstrate this effect. In one experiment, two conditions containing identical stimuli combinations were used to create differential inhibition levels in normal Simon trials. Both conditions are composed of 75% ordinary Simon trials with black and white diamonds as stimuli, and the other 25% trials are of grey squares and grey circles. For these 25% trials, participants responded to the stimuli shapes, while ignoring the locations in the first condition (called CLI condition, Context in which Location is Irrelevant), and to the location in the second condition (called CLT condition,Context in which Location is the Target).The delta plot of the ordinary Simon trials in these two conditions revealed a negative slope in the CLI condition in which location needs to be totally ignored, and a positive slope–which he interpreted as evidence of attenuated inhibition–in the CLT condition in which location was the target for 25% of the trials and thus less inhibited. In another experiment, Ridderingkhof (2002) found that trials preceded by an congruent trial showed more positive slope and larger overall congruency effect in delta plot compared with those preceded by an incongruent trial, which he reasoned is because in the former condition, the subjects became less alert to inhibit their activation.

Ridderinkhof (2002) further distinguished two levels of strategic task-set adjustment controlling inhibition. He demonstrated it in an experiment containing two conditions: a congruent-dominant condition in which 75% trials were congruent, and an incongruent-dominant condition in which 75% trials were incongruent. There was a macro-level adjustment, which appeared to be influenced by overall conflict probability, and specifically indicated by the smaller proportion of fast incorrect responses to incongruent trials and more negative slopes of RT delta plot when the majority trials were incongruent rather than congruent. There was also a micro-level adjustment, which was shown to be subject to post-error remedial modification, specifically evidenced by the smaller proportion of fast incorrect responses to incongruent trials and more negative RT delta plot slopes in post-error trials than in post-correct trials. Moreover, Ridderinkhof found interaction between these two conditions: the accuracy for fast responses increased from chance level in post-correct trials to around 75% in post-error trials, and post-correct trials had more positive RT delta plot slope than post-error trials, but only when most trials were congruent; when most trials were incongruent, there appeared to be little micro-level adjustment, which was presumably excluded by macro-level adjustment.

Pratte (2007) found delta plot curves in number priming similar to that in Simon task. In his experiment, subjects responded to whether a target number shown in the center of the computer screen was smaller or bigger than 5, which was preceded by a very briefly shown prime number (also shown in the center of the computer screen) that was on either the same or the opposite side with the target in terms of its relationship to 5, and hence congruent or incongruent trials. The congruency effect revealed in the delta plot also had a positive initial value but a constant negative slope. According to Pratte's analysis, the primes which could produce priming effect on targets must be visible to some extent, if this were true, then the weakly visible prime numbers might have also given rise to a facilitation-followed-by-inhibition process, due to a mechanism either similar or dissimilar to that of Simon task in nature, which remains unknown.

Because attention-deficit/hyperactivity disorder (AD/HD) has been suspected of being related to handicapped inhibition, Ridderingkhof, Scheres, Oosterlaan & Sergeant (2005) used Eriksen flanker task, another type of conflict task to test 20 children with AD/HD in comparison with matched control participants, and observed that the delta plot leveled off later for AD/HD children than for control children, which suggests slower response inhibition in AD/HD children.

A challenge to dual-process models

Despite its compatibility with a host of discoveries concerning Simon tasks, the facilitation-followed-by-inhibition theory cannot account for the delta plot patterns of all conflict tasks. In a series of experiments conducted in our lab, we observed a constant increasing congruency effect with RT in Stroop task (Pratt, Rouder, Morey, Wenzlick, & Feng, 2008), which seems to indicate absent or very weak inhibition. Moreover, the congrent/incongruent condition of preceding trials did not show any significant effect on the delta plot curves of subsequent trials in the Stroop task in our experiments as well. Positive slopes in delta plots were also found for strength tasks as diverse as identifying squares of different brightness (Ratcliff & Rouder, 1998), judging numbers bigger or smaller than 5 (Rouder et.al., 2005), and lexical decision tasks using high vs. low frequency words (Gomez, Ratcliff, & Perea, 2007). Actually, compared with the negative slope of Simon task, these positive slopes are relatively easy to explain: they imply that 1) RT distributions conform to stochastic dominance, i.e., the faster distribution is constantly faster than the slower distribution at any corresponding point; 2) the mean and standard deviation of RT increases together along the time course. Wagenmakers & Brown (2007) even showed that for a variety of strength manipulation experiments the ratio of standard deviation to mean keeps unchanged, and they proposed this relationship as a law. It seems none of the dual-process models introduced so far could be compatible with these findings.

Some alternative theories outside of the dual-process paradigm might have a better chance to provide an overarching mechanism for Simon, Stroop and perhaps other types of context effects. One relatively successful example is the dimensional overlap taxonomy (DO) developed by Kornblum and colleagues (Kornblum & Lee, 1995; Kornblum, Stevens, Whipple, & Requin, 1999). In this approach, eight categories of context tasks are demarcated based on factorial combination of possible mutual overlaps of relevant features, distractors, and responses, and one-to-one correspondence between task type and delta plot pattern was suggested. Because Stroop and Simon tasks belong to different types (type 3 and type 8), this taxonomy is a plausible explanation for the mechanism of their delta plot slope difference. Another inspiring theory was proposed by Wiegand and Wascher (2005), which emphasizes the unique nature of laterality among other sources of interference, and thus leaves a special niche for Simon task featured by the lateralized nature of both its distracting feature and its response. Both of these theories are compatible with different patterns of delta plots for Simon and Stroop tasks, but as will be shown in experiment 2 of this study, they both cannot deal with any unconventional delta plot pattern that appears in Simon task.

The current study is designed to test Ridderinkhof's dual-process theory about Simon task and is composed of two experiments. The first experiment intended to manipulate the suppression level by imposing different levels of working memory load during a classic Simon task, thus to test whether more positive delta plot curve will be found for the higher working memory load condition. In the second experiment, task difficulty was manipulated during a Simon task to see whether it could affect the delta plot slope.

Experiment 1

Motivation & Predictions

The current study hopes to test the aforementioned facilitation-followed-by-inhibition model. For this purpose, a dual task paradigm was adopted. According to Ridderinkhof's assumption the facilitation is automatic and unconscious while the inhibition relies on conscious executive control (Ridderinkhof, 2002; also see Botvinick, Barch, Carter, & Cohen, 2001; MacDonald, Cohen, Stenger, & Carter, 2004), A high working memory load which preoccupies cognitive control should therefore prevent inhibition. Participants in this experiment performed a classic Simon task while maintaining two levels of working memory load by nonstop rehearsing: a low load condition, in which the delta plot should be similar to ordinary Simon task; and a high load condition, in which the slope in the delta plot would be expected to be more positive, if Ridderinkhof's theory is correct.

Method

Participants. 47 undergraduate students of the University of Missouri in the age range of 18 to 22 participated this experiment and were rewarded credits for doing so. The first 6 participants' data were removed due to experimenter error (the instruction was not specific enough in terms of constant aloud rehearsal of number sequences), and one participants' data were removed due to her unusually low accuracy in the Simon task. Therefore data of 40 participants including 21 males and 19 females were included in the final analysis.

Design. The dual task was a 2X2X3 within-subject balanced factorial design with stimulus color, stimulus position and number sequence types serving as factors. There were three number sequence types: a 7 digit random sequence serving as high WM load condition, a 2 digit random sequence and participants' own 7 digit phone number (without area code). The latter two both serving as low WM load condition. The color of the stimuli in Simon task were either red or green, and their positions were either left or right of the screen center.

Apparatus & Stimuli. For both experiments in this paper, participants were tested in individual cubicles and the experiments were run on Pentium 4 PCs running MS-DOS. Stimulus display and response collection was controlled by a custom-written set of C routines. Monitors were 17-inch Dell CRTs with resolution of 800 pixels by 600 pixels refreshing with a frequency of 60 hz. The fixation point was a small white cross at the center of the display. The digits in number sequence display were white, approximately 2 degrees of arc each, with intervals of 2 degrees of arc for 2 digit and 7 digit random sequence and no interval for phone numbers, and the sequence center overlapped with the display center. The color squares in Simon task were red and green of comparable brightness, 100 X 100 square pixels subtending 2° of arc, and their centers were 150 pixels or 3° either left or right to the center of the display. Participants were seated about 40 cm away from the computer screens.

Procedure. At the beginning of each experiment, participants were required to type in the last 7 digits of their own phone number without area code. There were in total 252 trials for each participant, which were evenly distributed in 7 blocks each containing 36 trials. The 3 types of number sequence, 2 types of stimuli color and 2 types of stimuli position, were all randomized with equal possibility for each combination.

Each trial began with a 100 ms display of the fixation point, after which a

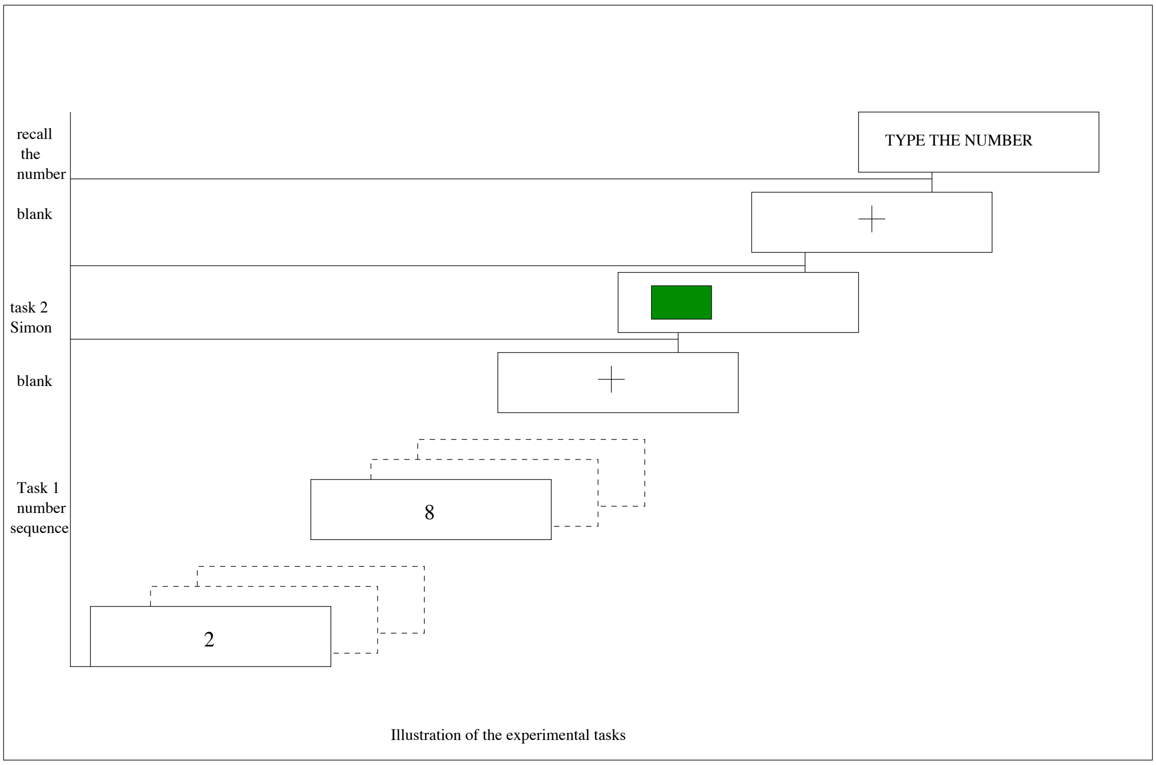

Figure 3. Flow chart of the Experimental 1 tasks

number sequence was displayed. Participants began rehearsing aloud the number sequence immediately. The number sequence type was random for each trial, but three number sequence types were displayed with equal chance, 84 trials in total of each type for each participant. The experimenter pressed the key on a box externally connected to the computer after the participant rehearsed the sequence twice, and then the sequence display was replaced by a blank screen but participants continued rehearsing, until a red or green color square appeared on one side of the display. The interval between the disappearance of the number sequence display and the onset of a color square was a random variable with geometric distribution of mean 1.2 seconds. Participants pressed the key labeled 'green' ('z') if the square was green and the key labeled 'red' ('/') if the square was red. After the response was made, a sentence "Type the number sequence" and a line of underscore lines were presented, on which participants typed in the number sequence they rehearsed, and they could use a backslash key to change their answers.

Results

For data analysis, trials in which responses were too fast (RT shorter than 200 ms) or too slow (RT longer than 2000 ms) were removed, so were trials in the first blocks of each participant that showed apparent practice effect, i.e., increasing accuracy and decreasing RT. RT truncation were so determined because deliberate responses are unlikely to be faster than 200 ms, and the truncation of RT between 200 ms and 2000 ms includes 98.64% of the total number of trials. Moreover, the following analysis were also conducted on the data of trials of RT between 200 ms and 3000 ms, and the results including the delta plot pattern do not show any significant difference.

Mean Simon task accuracy in each congruency and each number sequence condition was examined, which showed a 1.55% significant accuracy Simon effect in the 7 digit condition (96.55% vs. 98.10%, t=2.07, p=.045), a 1.34% significant accuracy Simon effect in the 2 digit condition (97.20% vs. 98.54%, t=2.07, p=.045),and a 2.08% significant accuracy Simon effect in the phone number condition (96.65% vs. 98.73%, t=2.72, p=.007). The accuracy for Simon task is quite high overall.

Mean number sequence recall accuracy in the 7 digit and 2 digit number sequence conditions was also examined. The mean accuracy of recall was 99.5% in the 2 digit condition and 77.5% in the 7 digit condition. Specifically, the mean 7 digit sequence recall accuracy in the Simon congruent trials and Simon incongruent trials was 77.07% and 77.92% respectively. The Simon task congruency did not affect the number sequence recall that happens immediately after it.

Response time is then analyzed as the main dependent variable. Only RTs in trials in which correct responses were made in the Simon task are used for the

RT analysis. First, Simon effect was examined in each number sequence condition. Second, a 2X3 ANOVA was conducted to test the main effect of congruency and number sequence type, as well as the interaction between them. A delta plot was then made to illustrate the temporal course of congruency effect in different number sequence types. Finally, linear ordinary least squares regression lines were fit to each line in the delta plot and the linear OLS slopes in different number sequence types were compared.

In terms of mean RT, a family-wise Tukey Test was conducted to compare the congruency in three conditions to control Type I error induced by multiple comparison. Only in the phone number condition a significant 18.0 ms Simon effect was found (659.9 ms vs. 677.9 ms, q(39)=1.80, $p = .045$). The Simon effect was 5.9 ms in the 7 digit condition (740.5 ms vs. 746.5 ms, q(39)=.60, $p = .56$) and 13.6 ms in the 2 digit condition (654.2 ms vs. 667.8 ms, q(39)=1.36, $p = .12$), both insignificant. The delta plots for each number sequence type in this experiment is shown in Figure 4, and the corresponding RT distribution plots in the three conditions are in Figure 5.

A 2X3 ANOVA (analysis of variance) was then applied to the averaged reaction time of each person under 2 congruency conditions and 3 number sequence types. Significant effects were found for number sequence type (F(1,39)=30.61, $p < .05$), but the effect of congruency condition (F(1,39)=3.67, $p = .063$) was only marginally significant and the interaction between number sequence type and congruency effect (F(1,39)=.72, $p = .49$) was not significant.

Unfortunately, curvatures resulted in the delta plots due to data noise, which made it difficult to judge whether the delta plot slopes vary with different working memory loads. Moreover, there are considerable problems with variance measurement: there is correlation across percentiles, however, later percentiles are highly variable and show massive violation of homogeneity of variance, as shown in Figure 6.

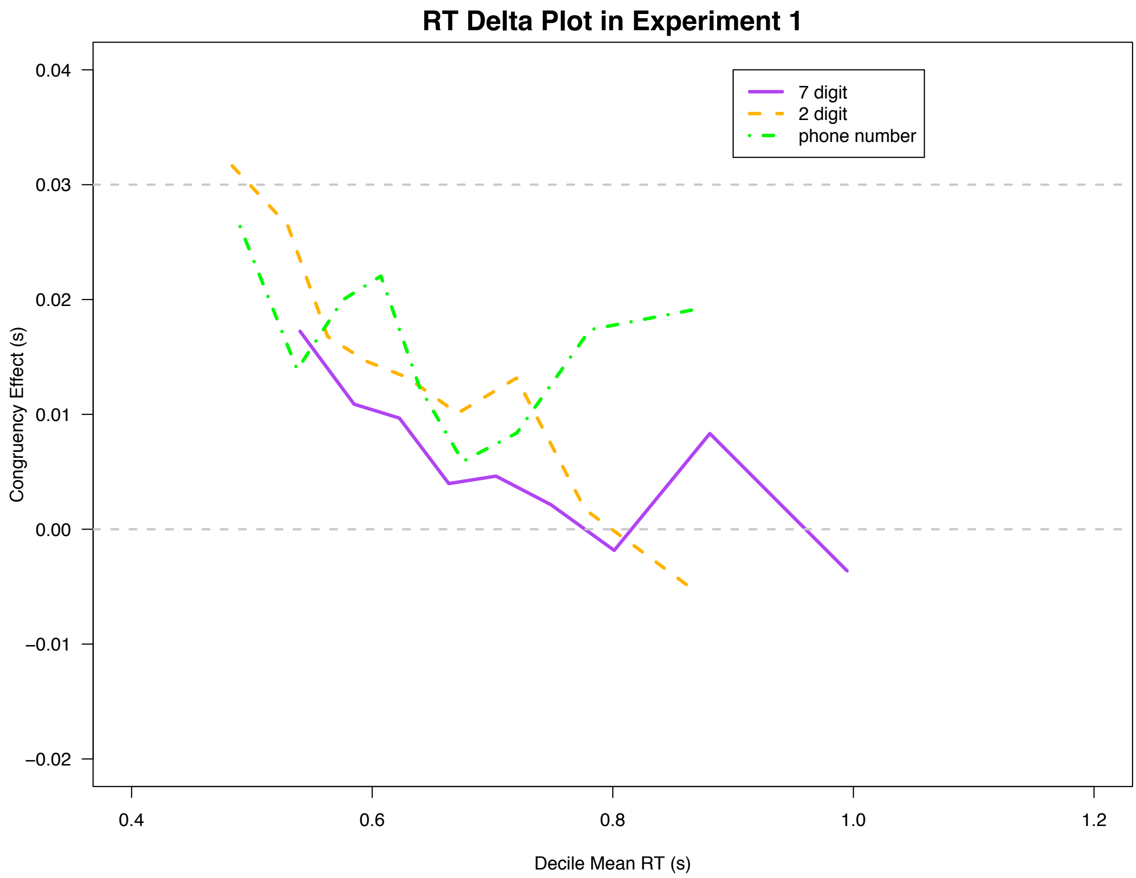

Figure 4. Delta plots of Experiment 1, the purple continuous line represents the 7 digit condition, the green dotted dash line represents the phone number condition, and the orange dash line represents the 2 digit condition.

To effectively detect whether a significant difference exists between congruency effect patterns under different working memory load conditions, ordinary least square regression was fit to individuals' delta plot in each number sequence type condition and linear regression slopes of these lines were calculated. OLS was found to give reasonable estimation of individual slopes even when it violates some underlying assumptions of delta plot, and this method has more power than other alternatives (Pratte et.al., 2008). Since the data of the phone number condition is too chaotic to be usable, and 7 digit and 2 digit conditions are enough to make comparison between high and low working memory loads, linear slopes in only these two conditions were compared. Decile RT points from 10 percent to 90 percent of each individual

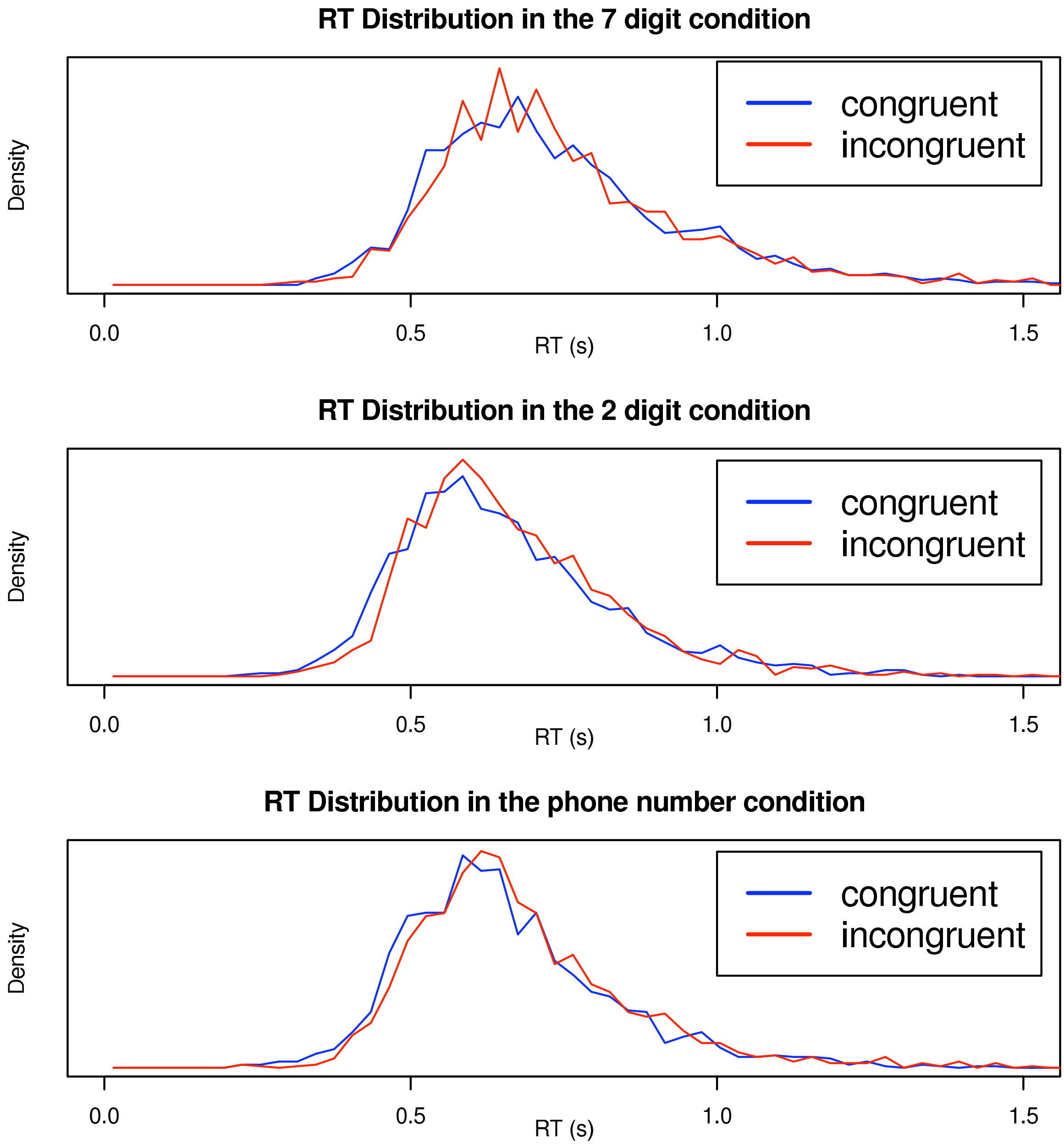

Figure 5. The distribution of RT in the three conditions in Experiment 1. The blue lines are the congruent conditions, and the red lines are the incongruent conditions.

were fit to a linear slope using this method in each of these two conditions, and a within-subject t test was conducted comparing the slopes in these two conditions.

The results show that, the slopes in the 7 digit condition was found insignificantly negative (M=-.075, t(39)=1.44, p=.16) while the slopes in the 2 digit condition was significantly negative (M=-.102, t(39)=2.10, p=.04). The slopes in these two conditions are shown in Figure 7. Simon effects found in our lab in the past were in the range between .10 and .19 (Pratte, 2008), so the slopes here are of reasonable values. However, no significant difference was found between the slopes of these two conditions (t(39)=-.46, p=.65). Thus, in this experiment no congruency time course difference was found between the high WM load condition and the low WM load condition. OLS linear individual slopes were also calculated for RT between only the 10 percentiles and the 50 percentiles, which have relatively small variance, and comparison of these slopes in 7 digit and 2 digit condition reconfirms the above conclusion, no difference was found.

Another measurement of the difference of slopes of RTs under two conditions as proposed by Zhang & Kornblum (1997) is the ratio of their standard deviation: if that value significantly deviates from 1, significant difference is implied. Thus, to double-check the result, a paired T test was conducted to compare each individual's such ratios in 2 digit versus 7 digit conditions, and the result again showed insignificant difference (t(39)=.54, p=.56).

In addition, the correlation coefficient between individuals' number recall accuracy and delta plot slopes were also examined in both 7 digit and 2 digit conditions, to address whether participants with better number sequence memory have different delta plot slopes than those with worse number sequence memory. The result showed this is not true: the correlation coefficient was -.194 ($p < .5$) in the 7 digit condition and -.125 ($p < .5$) in the 2 digit condition, both insignificant, as shown in Figure 8.

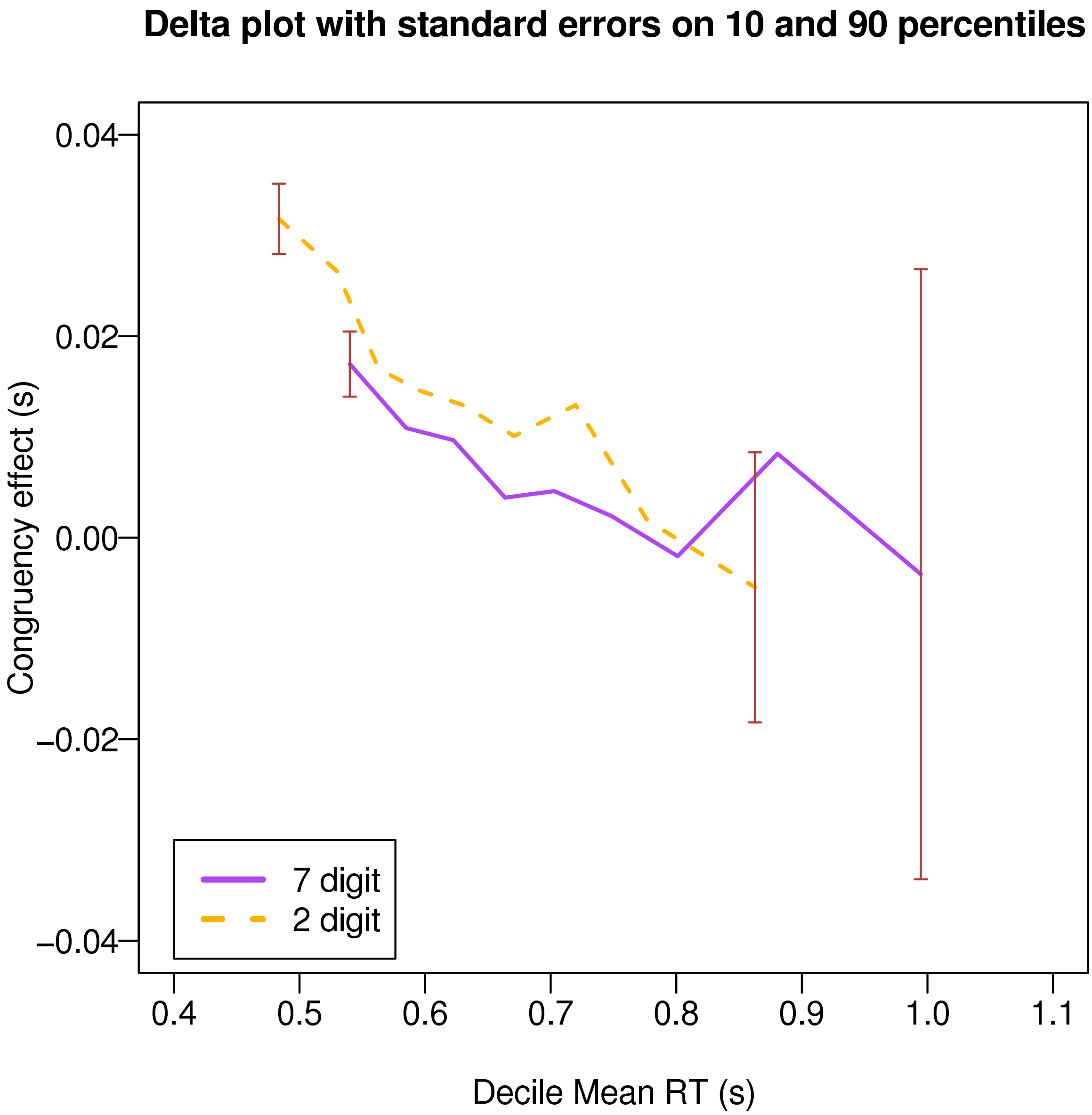

Figure 6. The error bars illustrate the standard errors on the 10th and 90th percentiles of the 7 digit and 2 digit conditions. The variance increases dramatically in larger percentile.

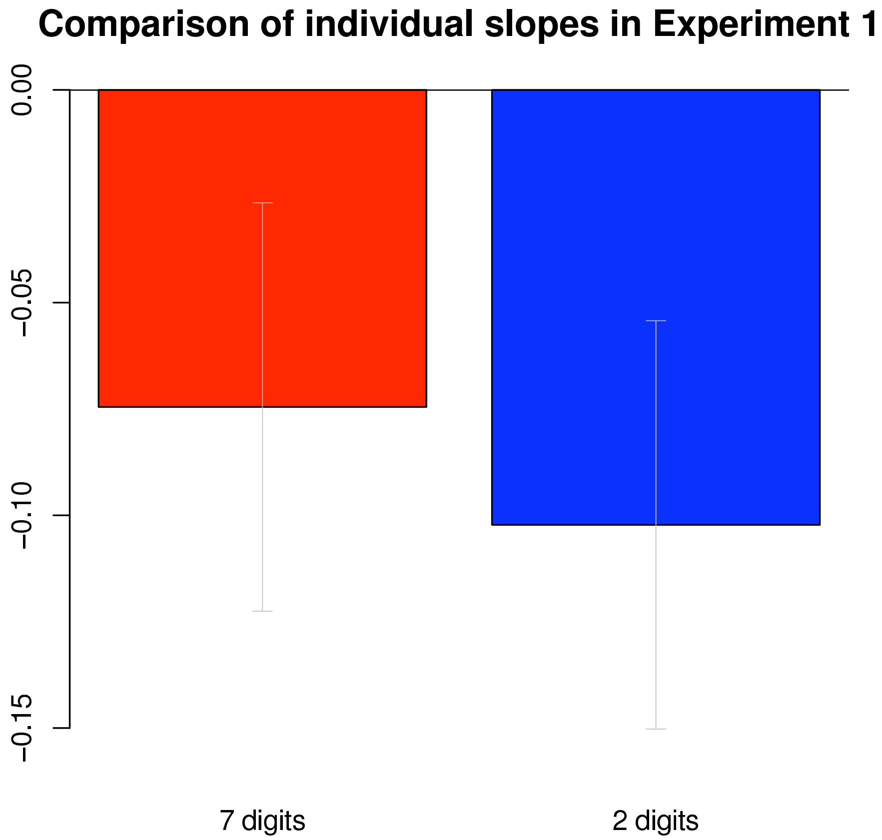

Figure 7. Comparison of mean individual QLS regression slopes in the 7 digits and 2 digits conditions in Experiment 1. The gray error bars shows the within-subject standard error of slopes in these two conditions.

Discussion

Because no significant difference was found between the slopes of the low and high working memory load conditions, this experiment does not support Ridderinkhof's theory. There are at least three possibilities why this is the case. First, inhibition may not necessarily result in decreasing congruency effect, e.g., the activation triggered by position might be in a different pathway than that by color. Second, inhibition, a not clearly-defined concept in psychology so far, might have multiple kinds, some of which may affect congruency effect while others do not. Processes different than inhibition might also decrease congruency effect. Finally, there is the chance that inhibition was not effectively manipulated by the working memory

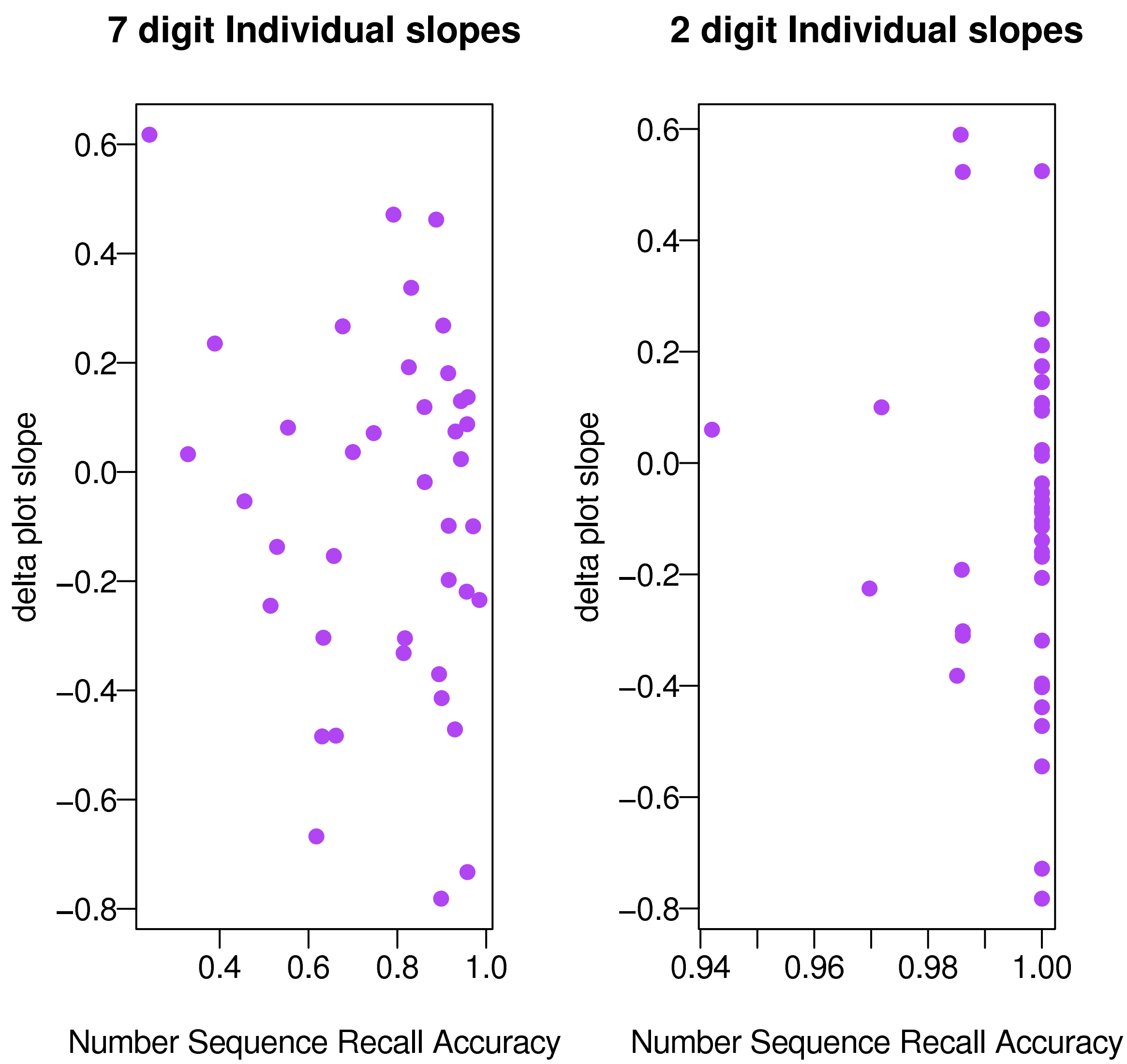

Figure 8. The relationship between individual number recall accuracy (x axes) and delta plot slopes (y axes)

load in this experiment. For example, the 7 digit load could be insufficient to exhaust cognitive control (although the 7 digit load was found already very demanding, given its recall accuracy only 77% and the experimenter observed many participants struggling to recall them), or inhibition might not be totally dependent on cognitive control.

Eimer(1999) proposed an explanation for the negative delta plot slope of Simon task which shares many similarity with Ridderinkhof's, but with a crucial difference. He tried to demonstrate that unconscious inhibition is possible (Eimer, 2003), and insisted that inhibition of the initial activation by the irrelevant feature can happen unconsciously and automatically without being triggered by the activation of the relevant feature. Although our experiment could not test this hypothesis, the existence of automatic, unconscious inhibition, which in logic could be independent of working memory capacity, is a possible explanation for the lack of difference found in the experiment that should be seriously considered in future studies.

Experiment 2

Motivation & Prediction

In Experiment 1, imposed working memory load did not affect the time course of the congruency effect, i.e., the delta plot slope of a Simon task. That could be either due to inhibition not being the cause of the decreasing congruency effect in Simon task, or to the working memory load not being sufficient to eliminate inhibition. Based on current research methods, it is almost impossible to thoroughly exclude either possibility, and it might be helpful to manipulate inhibition level during Simon task using another technique and observe how that affects the delta plot slope.

In Experiment 2 task difficulty was manipulated as a plausible way to affect suppression level, where task difficulty was defined as degrees of perceptual ambiguity of the stimuli affecting the efficiency to respond to them in an instructed manner. Intuitively, the more difficult task requires more inhibition, and thus if Ridderinkhof's theory is correct, there would be more suppression in the difficult condition manifested in a more negative delta plot slope than in the easy condition.

Method

Participants. 33 undergraduate students, including 20 males and 13 females, with age between 18 to 21 from the University of Missouri served as participants and acquired credits for it.

Design. Experiment 2 is a modified version of the classic Simon paradigm, in which stimuli were color squares of red/green mixture and participants were requested to respond to the dominant color of color squares. It was a 2X2X2 within-subject balanced factorial design with dominant stimulus color, stimulus position and the ratio of two colors of the stimulus as factors. Stimulus dominant color was either red or green, its position was either left or right to the screen center, and the ratio of the dominant color to the other color in the color square was 55:45 in the difficult condition and 90:10 in the easy condition.

Stimuli. The display was 800 X 600 square pixels. The fixation point was a small cross at the center of the display. The color squares were all 100 X 100 square pixels in area and were displayed with 150 pixels distance between their centers and the screen center. The square in each trial had either red or green as its dominant color occupying the most area, while the remaining space was complemented by the other color. Participants were seated about 40 cm away from the computer screens.

Procedure. Each trial began with a 100 ms display of fixation point, after which a color square was presented randomly at one side of the screen. The participants were required to press a left key ('z' on the keyboard) for squares with more red than green and a right key ('/' on the keyboard) to squares with more green than red.

There were, in total, 504 trials for each participant, which were evenly divided into 7 blocks each containing 72 trials. The dominant color of squares, their display position, and the congruency or incongruency of their matching were all randomized with equal possibility for each combination.

Results

As in Experiment 1, trials containing too slow (RT longer than 2000 ms) or too fast (RT shorter than 200 ms) responses were discarded. The beginning 40 trials in the first block of each participant were also discarded due to apparent practice effect. For RT analysis, only RTs in trials of correct Simon task responses were used.

Mean accuracy was first examined. In the easy condition, there was a significant

.4% accuracy Simon effect in the easy condition (95.60% vs. 96.02%, t(32)=0.68, $p < .05$), and a significant 6.7% accuracy Simon effect in the difficult condition (77.44% vs. 84.13%, t(32)=5.7, $p < .05$). Mean accuracy in the difficult condition was significantly lower than in the easy condition (95.81% vs. 80.79%, t(32)=12.64, $p < .05$).

Subsequently, reaction times were examined after trials with wrong responses were removed. In the difficult condition, the congruent trials have a mean RT of 845 ms (SE=26.8 ms) and the incongruent trials have a mean RT of 889 ms (SE=26.6 ms). In the easy condition, the congruent trials have a mean RT of 607 ms (SE=15.7 ms), and the incongruent trials have a mean RT of 618 ms (SE=14.1 ms). The Simon effects were significant for both conditions: in the difficult condition, M=44 ms, t(32)=5.52, $p < .5$; in the easy condition, M=11ms, t(32)=2.18, $p < .5$. The effect in the difficult condition was notably larger than in the easy condition.

A 2X2 ANOVA was applied to the individual mean RTs under each congruency condition and each difficulty level, which showed a significant effect of congruency (F(1,32)=33.48, $p < .5$), a significant effect of difficulty level (F(1,32)=196.37, $p < .5$), and a significant interaction between congruency and difficulty (F(1,32)=11.88, $p < .5$).

Interestingly, the delta plot shows decreasing congruency effect in the easy condition but increasing congruency effect in the difficult condition, as shown in Figure 9. As shown in Figure 11, The linear slopes of ordinary least squares regression in the easy condition are significantly negative (M=-.11, t(32)=-3.57, $p < .5$), and the linear slopes in the difficult condition are significantly positive (M=.08, t(32)=2.82, $p < .5$). The difference between the slopes in these two conditions is also significant (t(32)=-4.76, $p < .5$).

Finally, the possibility of speed-accuracy trade-off was examined in the following

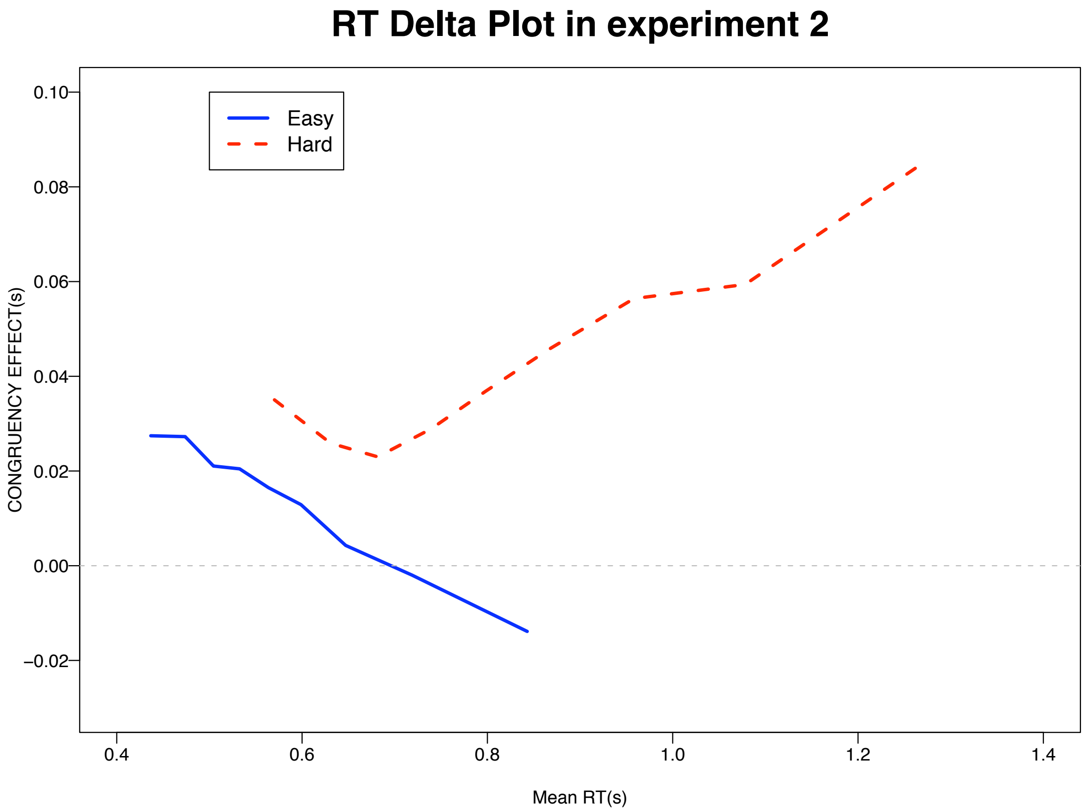

Figure 9. Delta plot in Experiment 2, the blue continuous line is the easy condition and the red dash line is the difficult condition

way. In each of the four congruency by difficulty level conditions, each individual's responses were divided into five quintile bins according to their reaction time length; then individual mean RT and mean accuracy were calculated for responses in each quintile bin, and for these mean RTs and mean accuracy were averaged across people to get an overall mean RT and an overall mean accuracy in each quintile bin. Eventually, five data points were plotted for each condition, with their x values representing the mean RT and their y values representing the mean accuracy, as shown in Figure 12. Speed-accuracy trade-off pattern was apparent in three out of the four conditions.

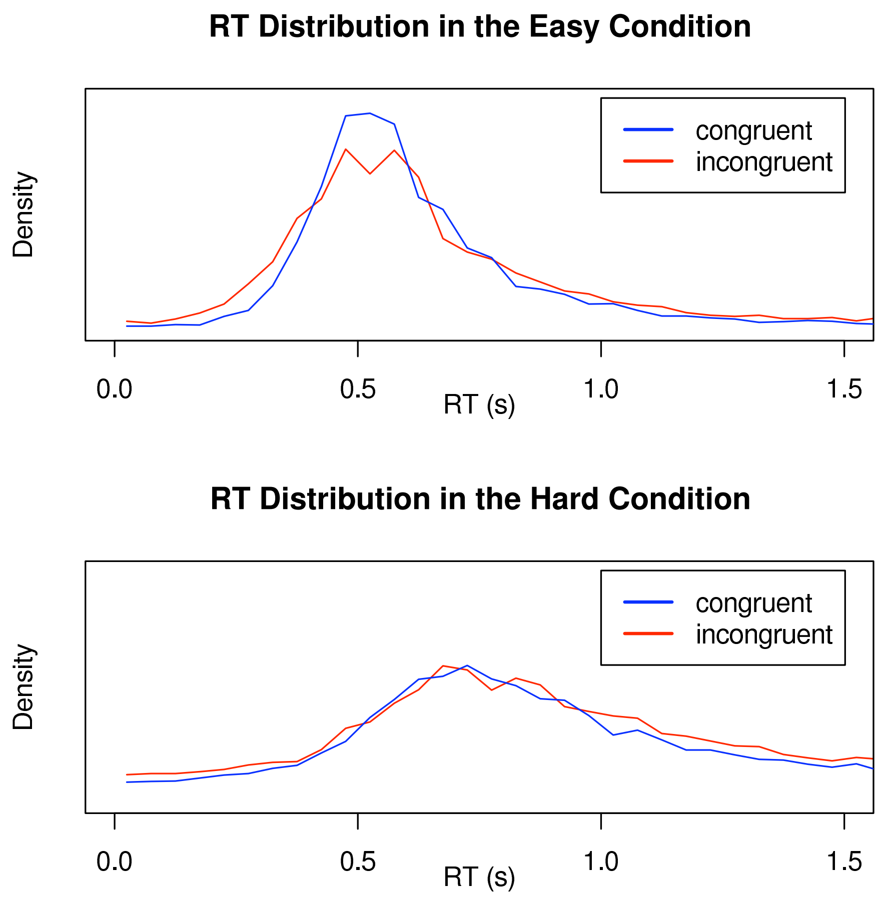

Figure 10. The distribution of RT in the two conditions in Experiment 2. The red lines are the incongruent conditions, and the blue lines are the congruent conditions.

Discussion

The Simon effect was significant in both mean accuracy and mean RT in both conditions, and was significantly larger in the difficult condition than the easy condition. Moreover, the mean accuracy was much lower and the mean reaction time was much longer in the difficult condition than in the easy condition.

A typical delta plot slope was found for the easy condition, but the discovery of a positive slope for the difficult condition is not consistent with Ridderinkhof's theory (2002). Intuitively, there should be less inhibition in the easy condition than in the difficult condition, and if the steepness of the slope of delta plot reflects inhibition level as proposed by Ridderinkhof, the slope in the delta plot should be steeper in

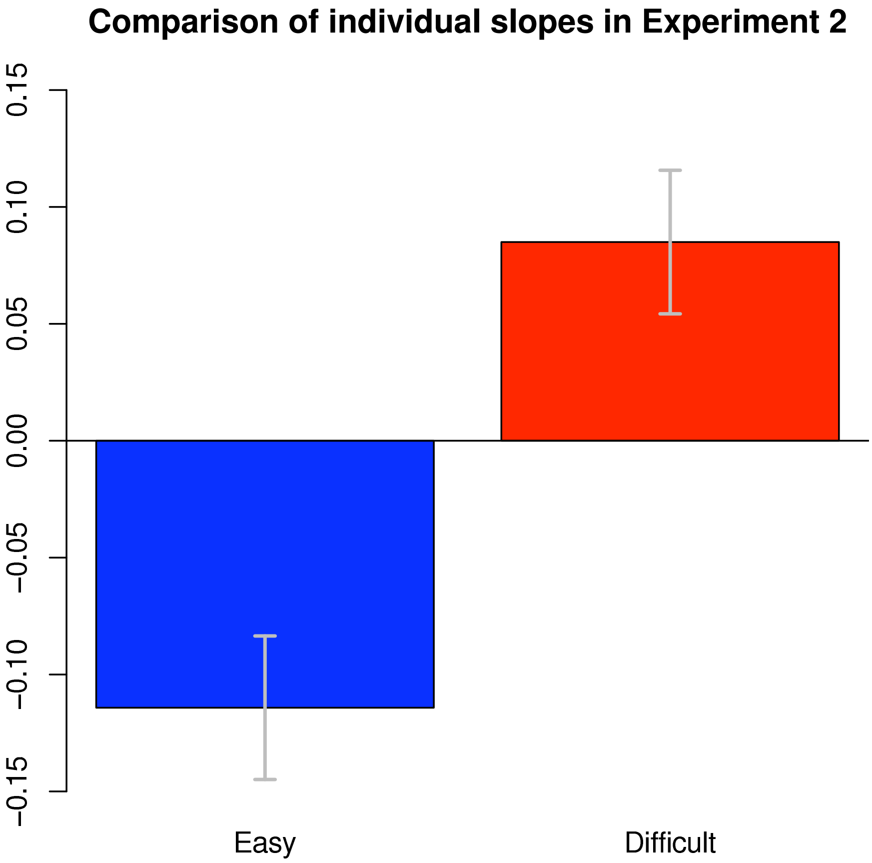

Figure 11. Comparison of the means of individual QLS regression slopes in easy and difficult conditions in Experiment 2. The gray error bars show the between-subject standard errors.

the difficult condition than in the easy condition. However, the slope observed in the difficult condition was not only less negative, but strikingly positive, which resulted in a much larger mean Simon task than usual. Unlike the delta plot curves of the 7 digit and 2 digit conditions in Experiment 1 which are basically on the same line with some shift indicating similar processes in these two conditions, the dramatic slope difference between the easy and hard conditions may indicate quite different processes between them. Actually, positive delta plot slopes were characteristic of strength effects and most context effects, and could be considered as the default situation according to Pratte.et.al.(2008); in contrast, negative delta plot was only found in a few tasks like Simon and number priming, which could be due to the common lateralized nature of

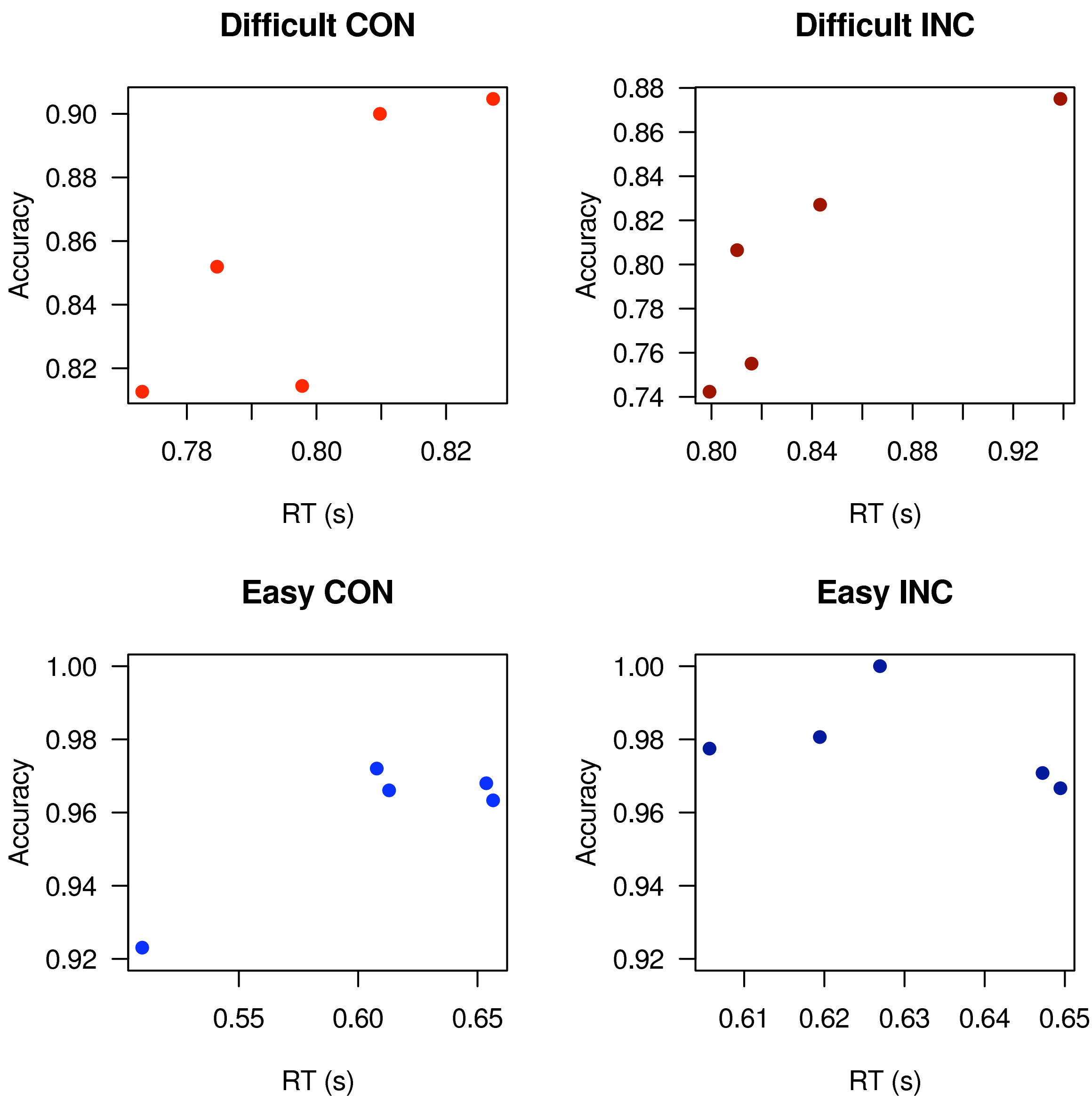

Figure 12. Accuracy as a function of RT in the four conditions in Experiment 2

both their irrelevant stimulus (feature) and response (Pratte.et.al, 2008). However, Ridderinkhof's theory rarely considers positive delta plot slope–in other words, slopes equal to 0 is considered by Ridderinkhof as the indication of zero inhibition.

This finding defies explanation by other Simon effect theories as well. Neither Kornblum's DO taxonomy (Kornblum & Lee, 1995; Kornblum, Stevens, Whipple, & Requin, 1999) claiming strict correspondence between type of distractor-stimulus-response overlap and delta plot pattern nor Wiegand and Wascher (2005)'s theory granting special status for lateralized processing could accommodate such an unconventional delta plot pattern in a Simon task. So far, no theory addressing congruency effect time course in Simon tasks known by the author could provide a satisfying interpretation for this phenomenon.

The positive slope in the difficult condition delta plot was also a counter-evidence to the perceptual load theory proposed by Lavie (1995). According to this theory, high perceptual load of the target should exhaust cognitive control and attenuate the interference from distractors. But the finding here suggests even larger interference by distracting information in the high perceptual load (difficult) condition.

There are still at least two possible accounts for the surprising positive slope found in the difficult condition. First, it was possible that participants could be more biased by the position in longer responses; i.e., when they were more hesitant to make a choice between two options, they could be more easily influenced by the irrelevant position information. However, this possibility has been disapproved by the finding of speed-accuracy trade-off, which shows that largely better accuracy was achieved for longer responses in both easy and difficult conditions.

A second possibility is that perceptual difficulty induces a long interval between the encoding of the irrelevant position information and of the target color information.

Therefore, when eventually the color information is deciphered, the initial facilitation by the position has already been accomplished, and thus does not interfere with the process triggered by the target feature towards response; in contrast, in the easy condition just like in typical Simon task, the encoding of the irrelevant position feature was temporally too close to the encoding of the target feature, and interferes with its activation when the correct response corresponding to the target feature and the stimulus position were on the same side, which makes the relatively slightly longer responses in the congruent condition slower than their counterparts in the incongruent condition.

What further complicates the situation is that a subsequent attempt in our lab to replicate the positive slope in Experiment 2 failed. This experiment contained three conditions, besides the same easy and hard conditions as in Experiment 2, there was also a middle condition with color ratio of 59:61, which should not affect delta plot slopes in the other two conditions. However, the hard condition in this experiment had significantly negative rather than positive slope. Thus, it seems risky to make interpretation based merely on the results of Experiment 2.

In sum, how perceptual difficulty manipulated in this experiment affected delta plot slope is still a mystery. This finding cannot be explained with any account of Simon effect mentioned above, and is also inconsistent with perceptual load theory. Some difficult questions await clarification before a reasonable explanation can be provided for the finding here. One question is how to exactly define difficulty, and what difficulty means specifically in the current manipulation. Another question is what exact relationship exists between perceptual load and executive control, whether the former occupies the capacity of the latter. Although the relationship between perceptual difficulty and the need to inhibit is only assumptive, it is still worth further discussion whether and how inhibition was affected in the difficult condition in this experiment, and the most crucial question is how a model of Simon effect could accommodate such delta plot pattern in such condition.

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General Conclusion

In Experiment 1, the manipulation of inhibition levels by imposing working memory load during a Simon task did not result in any impact on the delta plot slopes. This is inconsistent with Ridderinkhof's theory which predicts less negative delta plot slope when inhibition is extenuated. In Experiment 2, a variation of Simon task in which target color purity was manipulated, dramatically positive delta plot slope was found in the perceptually difficult condition. This finding cannot be accommodated by Ridderinkhof's theory, which does not explain positive delta plot slopes at all. In several follow-up experiments which are not included in this paper, flat delta plot slopes were repetitively observed in different tasks involving perceptual decision making of the target of different difficulty level, and that is unlikely to be just the result of less inhibition. In a nutshell, on one hand manipulation of inhibition may not necessarily affect delta plot slopes, and on the other hand flat or even positive delta plot slopes are not likely to be exclusively the consequence of lack of inhibition. Ridderinkhof's theory which addresses delta plot slope as a function of inhibition level is not supported at all in the findings summarized above.

The dominant majority of theories accounting for the Simon effect or context effects active today take a dual process view, assigning the fast facilitation and gradual overcompensation observed in the congruency effect pattern to two separate processes. De Jong et.al.'s introduction of delta plot as a insightful way to represent and scrutinize the time course of congruency effect was instrumental for the wide acceptance of this dual process view. In conflict tasks like Simon, given the realistic participant size in the dozens and trial number per person in the hundreds in the current experiment routine, the variation of reaction time distribution within each congruency condition is usually much larger than the mean effect between conditions, and this huge variation is filled with noise induced by task irrelevant factors. By ignoring the absolute values of RT, delta plot highlights the difference between RT on corresponding percentiles in the two conditions, and indirectly reveals the comparison between the standard deviations of RT distributions in these conditions. More importantly, as demonstrated by Speckman and his colleagues (Speckman, Rouder, Morey & Pratte, 2008), delta plot is especially helpful in comparing two distributions like in conflict tasks, in that homogeneously positive or negative curves indicates one distribution coherently dominates the other in means (e.g., the difficult condition in Experiment 2), whereas monotonous slopes indicate one distribution coherently dominates the other in variance. Thus, delta plot can help extrapolate difference of processes involved in the two distributions. These merits render delta plot valuable for providing evidence for the dual process view, as well as answering some of the basic questions about what these two processes are.

Given the maximum congruency effect value observed at the fastest responses in typical Simon tasks, most researchers today agree that the first process is automatically triggered at the onset of the stimulus or the prime. However, they proposed a variety of distinct hypotheses concerning the nature and feature of the second process, and arguments abound over whether this process is deliberate or automatic (see Eimer, 1999; Ridderinkhof, 1997; Zhang & Kornblum, 1997), when it initiates (e.g., the encoding of the target feature, or the moment of applying a spatial stimulus code, etc; see Ridderinkhof, 1997; De Jong, Liang & Lauber, 1994), and what determines it (e.g., the target feature alone, or the dimensional overlap among the irrelevant feature and the response, like the DO model proposed by Zhang & Kornblum, 1997). Moreover, some researchers believe the time course of this process is confounded in the RT data by the automatic decay or peripheral motor inhibition of the fast facilitation

(Eimer, 1999).

The understanding of the second process is probably limited by the paucity of information that could be extracted with the current data analysis and representation techniques. Delta plot has its limits. On one side, RT delta plot curves could hardly be made for individuals, because it does not show relatively stable and reliable pattern without large amount of data, and with currently available experiment paradigm each participants can only provide data on barely 100 trials in each condition. Therefore delta plots are always the result of averaging across participants' data. However, there is probably wide individual difference for many tasks, and the delta plots, always made with data averaging across participants, not only mask such difference, but also may lead in distortion of the general situation due to such averaging. On the other hand, the clarity and conciseness of delta plot is at the cost of losing a lot of information of the overall RT distribution during the transformation. Specifically, as already demonstrated by the results of the above experiments, delta plot slope is probably decided by multiple factors which vary from task to task, and is therefore unlikely to have one-to-one correspondence with the inhibition level. It may even misleadingly highlight effects of unknown factors hardly distinguishable from that of the factor of focus: many similar tasks give strikingly different delta plot slopes, with little consistency or predictability.

Therefore, to answer the question of what role inhibition contributes to the Simon effect, and what results the negative slope in typical Simon task delta plot, seminal perspectives to represent the RT data is probably required, and factors other than inhibition might be found crucial in the time course of the congruency effect of Simon task. Just like the dual-process view of the Simon effect was established with the introduction of delta plot method in the mid 1990s, future progress will probably come from novel angles of observing the data.

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