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Redundancy Gain in the Simon Task: Does Increasing Relevant Activation Reduce the Effect of Irrelevant Activation?

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In the present study, we tested the idea that relevant and irrelevant location-based activations are combined when selecting a response in the Simon task. For this purpose, we manipulated the strength of the relevant activation by using single versus redundant relevant stimuli to indicate the correct response. Assuming that relevant and irrelevant activations are summed during the decision process, the Simon effect should be reduced in the presence of the stronger relevant activation produced by redundant stimuli. Contrary to this expectation, the results revealed that the Simon effect was larger overall with redundant stimuli than with single stimuli. Importantly, distributional analyses indicated that the Simon effect was not reduced for redundant stimuli even when controlling for the opportunity for irrelevant location activation to dissipate after stimulus onset. These results are thus inconsistent with accounts in which the summation of decision-level activations is the cause of the Simon effect. Instead, these results are consistent with the idea that redundancy and irrelevant location information influence activations at different levels. Considering the findings of previous studies, the most likely account is that redundancy affects decision-level activations whereas relevant and irrelevant activation are integrated at the motor level to produce the Simon effect (i.e., decision locus of redundancy gain and motor locus of Simon effect).

Public Significance Statement
People are often required to select responses in the presence of multiple sources of information, both relevant and irrelevant. In the present study, we examined how activations from these different sources are combined. The results suggest that activations from multiple sources of relevant information are combined during decision making, whereas activation from irrelevant location information influences the subsequent process of executing the motor response.

Keywords: Simon effect, redundancy gain, race model inequality, delta plots

A major goal of cognitive psychology is to understand the underlying processing mechanisms involved in translating stimulus information into motor responses. One promising way of pursuing this goal is to study human performance in so-called *conflict* tasks (e.g., Simon, Stroop, and flanker tasks), where participants are presented not only with task-relevant information but also with potentially conflicting task-irrelevant information. For example, in the most common or *standard* visual version of a task first introduced with auditory stimuli by Simon (1967) and elaborated by Simon and Rudell (1967) and Simon (1968), a stimulus is presented on the left or right side of a fixation cross (e.g., Hommel, 1994; Miller & Roüast, 2016; Proctor, Miles, & Baroni, 2011; Seibold, Chen, & Proctor, 2016). Participants are instructed to make a left or right key press on the basis of a task-relevant (and nonspatial) feature of this stimulus (e.g., its color or letter name; Craft & Simon, 1970) and to ignore the task-irrelevant stimulus location. However, reaction times (RTs) tend to be faster when stimulus location and response keys are on the same side (i.e., congruent trials) than when they are on opposite sides (i.e., incongruent trials). This so-called *Simon effect* demonstrates that human performance is not immune to the impact of the task-irrelevant stimulus location and thus suggests that the processing of task-irrelevant information can influence the process of selecting the appropriate response based on the task-relevant information (for reviews see, e.g., Kornblum, Stevens, Whipple, & Requin, 1999; Lu & Proctor, 1995; Luce, 1986; Mewaldt, Connelly, & Simon, 1980; Zhang, Zhang, & Kornblum, 1999; Zorzi & Umiltà, 1995). Similar effects of task-irrelevant information on RT have now

been demonstrated in a variety of paradigms (e.g., Eriksen & Eriksen, 1974; Stroop, 1935).

Many theoretical accounts of the standard Simon effect and other conflict effects are based on the idea of two parallel processing pathways (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001; Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; De Jong, Liang, & Lauber, 1994; Eimer, Hommel, & Prinz, 1995; Kornblum, Hasbroucq, & Osman, 1990; Logan, 1980; Ridderinkhof, van der Molen, & Bashore, 1995; Zhang et al., 1999). In these models, task-relevant stimulus information is processed by controlled processes via one pathway and the irrelevant spatial location is processed automatically by another pathway. The outputs of the controlled and automatic processes converge during decision making so that response activation produced by the relevant stimulus information is combined with irrelevant location-based response activation (e.g., De Jong et al., 1994; Ridderinkhof, 2002a). The automatically produced location-based activation is helpful in congruent trials so that RTs are faster in these trials than in neutral trials (e.g., Hietanen & Pia, 1995; Treccani, Cona, Milanese, & Umiltà, 2017; Umiltà, Rubichi, & Nicoletti, 1999), but it is harmful in incongruent trials, which therefore have slower responses. Several elaborated models of conflict effects in the Simon paradigm and other conflict tasks have incorporated this type of activation summation within detailed mathematical frameworks (e.g., Cohen, Servan-Schreiber, & McClelland, 1992; Hübner, Steinhauser, & Lehle, 2010; Servant, White, Montagnini, & Burle, 2016; Ulrich, Schröter, Leuthold, & Birngruber, 2015). For example, a recent activation summation model, the Diffusion Model for Conflict Tasks (DMC model; Ulrich et al., 2015), assumes that the total RT in a trial is determined by the duration of a single decision process in which task-irrelevant and task-relevant activations are combined plus "the residual duration of all processes outside the decision process (e.g., stimulus encoding and response execution)" (Ulrich et al., 2015, p. 153).

Interestingly, the size of the Simon effect is modulated by many different factors, of which two are particularly relevant to the goals of the present study. Specifically, the size of the Simon effect decreases with increases in the proportion of incongruent (as opposed to congruent) trials within a block (e.g., Hommel, 1994), and it also decreases following incongruent trials, as compared with following congruent trials (e.g., Hazeltine, Akçay, & Mordkoff, 2011; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002). To account for these findings, it has been suggested that automatic activation is more strongly suppressed when it is more harmful in general or when it was more recently harmful (e.g., Cona, Treccani, & Umiltà, 2016; Stürmer et al., 2002; Treccani et al., 2017; Wühr & Ansorge, 2005). A related possibility is that attentional resources may be better focused on the task-relevant feature when irrelevant task features are experienced as harmful (e.g., Fischer, Dreisbach, & Goschke, 2008; Kreutzfeldt, Stephan, Willmes, & Koch, 2016; Notebaert & Verguts, 2008). Importantly, these explanations suggest that the Simon effect is reduced in these two cases because of an increase in the ratio of the signal strength (i.e., relevant activation) to the noise strength (i.e., irrelevant activation) when selecting a response.

The goal of the present study was to investigate such signal-to-noise ratio explanations of the effects of congruence proportion and sequential congruence. Specifically, the present study was designed to examine directly how the strength of the relevant stimulus information influences the Simon effect. For this purpose, we used a task in which there were two relevant stimulus dimensions and contrasted single-stimulus conditions in which the correct response was indicated by just one of the relevant dimensions against redundant-stimulus conditions in which it was indicated by both dimensions. Many previous studies have shown that responses are faster when two redundant stimuli are presented simultaneously than when only a single stimulus is presented (e.g., Miller, 1982; Raab, 1962), which suggests that presenting redundant relevant stimuli tends to increase the strength of the relevant information. For example, responses are faster when both a letter and a color indicate the correct response than when only one of these stimulus features does (e.g., Mordkoff & Yantis, 1993). Furthermore, analyses of RT distributions using the race model inequality (Miller, 1982) show that this so-called *redundancy gain* is often too large to result from purely statistical facilitation (i.e., too large to result from race models like that considered by Raab, 1962). Instead, many detailed distribution-level analyses of observed redundancy gains (e.g., Hughes, Reuter-Lorenz, Nozawa, & Fendrich, 1994; Miller, 1982; Mordkoff & Yantis, 1993; Schwarz, 1994, 2006) indicate that the fastest responses to redundant trials are too fast to have been produced by the faster of two processes responding to the two single target dimensions (i.e., "winner of the race"), implying that the results are more consistent with coactivation models in which the activations produced by redundant stimuli are combined together to produce the response (e.g., Fific, Nosofsky, & Townsend, 2008; Miller & Ulrich, 2003; Schwarz, 1989; see Miller, 2016 for a recent discussion of race and coactivation models). Thus, the use of redundant stimuli appears to be an ideal method of increasing the relevant activation. According to the view that any increase in the relevant activation reduces the Simon effect, then, this effect should be smaller when the correct response is signaled by redundant relevant stimuli than when it is signaled by a single relevant stimulus.

Unfortunately, a potential artifact complicates any comparison of the Simon effect in trials with single versus redundant relevant stimuli: Under many circumstances, the Simon effect tends to be larger for faster responses than for slower ones (e.g., Burle, Van den Wildenberg, & Ridderinkhof, 2005; Ellinghaus, Karlbauer, Bausenhart, & Ulrich, 2017; Hommel, 1994, 1995b; Miller & Roüast, 2016; Ridderinkhof, 2002a; Xiong & Proctor, 2016). Specifically, this pattern is evident in *delta plots* constructed from the distributions of RTs in congruent versus incongruent trials (e.g., Burle, Spieser, Servant, & Hasbroucq, 2014; De Jong et al., 1994). Delta plots display the difference between congruent and incongruent mean RTs separately at bins ranging from the fastest to the slowest RTs (e.g., the first bin might include the fastest 10% of RTs in each condition; the second bin, the second fastest 10%, and so on). In many studies of the standard Simon task, the Simon effect is largest for the fastest RT bin and decreases as RT increases, a pattern referred to as a *decreasing delta plot* (for reviews see, e.g., Dittrich, Kellen, & Stahl, 2014; Pratte, Rouder, Morey, & Feng, 2010; Proctor et al., 2011; Schwarz & Miller, 2012; Van den Wildenberg et al., 2010). The decreasing delta plot is often interpreted as a sign that the irrelevant location-based activation either passively decays (e.g., De Jong et al., 1994; Hommel, 1993, 1994) or is actively suppressed (e.g., Ridderinkhof, 2002a, 2002b) as time passes following stimulus onset. In

either case, the tendency for the Simon effect to decrease as RT increases presents a potential artifact with respect to the comparison of Simon effects for single versus redundant stimuli, because responses to the latter will tend to be faster.

As one way to address this potential artifact, we compared the delta plots observed for single and redundant stimuli in addition to comparing the mean Simon effects for these conditions. Because the single and redundant RT distributions overlap considerably, the delta plots for these two conditions can be compared at equal RTs, thus controlling for differences in absolute RT and in the time-based opportunities for the decay or suppression of irrelevant location information. Based on the idea that increasing the strength of the relevant activation should decrease the effect of the irrelevant activation during decision making, we expected that at equal RTs the Simon effect should be smaller for redundant than for single stimuli (i.e., at each value of RT, the delta plot for redundant stimuli should be below the delta plot for single stimuli).

As a further way to address this potential artifact and quantify its possible contamination of the results, we also examined in detail (see Appendix A) how increases in relevant activation affect the mean RTs and delta plots predicted by the DMC model (Ulrich et al., 2015). This is a plausible model specifying exactly how short-lived location-based activation could produce decreasing delta plots in the Simon task (for recent discussions see, e.g., Salzer, de Hollander, & Forstmann, 2017; White, Servant, & Logan, 2017). Consistent with the analyses of Ulrich et al. (2015), our simulation results support the idea that increasing the relevant activation would have two counteracting effects on the size of the Simon effect at the level of mean RTs: (a) Increasing the relevant activation strengthens its contribution to the overall activation relative to the contribution of the irrelevant activation, and that tends to decrease the Simon effect. (b) On the other hand, increasing the relevant activation produces faster responses, which tends to increase the mean Simon effect because absolute irrelevant activation is higher for faster responses. As is elaborated in Appendix A, the net result of these two counteracting influences is that this model predicts the mean Simon effect should stay almost constant when the relevant activation is increased. Importantly, however, distributional analysis (i.e., delta plots) of the simulated RTs revealed that the Simon effect was smaller with strong than weak relevant activations across the full range of the RT distributions—that is, when controlling for RT. Thus, these simulation results reinforce the idea that distributional analyses can elucidate the effect of relevant activation strength on the size of the Simon effect.

Experiment

The stimuli in the present study were created by using the two different stimulus features of letter and color, because previous studies have shown that these features produce strong violations of the race model inequality (e.g., Mordkoff & Yantis, 1993). Each stimulus display always contained a single white letter surrounded by a colored rectangle, and this combination was randomly presented at the left or right of the fixation cross as in the most common version of the Simon task (e.g., Proctor et al., 2011). Participants were instructed to respond with the left or right index finger depending on the letter or color in the stimulus display, ignoring location. Two target letters were randomly assigned to the

left and right response hands, and one nontarget letter was uninformative as to the correct response, and similarly for three colors. In each trial, then, the correct response could be signaled by the letter alone (i.e., target letter plus nontarget color), by the color alone (i.e., target color plus nontarget letter), or redundantly by both features. Because the same features were presented (i.e., always a letter and a color) in both single and redundant trials, the magnitude and timing of location-based activation produced by the onset of stimuli should not differ between these conditions. Furthermore, both single and redundant stimuli were randomly intermixed within each trial block to ensure that no differences in strategic preparatory processes could differentially impact irrelevant location-based processing in these two conditions. Thus, these conditions allow examination of the separate effects of redundancy and Simon congruency, as well as their interaction, for both mean RTs and RT distributions. Critically, based on the previously discussed activation-based accounts of Simon-task phenomena, we expected that at least when the absolute size of irrelevant activation is similar for the two conditions—which should be the case at equal points in the RT distributions—the irrelevant activation would be a lower proportion of the total activation for redundant compared to single stimuli, and this should decrease the Simon effect for the redundant stimuli.

Method

Participants. Sixty students (52 female) in psychology at the University of Otago, New Zealand, participated in partial fulfillment of course requirements in the experiment. They ranged in age from 17 to 31 years ($M = 19.8$ years) and 48 were right-handed. Mean handedness score was $M = 53.6$ as measured by the Edinburgh Handedness Inventory (Oldfield, 1971). All participants had normal or corrected-to-normal vision and gave informed consent before testing. The experiment was approved by the University of Otago ethics committee and was performed in accordance with the ethical standards described in the 1964 Declaration of Helsinki. Each participant was tested in a single experimental session lasting approximately 45 min. Two additional participants were tested but not included in the data analyses due to accuracy below 85%.

Apparatus and stimuli. The experiment was conducted in a dimly illuminated room. Stimulus presentation and recording of responses were controlled by an IBM-PC compatible computer using MATLAB with the Psychophysics Toolbox extensions (Brainard, 1997; Kleiner et al., 2007). All visual stimuli were presented on a black computer monitor, which was viewed from a distance of approximately 60 cm. A centrally positioned white plus sign (+) served as fixation point. Each stimulus consisted of a white letter (RGB[255,255,255], 195 lux) surrounded by a colored square (red: RGB[255,0,0], 57 lux; green: RGB[0,255,0], 157 lux; blue: RGB[0,0,255], 157 lux). Outline squares were constructed from lines that were approximately 1.41° in length and 0.13° in thickness. Letters were presented at the geometric center of the square in a 20-point font that subtended approximately 0.5°. The stimuli appeared to the left or right of the fixation point with a viewing angle of approximately 3.45° for the distance between the center of the screen and the center of the square. In redundant-stimulus trials, both stimulus features (color and letter) indicated the same response. In single-stimulus trials, one stimulus feature indicated the correct response, whereas the other feature was uninformative. In order to eliminate interstimulus contin-

gencies (Mordkoff & Yantis, 1991), we also included catch-trial stimuli for which both features were uninformative. Consequently, responses were required on 85.71% of the trials. Responses were key presses with the left and right index fingers on the Z and /? keys of a standard computer keyboard.

Procedure. For each participant three consonants were randomly selected for use as stimulus letters, with one each assigned to the left and right hand, whereas for one letter no response was specified (uninformative). The stimulus colors red, green, and blue were also assigned randomly to these response conditions. Each participant was tested in eight blocks of 112 randomly ordered trials per block (896 trials in total). Each block consisted of eight presentations of each of the 14 possible stimulus displays based on the seven stimulus types (2 single-letter plus uninformative color, 2 single-color plus uninformative letter, 2 redundant, and 1 uninformative letter plus uninformative color catch trial stimulus) and the two possible stimulus location (left, right). Participants were instructed to respond as quickly and accurately as possible if at least one stimulus feature indicated a response and to withhold the response if neither the color nor the letter indicated a response (catch trial). Furthermore, they were also instructed to keep their eyes focused on the fixation cross. At the beginning of each trial, the fixation cross appeared on the screen and after 500 ms a stimulus was presented to the left or right side of the fixation cross, which remained on the screen. The stimulus remained on the screen until the participant responded, up to a maximum of 2 s (i.e., the stimulus was presented for 2 s in catch trials). After each response, feedback was displayed for 1 s to indicate that the response was correct or for 3 s to indicate that the response was an error. RT was measured from stimulus onset until a key press response was made.

Results

Preliminary analyses indicated markedly slower responses for the first two blocks (825 ms and 706 ms vs. 622–667 ms for the remaining six blocks), so we excluded these blocks from the data analysis as practice.[1] Excluding the catch trials, on which there were 4.1% false alarms, we computed the mean correct RT and the percentage of erroneous responses (PE) for the remaining trials for each participant and each condition. For RT analyses, we first excluded error trials (4.1%) and we then discarded trials with RTs less than 200 ms as anticipations (<0.001%). When comparing the Simon effect across single-stimulus and redundant displays, we combined the two single-stimulus dimensions (letter, color). Preliminary analyses indicated that letter responses were 40 ms slower but 1.2% less-error-prone than color responses ($p < .001$ and $p = .021$, respectively; see Appendix B for more detailed analyses of responses to the separate stimulus dimensions).

Main analyses. Figure 1A shows the mean RTs for the single and redundant stimulus conditions plotted separately for congruent and incongruent trials. A repeated-measures ANOVA with the within-subject factors of stimulus condition (single, redundant) and congruency (congruent, incongruent) was conducted for the RT data. This ANOVA revealed a significant main effect of redundancy, $F(1, 59) = 522.76$, $p < .001$, $\eta_p^2 = .90$. As can be seen from Figure 1A, the mean RT was shorter for redundant stimuli (572 ms) than for single stimuli (677 ms). Furthermore, the main effect of congruency was also significant, $F(1, 59) = 7.38$, $p =$

.009, $\eta_p^2 = .11$. On average, RTs were shorter in congruent than in incongruent trials (620 ms vs. 629 ms), resulting in an overall Simon effect of 9 ms. There was also a significant interaction reflecting a larger Simon effect for redundant stimuli (15 ms) than for single stimuli (3 ms), $F(1, 59) = 10.64$, $p = .002$, $\eta_p^2 = .15$. A parallel ANOVA on the PEs also revealed significant main effects of redundancy, $F(1, 59) = 80.28$, $p < .001$, $\eta_p^2 = .58$, and congruency, $F(1, 59) = 7.14$, $p = .010$, $\eta_p^2 = .11$. Responses were less error-prone for redundant than for single-stimulus trials (2.2% vs. 5.0%) and also less erroneous for congruent than for incongruent trials (3.2% vs. 4.1%). The interaction between these factors was not significant ($p = .083$) and the descriptive pattern was consistent with the one found for RTs—that is, there was a larger Simon effect for redundant stimuli (2.8% − 1.6% = 1.2%) than for single stimuli (5.3% − 4.8% = 0.5%, with a standard error of 0.4% based on pooled error terms of the two main effects and the interaction).

In order to test whether race models could be entirely responsible for the observed redundancy gain, we used the method described by Ulrich, Miller, and Schröter (2007). Vincentized RT distributions (20 percentiles) for the single- and redundant-stimulus conditions were tested for consistency with the race model inequality (RMI; Miller, 1982). More precisely, we compared the empirical cumulative density function of the redundant condition with a predicted upper bound cumulative density function based on the two single conditions (i.e., "race-winner distribution"). If the cumulative distribution observed in the redundant condition exceeds the upper bound distribution predicted by race models at any time point, then the observed redundancy gain cannot be explained entirely by statistical facilitation. Following the recommendations of Kiesel, Miller, and Ulrich (2007), the observed and predicted upper-bound distributions were compared using paired *t* tests within the range of percentiles from 10–25% in order to hold the overall Type I error rate close to 5%. Separate comparisons were carried out for congruent and incongruent trials, and significant violations of the inequality ($p < .05$) were found for both conditions. For congruent trials, the RMI violations were significant at the 12.5th ($p = .030$), 17.5th ($p = .020$), and 22.5th ($p = .031$) percentiles, and for incongruent trials they were significant at the 12.5th ($p = .004$) and 17.5th ($p = .005$) percentiles (see Figure 1B for differences between empirical cumulative density functions and the boundary provided by the race model inequality). Thus, the present results replicated previous findings of race model inequality violations with these stimulus features (e.g., Mordkoff & Yantis, 1993; Ulrich et al., 2007), and they also extend these findings to a task with uncertain stimulus location.

In a next step, we constructed delta plots to examine the time course of the Simon effect separately for single and redundant trials. Specifically, we rank-ordered each participant's RTs within each of four conditions (i.e., single/redundant × congruent/incongruent), and then partitioned the RTs of each condition into 10 bins. We then conducted a three-factor ANOVA with factors of congruency (congruent, incongruent), stimulus condition (single, redundant), and bin (1–10). As expected, this analysis revealed significant main effects of redundancy, $F(1, 59) = 517.77$, $p <$

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[1] Qualitatively very similar results were also obtained in analyses including all blocks or excluding only the first block.
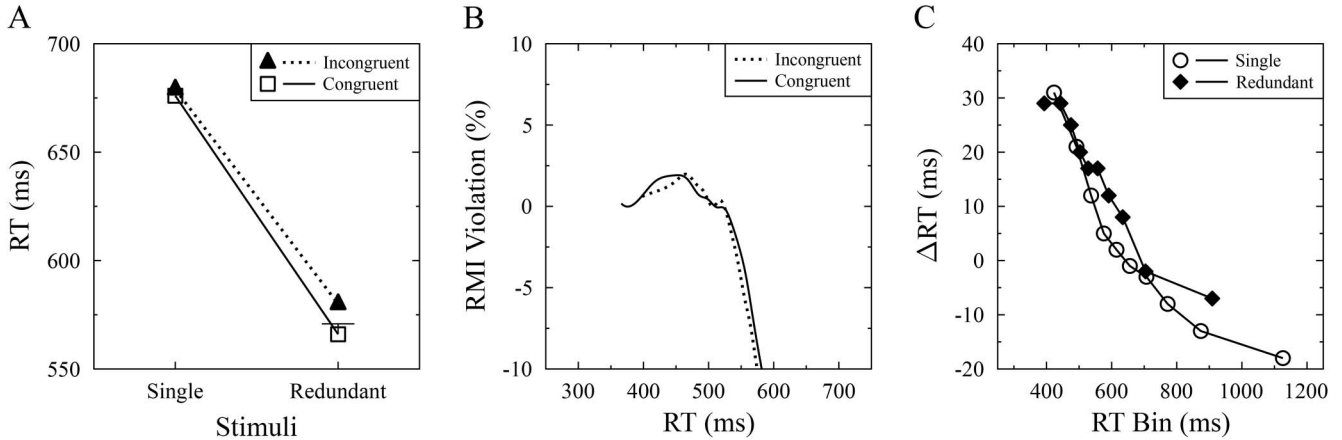
Figure 1. A. Mean reaction time (RT) as a function of congruency (congruent, incongruent) and stimulus condition (single, redundant). The error bar indicates 1 *SE* (standard error) based on the pooled error terms of the two main effects and the interaction (= 5 ms). B. Violations of the race model inequality (RMI) in percent (i.e., differences between obtained and race-model predicted cumulative density functions) separately for congruent and incongruent trials. C. Delta plots showing incongruent minus congruent differences in mean RT within each of 10 deciles, plotted against the decile averages, separately for each stimulus condition (single, redundant).

.001, $\eta_p^2 = .90$, congruency, $F(1, 59) = 7.27$, $p = .009$, $\eta_p^2 = .11$, and bin, $F(9, 531) = 552.25$, $p < .001$, $\eta_p^2 = .90$. as well as a significant interaction between redundancy and congruency, $F(1, 59) = 10.14$, $p = .002$, $\eta_p^2 = .15$. The interaction between redundancy and bin was also significant, $F(9, 531) = 118.96$, $p < .001$, $\eta_p^2 = .67$, which just reflected an increase of the redundancy gain across bins. Consistent with previous reports, there was a significant interaction between congruency and bin, $F(9, 531) = 19.84$, $p < .001$, $\eta_p^2 = .25$, with the Simon effect decreasing for slower responses. As is depicted in Figure 1C, the Simon effect dissipated over time for both stimulus conditions. Importantly, across essentially the entire range of RTs, the Simon effect with single stimuli was consistently less than or equal to that observed with redundant stimuli. Given that the three-way interaction was not significant ($p = .493$), this analysis suggests that the delta plots for single and redundant trials followed similar time courses and overlapped.

As a further comparison of the delta plots in the single and redundant conditions, we computed for each participant the slope of the delta plot in each condition using a linear approximation. The mean slopes of the single and redundant delta plots were quite similar (-0.07 and -0.09, respectively), and a paired *t* test indicated no significant difference between them ($p = .319$). In order to compare Simon effects equating for RT, we also compared the intercepts of these linear functions, adjusting the intercept to each participant's overall mean RT for both the single and redundant conditions. This analysis indicated that the Simon effect predicted for RTs at the participants' means were—if anything—slightly larger for redundant trials (9 ms) than for single trials (5 ms), although a paired *t* test indicated that the difference was not significant ($p = .416$). Thus, these linear-fit-based comparisons provide further support for the conclusion that the Simon effect is not larger for single than redundant stimuli at the same absolute RTs. To the contrary, these results indicate that the two delta plots followed similar time courses (reflected in similar slopes) and overlapped (reflected in similar Simon effects at the same RTs). In

contrast, as can be seen in Appendix A, the same analysis applied to RTs predicted by the DMC model of Ulrich et al. (2015) clearly results in larger Simon effects for conditions with lower activation.

Sequential analyses. Although there was a clear Simon effect for fast responses in the single condition (i.e., Simon effect >10 ms for the first three bins), the Simon effect was virtually absent at a mean RT level for these stimuli (i.e., 3 ms). To test the impact of redundant stimuli in a situation where there was a salient Simon effect for single stimuli at a mean RT level, we considered the previous trial's congruency in additional analyses, because the Simon effect generally increases after congruent trials (e.g., Stürmer et al., 2002). These analyses also allowed us to check whether a congruency sequential effect (CSE) was present in the current study, as it is in many other Simon studies (e.g., Hazeltine et al., 2011; Stürmer et al., 2002). Figures 2A and 2B show the mean RTs after congruent and incongruent trials, respectively, as a function of stimulus condition and congruency in the current trial.

A repeated-measures ANOVA was conducted on these mean RTs with the within-subject factors of stimulus condition (single, redundant), congruency of the current trial (congruent *n*, incongruent *n*), and congruency of the previous trial (congruent *n* − 1, incongruent *n* − 1). This ANOVA revealed significant main effects of redundancy, $F(1, 59) = 522.54$, $p < .001$, $\eta_p^2 = .90$, congruency, $F(1, 59) = 8.65$, $p = .005$, $\eta_p^2 = .13$, and previous trial congruency, $F(1, 59) = 4.35$, $p = .041$, $\eta_p^2 = .07$. As in the previous analysis, there was a significant interaction between stimulus condition and congruency, with a larger Simon effect for redundant than for single stimuli, $F(1, 59) = 11.55$, $p = .001$, $\eta_p^2 = .16$. The Simon effect was also significantly modulated by previous trial congruency, $F(1, 59) = 204.90$, $p < .001$, $\eta_p^2 = .78$. As is evident in Figures 2A and 2B, there was a strong Simon effect on mean RT after congruent trials (39 ms) but a smaller and even reversed Simon effect after incongruent trials (-20 ms). The three-way among these factors was not significant ($p = .136$). Thus, this analysis shows a strong CSE
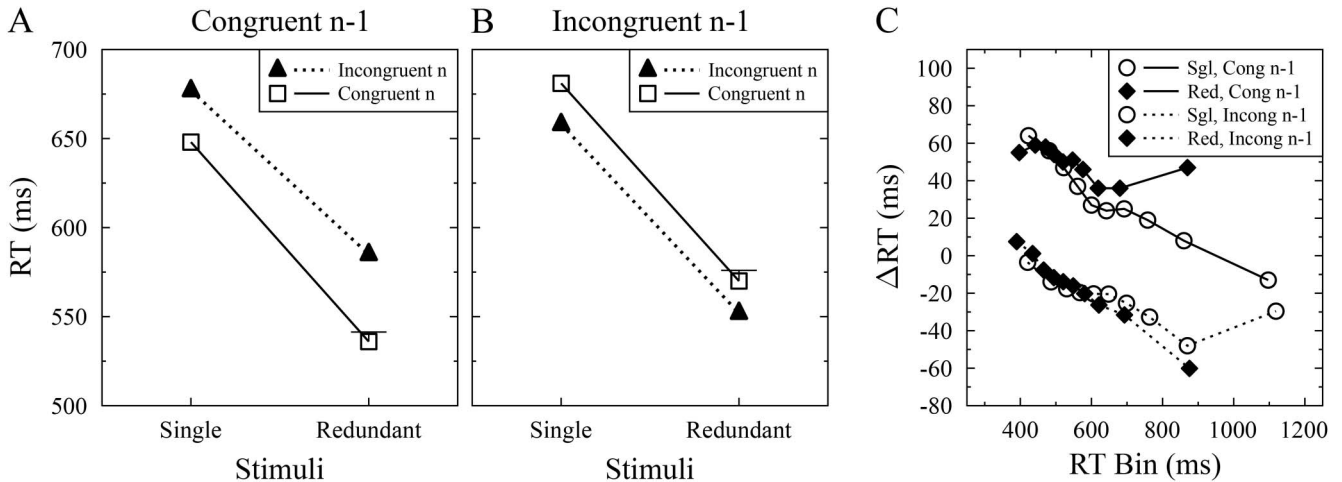
Figure 2. A. Mean reaction time (RT) as a function of congruency in the current trial (congruent *n*, incongruent *n*) and stimulus condition (single, redundant) when the previous trial was congruent (i.e., congruent *n* − 1). B. Mean RT as a function of congruency in the current trial (congruent *n*, incongruent *n*) and stimulus condition (single, redundant) when the previous trial was incongruent (i.e., incongruent *n* − 1). The error bars indicate 1 *SE* (standard error) based on the pooled error terms of the two main effects and the interaction of the specific congruency condition in the previous trial (i.e., congruent *n* − 1, incongruent *n* − 1) C. Delta plots showing incongruent minus congruent differences in mean RT within each of 10 deciles, plotted against the decile averages, separately as a function of single (Sgl) versus redundant (Red) current-trial stimuli and of congruent (Cong *n* − 1) versus incongruent (Incong *n* − 1) previous-trial stimuli.

for both redundant and single stimuli. Most important, although there was a clear Simon effect (29 ms) for single stimuli after congruent trials, the Simon effect for redundant stimuli (49 ms) again exceeded this Simon effect. The descriptive pattern of mean PEs was similar to the one observed for mean RTs. A parallel ANOVA on the PEs only yielded significant main effects of redundancy, $F(1, 59) = 72.87, p < .001, \eta_p^2 = .55$, and congruency, $F(1, 59) = 7.57, p = .008, \eta_p^2 = .11$, plus a significant interaction between congruency in the current trial and congruency in the previous trial, $F(1, 59) = 35.03, p < .001, \eta_p^2 = .37$. No other effects were significant (all *p*s > .190).

Finally, we also checked the delta plots to see whether the substantial Simon effect following congruent trials varied between single and redundant stimuli across the entire range of RTs. Figure 2C shows the delta plots for single and redundant stimuli, separately after congruent and incongruent trials. As can be seen in the figure, all of the delta plots were decreasing, and they did so at approximately the same rate. An ANOVA including factors of stimulus condition, congruency, previous trial congruency, and bin yielded a significant four-way interaction, $F(4, 236) = 4.77, p = .001, \eta_p^2 = .08$, however. Separate analyses with the factors of congruency, stimulus condition, and bin were therefore conducted for trials following congruent versus incongruent previous trials. Following congruent trials, the ANOVA revealed that all effects were significant (all *p*s < .001), including the three-way interaction, $F(9, 531) = 4.46, p < .001, \eta_p^2 = .07$. The mean slope of the line fitted to the single delta plot (−0.11) was descriptively, but not reliably, steeper than the mean slope of the line fitted to the redundant delta plot (−0.05), $p = .135$. In the intercept analysis, the predicted Simon effect at the individual mean RTs was significantly higher for redundant (24 ms) than for single stimuli (17 ms), $p = .027$. Thus, these analyses again suggest that, when

controlling for RT, the Simon effects for redundant stimuli are—if anything—larger than the ones for single stimuli. For completeness, we also computed parallel analyses on the corresponding means of delta plots after incongruent trials (see Figure 2C). The ANOVA revealed that the interaction between congruency and stimulus condition ($p = .429$) was not significant, but all other effects were significant (all *p*s < .023), including the three-way interaction with bin, $F(9, 531) = 2.18, p = .022, \eta_p^2 = .04$. The slope analysis indicated that the mean slope was less steep in the single condition (−0.04) than in the redundant condition (−0.17), $p = .004$. The predicted reversed Simon effect at the same mean RT was not significantly different for redundant (−14 ms) than for single stimuli (−10 ms), $p = .298$.

Discussion

In the present study, we examined the effect of increasing the relevant activation of Simon task stimuli to see whether this would reduce the effect of the irrelevant location-based activation. Specifically, we compared Simon effects with stimuli that signaled the correct response via a single feature (i.e., letter or color) versus Simon effects with stimuli that signaled the correct response redundantly via both features. Based on previous evidence from redundancy gain paradigms, we expected that the relevant activation would be stronger with redundant compared to single stimuli. This expectation was supported by the effects of redundancy— both on mean RTs and at the level of RT distributions—observed in our experiment, so the results suggest that we were successful in manipulating the strength of the relevant activation. With respect to the effects of the irrelevant location-based activation, the present results replicated previous findings of decreasing delta plots for

both single and redundant stimuli, and these results suggest that the Simon effects in the present experimental conditions were produced by the same mechanisms at play in other experiments, as too did the finding of CSEs like those found previously. The similar shape of the two delta plots even suggests that location-based processing followed a similar time course in the two conditions.

Based on previous activation-based accounts of Simon-task phenomena reviewed in the introduction, we expected that the Simon effect would be smaller when the relevant activation was stronger (i.e., smaller with redundant stimuli than with single stimuli). According to these accounts, the Simon effect is determined by the proportions of activation arising from the relevant and irrelevant (i.e., location-based) stimulus dimensions, with a smaller effect when there is proportionally more relevant activation. Assuming the same absolute strength of irrelevant location-based activation for both single and redundant stimuli in the present paradigm, the relevant activation would be a larger proportion of the total activation for trials with redundant compared to single stimuli, leading to the prediction of a reduced Simon effect for redundant stimuli, other things being equal.

The present results indicate, however, that the Simon effect on mean RT tends to be larger—not smaller—for redundant stimuli than for single stimuli. As was noted in the introduction and is illustrated in Appendix A with computer simulations of the DMC model (Ulrich et al., 2015), however, the finding that faster responses tend to have larger Simon effects warrants some caution in comparing the overall mean Simon effects for single versus redundant stimuli, since responses tend to be faster for the latter stimuli. We nonetheless expected that the Simon effect should be reduced for redundant compared to single stimuli at least when controlling for the absolute length of RT—and, hence, controlling the opportunity for irrelevant location information to dissipate after stimulus onset. Contrary to this expectation, delta plot analyses revealed that the Simon effect for redundant stimuli was not less than the Simon effect for single stimuli when controlling for RT. It should be emphasized that this finding held for the full range of RTs, including the faster responses (i.e., RT $< \approx 600$ ms) for which Simon effects of at least 10 ms were present for both single and redundant stimuli.

Nevertheless, it is somewhat unusual—at least at first glance—that virtually no Simon effect (only 3 ms) was found on overall mean RT in the single condition, and various procedural aspects of the present study could have contributed to this unusual finding. For example, the present study required two relevant dimensions and thus involved a larger number of stimulus-response (S-R) associations than are used in most Simon studies. The Simon effect typically decreases with an increasing number of S-R rules (e.g., Hommel, 1995a; Metzker & Dreisbach, 2009; Mewaldt et al., 1980). To account for this decrease, it has been suggested that (a) priming activation from spatial to nonspatial response codes spreads to more stimuli with larger stimulus sets (i.e., "fanning effect"; Metzker & Dreisbach, 2009), (b) location-based processing and working memory load (i.e., higher due to more S-R rules) compete for limited working memory capacity, thereby reducing the Simon effect (Wühr & Biebl, 2011), or (c) responses are slower with larger stimulus sets and these slower responses are less affected by decaying irrelevant activation (Hommel, 1995a). The last account seems especially plausible given the decreasing delta plots found in the present study. In addition, the inclusion of catch

trials in the present study might have induced some cautious response behavior that additionally slowed responses and thereby decreased the Simon effect. We do not think that the particular stimuli used here were responsible for the small size of the Simon effect, because in an additional Simon experiment with a similar experimental set-up, we found that our particular stimulus materials were indeed able to produce significant Simon effects on overall mean RT in conditions with a single relevant stimulus dimension (i.e., with simplified S-R mappings and no catch trials).[2] Thus, these factors might contribute to an overall reduced Simon effect in the present study, but they cannot account for the difference between single and redundant trials. These conditions were tested within blocks in which both the S-R mapping condition and the percentage of no-go trials was held constant, so any stimulus or task-specific perturbation of the Simon effect would be expected to influence both of these conditions equally. Furthermore, the overall pattern of results found in the present study was identical after congruent trials, where there was a large mean Simon effect for both single (29 ms) and redundant trials (49 ms).

Overall, these results appear inconsistent with simple models in which the Simon effect is caused by summing decision-level activations produced by one or both relevant stimulus dimensions with that produced by the irrelevant dimension. Even though current activation summation models (e.g., the DMC model) are rather neutral about the specific stage at which activations are combined, they do suggest that relevant and irrelevant activations are combined at some common stage. These models thus seem to require some elaboration to account for the present results, because these results suggest that there are at least two stages of activation summation. Specifically, these results suggest that the combination of activations based on two relevant dimensions occurs at one processing stage (i.e., perception, decision, or motor execution), whereas the relevant activation converges with the activation produced by the irrelevant dimension at a different stage. There are at least two possibilities for how these stages might be arranged.

First, redundancy gain might be attributed to the perceptual stage, with the irrelevant location-based activation coming in at the subsequent decision stage in which the response is selected. In this account, the decision process starts earlier with redundant stimuli

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[2] The same apparatus, stimuli, and basic procedure were used as in the main experiment, but for the first four blocks only one stimulus dimension (e.g., color-relevant blocks) always indicated the correct response, and for the remaining four blocks the other stimulus dimension indicated the correct response (e.g., letter-relevant blocks; order of dimensions was counterbalanced across participants). Similar to the main experiment, in color-relevant blocks, for example, a letter which was not associated with a left or right response was also presented. Note that a response was required in each trial (i.e., no catch trials). A fresh sample of 26 participants from the same pool was tested in this experiment. A repeated measures ANOVA with the factors stimulus dimension (letter, color) and congruency (congruent, incongruent) on RTs revealed significant main effects of stimulus dimension, $F(1, 25) = 29.23$, $p < .001$, $\eta_p^2 = .54$. and congruency, $F(1, 25) = 47.02$, $p < .001$, $\eta_p^2 = .65$. Letter RTs were 43 ms slower than color RTs and there was an overall Simon effect of 31 ms. The interaction was not significant ($p = .603$). A parallel ANOVA on PEs revealed only a significant main effect of congruency, $F(1, 25) = 26.04$, $p < .001$, $\eta_p^2 = .51$ (all other $ps > .160$). More errors were made on incongruent compared to congruent trials for both letter (6.4–3.7 = 2.7%) and color responses (6.3–2.8 = 3.5%). Thus, significant Simon effects were found for both the letter and color stimuli used in the main experiment.

than with single stimuli because of faster perceptual processing, but the relevant activation provided to the decision process—that converges with the irrelevant activation—is independent of redundancy. This account seems unlikely, however, because there is evidence that redundancy gain arises during the decision stage following perception (e.g., Miller, Beutinger, & Ulrich, 2009; Miller & Reynolds, 2003), at least with stimuli similar to those used in the present experiment.

Second, given the evidence that redundancy affects the decision stage, it seems most natural to explain the current results by assuming that the irrelevant activation comes in later (i.e., at the subsequent motor execution stage). Consistent with this idea of a motor locus of the Simon effect, several findings suggest that conflict resolution processes in the Simon task operate on a motor level (e.g., Klein, Petitjean, Olivier, & Duque, 2014; Leuthold & Schröter, 2006; Stürmer & Leuthold, 2003; Treccani et al., 2017). This interpretation fits also nicely with growing evidence that motor areas are involved in control processes (e.g., Coull, Vidal, & Burle, 2016; Usami et al., 2013), and it also fits well with evidence that the effect of redundancy does not extend into response execution (e.g., Mordkoff, Miller, & Roch, 1996).

Probably the most specific evidence for the involvement of the motor stage in the Simon task comes from a recent study by Servant et al. (2016). Using EEG recordings, the authors found that activity fluctuations over the primary motor cortex reflected the summed activation based on relevant and irrelevant processes. Moreover, the magnitude of EMG activity reflected ongoing evidence accumulation as predicted by activation summation models (Ulrich et al., 2015). Based on these findings, Servant et al. (2016) speculated that motor activity starts when evidence accumulation reaches a certain threshold that is below the decision threshold needed to complete the decision process (see also Servant, White, Montagnini, & Burle, 2015). Consequently, in their model the summation of relevant and irrelevant activation as proposed by the DMC model can also take place after motor processes have begun. The present results seem compatible with this model as long as redundancy only affects the timing of the relevant activation feeding into the motor process. Thus, we suggest that motor processes begin earlier with redundant than with single stimuli. Importantly, the integration of relevant and irrelevant activation only happens after the brain starts to engage in motor activity, thus implying a motor locus of the Simon effect.

Thus, activation-summation models like DMC might plausibly account for the present results simply by assuming that coactivation occurs during the central decision stage and then the irrelevant and relevant activations are combined at the motor stage to produce the Simon effect. More precisely, irrelevant spatial information directly triggers motor activity that sums with motor activation fed in from decision processes, either discretely after the final decision has been reached (e.g., Sternberg, 1969) or continuously as the decision is being made (e.g., McClelland, 1979). Strengthening the relevant activation with redundant stimuli speeds up the earlier decision processes, and as a result the summation of activations at the motor stage takes place earlier with a corresponding higher amount of decaying irrelevant activation. Note that the strength of motor activation provided by the relevant stimulus would be similar in redundant and single trials—only the onset of this activation would be earlier in the redundant trials. With

models like this, the net result is that the mean Simon effect would be larger in the redundant condition than in the single condition. Activation of the motor system by the relevant information would start earlier with redundant stimuli due to the faster decision process with these stimuli (i.e., decision locus of redundancy gain). As a result, this relevant activation would be combined with stronger irrelevant location-based motoric activation, since this latter activation decays over time (i.e., motor locus of Simon effect).

The idea of a motor locus of the Simon effect also seems in line with accounts of effector-system specific sequential modulations of Simon effects (e.g., Braem, Verguts, & Notebaert, 2011; Janczyk & Leuthold, 2017). Specifically, in these studies a CSE was found when the same effector system (i.e., hand or foot) was repeated in successive trials but not when the effector system changed. This finding demonstrates that a modulation of the Simon effect is effector system-specific and thus supports the idea that the effect arises at a motor level (e.g., suppression of effector-system-specific automatic response activation in MI; Janczyk & Leuthold, 2017).

In the present study, we also found CSEs for both the single and redundant conditions (see Appendix B for sequential analyses of responses to the two single dimensions). Interestingly, the overall Simon effects in these two conditions were not only reduced but even reversed after incongruent trials, which might indicate the presence of active suppression of irrelevant activation (e.g., Ridderinkhof, 2002a, 2002b). Suppression seems to be supported further by examining the delta plots of single and redundant stimuli after incongruent trials, which were almost exclusively decreasing in the negative area—thereby increasing the reversal of the Simon effect with slower responses. This illustrates again the general point that delta plot analyses may provide additional insights about underlying processes that are not available from mean RTs. Similarly, examining the corresponding delta plots might help to explain why decreasing the stimulus discriminability reduces mean Simon effects in some cases (Hommel, 1993, 1994) but not others (Baroni, Pellicano, Lugli, Nicoletti, & Proctor, 2012; Servant, Montagnini, & Burle, 2014).

In summary, the present study examined activation summation in the Simon task by using redundant stimuli to increase the strength of activation from the relevant stimulus. Contrary to the predictions of certain activation-summation models, the Simon effect was not reduced for redundant stimuli, and this finding suggests that stimulus redundancy and irrelevant location information affect activations at different levels. Specifically, it appears that increasing relevant activation via stimulus redundancy speeds the decision process without having motor effects, whereas irrelevant location-based information influences motor activation to produce the Simon effect (i.e., decision locus of redundancy gain and motor locus of Simon effect).

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(*Appendices follow*)

Appendix A

Simulations With the Diffusion Model for Conflict Tasks (DMC)

Like many previous models of the Simon effect, the DMC model of Ulrich et al. (2015) assumes simultaneous processing of both relevant and irrelevant stimulus features along controlled and automatic pathways, respectively. The outputs of these two processes are combined to drive a single Wiener diffusion process that is subject to noise with a standard deviation parameter of σ. The instantaneous drift rate of this process toward the correct response boundary b is determined at each time point by the sum of the inputs from the controlled and automatic processes, whose drift rates are μ_c and $\mu_i(t)$, respectively. In congruent trials the contributions of both processes increase the rate of drift toward the same (i.e., correct) response boundary, which results in a relatively high total drift rate and relatively short decision times. By contrast, in incongruent trials the irrelevant contribution opposes the relevant one, which decreases the total drift rate and increases decision times. RT in a given trial is the sum of the decision time needed to reach the response boundary b plus a normally distributed residual time (i.e., with μ_R and σ_R) reflecting the motor delay involved in executing the response. Thus, the model provides a straightforward account of the finding that mean RT is smaller in congruent trials than in incongruent ones. To account for the decreasing delta plots often observed in the Simon task, DMC assumes that the input of the automatic location-based process to the total drift process, $\mu_i(t)$, varies over time, in contrast to the temporally constant input of the controlled process, μ_c. Specifically, the input from the automatic process follows a time-varying pulse function that is modeled as a gamma density function with shape parameter a which reaches its peak amplitude A after a certain time $(a - 1) \cdot \tau$, after which it decreases (for further details, see Ulrich et al., 2015).
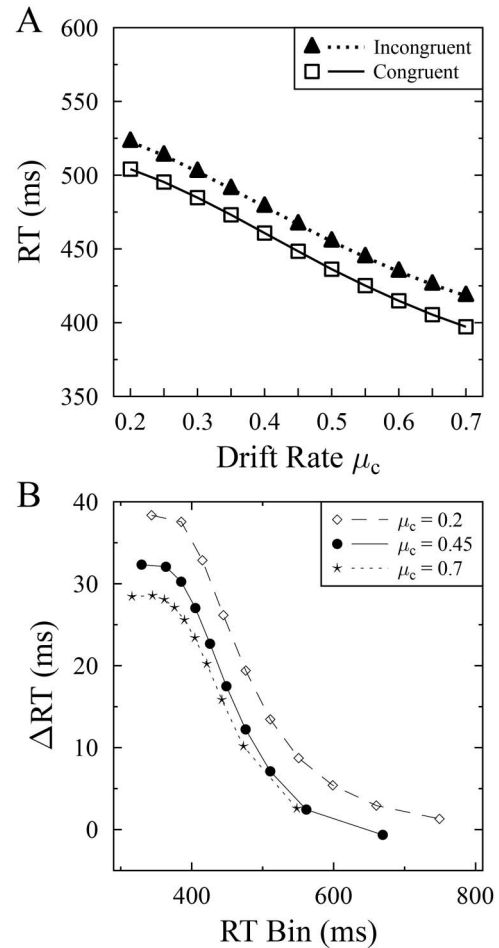

Figure A1. Predictions of the Diffusion Model for Conflict Tasks (DMC) model. A. Mean reaction time (RT) for congruent and incongruent trials as a function of the relevant drift rate μ_c in the range of 0.2–0.7. B. Delta plots showing incongruent minus congruent differences in mean RTs within each of 10 deciles, plotted against the decile averages, separately for μ_cs of 0.2, 0.45, and 0.7. For visual clarity, delta plots are only shown for the smallest, largest, and one intermediate value of μ_c.

Table A1

DMC Model Parameters Used for the Simulations

Parameter							
σ	b	A	a	τ	μ_R	σ_R	μ_c
4	75	20	2	30	300	30	0.2:0.1:0.7

Note. DMC = Diffusion Model for Conflict Tasks.

Computer simulations were used to examine how, according to this model, the size of the Simon effect should depend on the amount of relevant activation. Specifically, we assessed the model's predictions concerning the effects of the drift rate of controlled processes, μ_c, on both mean RT and RT distributions. As was noted in the introduction, increasing the relevant activation could potentially have two counteracting effects on the size of the Simon effect, because (a) absolute irrelevant activation is higher for faster responses, which tends to increase the Simon effect, but (b) the relative contribution of the relevant activation to the overall activation is increased when the relevant activation is strengthened, and that tends to decrease the Simon effect. The simulations allowed quantitative assessment of the combined effects of these two qualitatively counteracting factors so that the net effect can be estimated.

Simulations were run with the MATLAB code provided by Ulrich et al. (2015) and Table A1 shows the model parameters used for the simulations. We used the same parameters that were used by Ulrich et al. (2015) to examine the impact of changes in μ_c on the size of the mean Simon effect (see Table 1 and Figure 11 in Ulrich et al., 2015), extending their analysis to examine the impact on delta plots. Thus, following Ulrich et al. (2015), we assumed that the irrelevant activation would reach its maximum very early [i.e., maximal at $(a - 1) \cdot \tau = 30$ ms] and would decrease after this time. For each condition, 1,000,000 trials were simulated using a step size of $\Delta t = 1$ ms, and the means of the simulated RTs from correct trials are shown in Figure A1A.

As was also reported by Ulrich et al. (2015), the model predicts that the Simon effect on mean RT should be almost independent of the relevant drift rate. Thus, with these parameters the two counteracting effects of greater relevant activation appear to be comparable in size, leaving the Simon effect on mean RT virtually unchanged when relevant activation is increased. In essence, the tendency of stronger relevant activation to decrease the Simon effect approximately counteracts the tendency of faster responses to show larger Simon effects, resulting in approximately equal Simon effects for these faster, stronger versus slower, weaker conditions. These two counteracting effects are particularly apparent when comparing the corresponding delta plots predicted by the model. As can be seen in Figure A1B, all delta plots decreased over time with a similar shape. Not surprisingly, the individual bins of conditions with larger μ_cs had faster mean RTs than the corresponding bins of conditions with lower μ_cs. The mean slopes of the lines fitted to the delta plots were −0.11, −0.12, and −0.13 for $\mu_c = 0.2$, 0.45, and 0.7, respectively. Most importantly, at any given mean RT, the delta plots for higher μ_cs are below those with lower μ_cs. These differences are reflected in the intercepts of the linear functions fitted to the three delta plots, which give predicted Simon effects of 25 ms, 19 ms, and 15 ms, at the overall mean RT of 455 ms for $\mu_c = 0.2$, $\mu_c = 0.45$, and $\mu_c = 0.7$, respectively. Thus, the model appears to predict that the Simon effect should be larger for single stimuli than for redundant stimuli at the same absolute RTs, contrary to the findings of our experiment.

Appendix B

Additional Analyses of the Two Single Stimulus Conditions

In this appendix, we provide a comparison of the responses to single letter versus single color stimuli in the main experiment.

Main Analyses

Mean correct RTs and PEs were computed for each participant for each combination of single stimulus dimension (letter, color) and congruency (congruent, incongruent). A repeated-measures ANOVA on the mean RTs revealed only a significant main effect of stimulus dimension, $F(1, 59) = 19.11$, $p < .001$, $\eta_p^2 = .25$. RTs were shorter for single color stimuli (657 ms) than for single letter stimuli (697 ms). Neither the main effect of congruency ($p = .401$) nor the interaction between congruency and stimulus type was significant ($p = .114$; Simon effects of −2 ms for letter stimuli and +7 ms for color stimuli). A parallel ANOVA on the PE data revealed a significant main effect of stimulus type, $F(1, 59) = 5.65$, $p = .021$, $\eta_p^2 = .09$. PEs were higher for single color stimuli (5.6%) than for single letter stimuli (4.4%), indicating that at least some of the color/letter effect on RT was due to a speed-accuracy tradeoff. This ANOVA yielded neither a significant main effect of congruency ($p = .159$) nor a significant interaction between the

two factors ($p = .143$; Simon effect of 1% for letter stimuli and Simon effect of 0% for color stimuli).

We then constructed delta plots separately for letter and color stimuli using 10 bins. An ANOVA including the factors congruency, stimulus dimension, and bin revealed decreasing delta plots for both letter and color stimuli as indicated by a significant interaction between congruency and bin, $F(9, 531) = 10.99$, $p < .001$, $\eta_p^2 = .16$, which was not further modulated by stimulus dimension (i.e., $p = .884$ for the three-way interaction). Additional linear-fit based comparisons of the two single delta plots revealed negative slopes for both letter (i.e., slope of −0.05 of the line fitted to the observed delta plot) and color (i.e., slope of −0.06) stimuli. A paired t-test indicated no significant differences between the mean slopes ($p = .715$). The adjusted intercepts of these linear functions showed a descriptively higher predicted Simon effect at equal RT for color stimuli (9 ms) than for letter stimuli (2 ms), but a paired t-test on the mean intercepts revealed no significant difference ($p = .199$). Together, these analyses suggest that location-based activation follows the same time course for each of the two single dimensions.

(Appendices continue)

Sequential Analyses

Next, we carried out a sequential analysis of the two single stimulus dimensions to verify the usual CSE for single stimuli (i.e., reduced Simon effects after incongruent compared to congruent trials) and also to assess any sequential effects of whether the participant responded in consecutive trials to the same stimulus dimension. Thus, this analysis considered single stimulus trials that were preceded by single stimulus trials, considering both the congruency of the previous trial (congruent $n - 1$, incongruent $n - 1$) and the relevant stimulus dimension in the previous trial (letter $n - 1$, color $n - 1$).

Figures B1A and B1B depict the mean RTs for letter and color responses on trial n, respectively, as a function of congruency in the current and previous trials as well as the stimulus dimension in the previous trial. A repeated-measures ANOVA for these mean RTs with the four factors (i.e., congruency and stimulus dimension in the previous and current trials) revealed a significant four-way interaction ($p < .001$), and we thus conducted separate three-factor ANOVAs for color and letter stimuli with the factors of congruency in the current and previous trial and the previous trial stimulus dimension.

For letter stimuli, there was a significant main effect of stimulus dimension in the previous trial, $F(1, 59) = 121.18, p < .001, \eta_p^2 = .67$. Responses were 103 ms faster when a relevant letter (631 ms) instead of a relevant color (734 ms) was presented in the previous trial. Stimulus dimension in the previous trial interacted significantly with congruency in the previous trial, $F(1, 59) = 4.89, p = .031, \eta_p^2 = .08$. In essence, the beneficial effect of responding to a letter following a letter was smaller when the previous trial was congruent (88 ms) compared to incongruent (116 ms). Finally, the usual CSE was again present (i.e., a significant interaction between congruency in the current and previous trial), $F(1, 59) = 41.00, p < .001, \eta_p^2 = .41$, and this CSE was not further modulated by the stimulus dimension of the previous trial ($p = .789$). As can be seen in Figure B1A, the Simon effect was large after congruent trials but reversed after incongruent trials, both when the previous relevant stimulus was a letter (43 ms vs. -26 ms) and when it was a color (24 ms vs. -39 ms).

For color stimuli, there was also a significant main effect of the stimulus dimension in the previous trial, $F(1, 59) = 132.51, p < .001, \eta_p^2 = .69$. Responses were 117 ms faster when a relevant color (597 ms) instead of a relevant letter (714 ms) was presented in the previous trial. There was also a significant interaction between congruency in the current and previous trial, $F(1, 59) = 13.60, p < .001, \eta_p^2 = .19$, but this interaction was further modulated by the stimulus dimension of the previous trial, $F(1, 59) =$ 11.73, $p = .001, \eta_p^2 = .17$. As can be seen in Figure B1B, the Simon effect was significantly modulated by previous trial's congruency when the previous trial also required a response to the color dimension (51 ms vs. -40 ms). However, there was virtually no Simon effect after congruent trials and no reversed Simon effect after incongruent trials when the letter was relevant in the previous trial (4 ms vs. 4 ms).

Figures B1C and B1D show the mean PEs for letter and color responses, respectively, as a function of congruency in the current and previous trials as well as stimulus dimension in the previous trial. Although a four-way ANOVA on these mean PEs revealed that the four-way interaction was not significant ($p = .213$), we report separate ANOVAs for color and letter stimuli so that the analyses will be parallel to those conducted for RT. For letter stimuli, the ANOVA revealed a significant main effect of stimulus dimension of the previous trial, $F(1, 59) = 30.94, p < .001, \eta_p^2 = .34$. Responses were 3% more error-prone when the relevant stimulus was a color (6.7%) instead of a letter (3.7%) in the previous trial. There was also an interaction between previous and current trials' congruency, $F(1, 59) = 30.94, p < .001, \eta_p^2 = .34$, but no other effects, including the three-way interaction ($p = .639$), were significant. As is evident in Figure B1C, the Simon effect after congruent trials was larger than after congruent trials, and this CSE was present whether the previous relevant dimension was a color (2.7% vs. -2.6%) or a letter (3.8% vs. 0.6%).

For color stimuli (Figure B1D), there was also a significant main effect of stimulus dimension of the previous trial, indicating lower error rates when the previous relevant stimulus was a color (3.3%) rather than a letter (9.9%), $F(1, 59) = 69.54, p < .001, \eta_p^2 = .54$. Again, the interaction between previous and current trials' congruency was significant, $F(1, 59) = 15.69, p < .001, \eta_p^2 = .21$, with the Simon effect being reduced after incongruent compared to congruent trials (2.5% vs. -0.9% when the previously relevant dimension was color and 3.2% vs. -3.4% when the previously relevant dimension was letter). This interaction was not significantly modulated by which stimulus dimension was relevant in the previous trial, however ($p = .113$).

Taken together, these sequential analyses indicate that CSEs were present in both RTs and PEs for both letter and color stimuli whether the relevant target dimension repeated or switched—with one exception. For color stimuli, the CSE in RTs (but not in PEs) was modulated by the relevant stimulus of the previous trial. Whereas there was a CSE following relevant color stimuli, there was no CSE following relevant letter stimuli. We have no explanation for this unusual pattern with color stimuli.
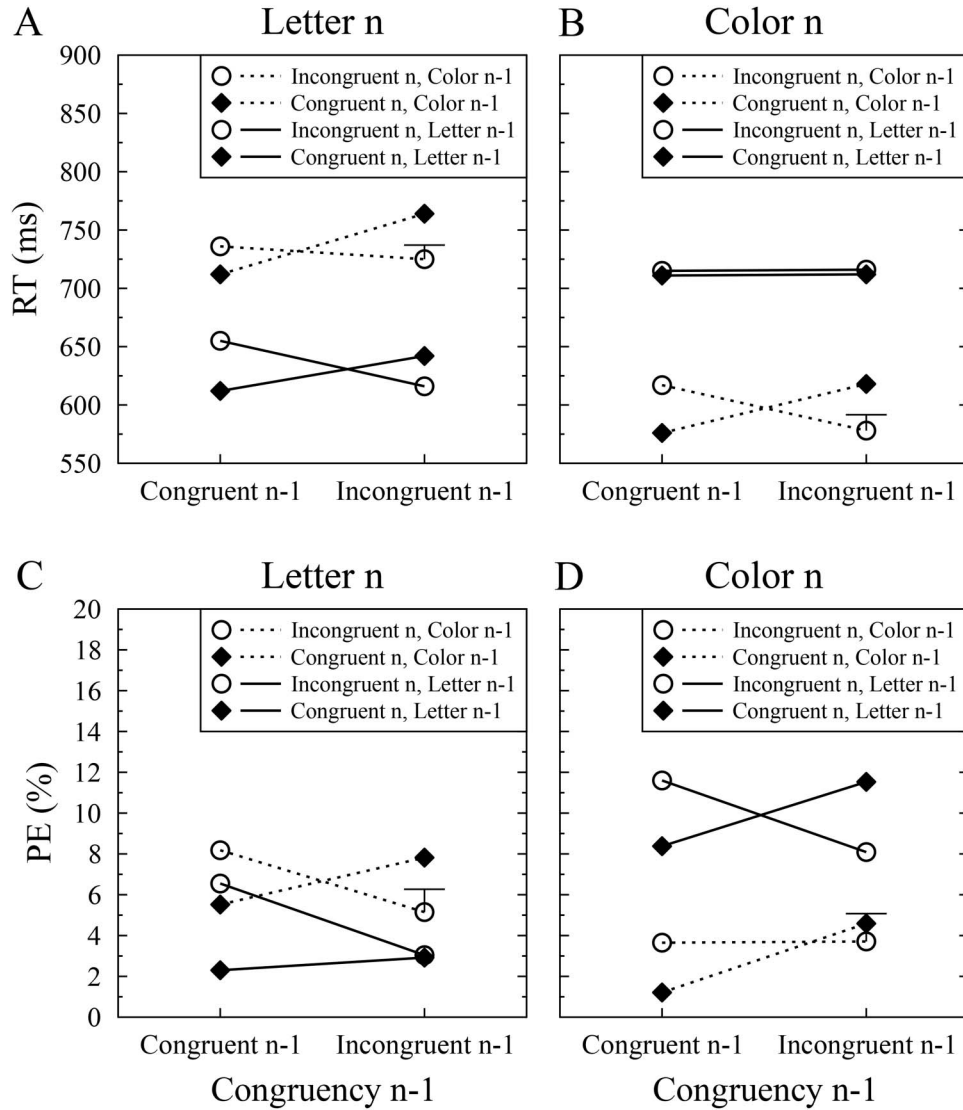
(Appendices continue)

Figure B1. Mean reaction time (RT; A, B) and mean percentage error (PE; C, D) as a function of congruency in the previous trial (congruent $n - 1$, incongruent $n - 1$), congruency in the current trial (congruent n, incongruent n), stimulus dimension in the previous trial (letter $n - 1$, color $n - 1$), and stimulus dimension in the current trial (letter n, color n). The error bar indicates 1 SE (standard error) based on the pooled error terms of all effects and interactions in the analysis of the specific stimulus dimension in the current trial (i.e., letter, color).