

Beyond mean reaction times: Combining distributional analyses with processing stage manipulations in the Simon task

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We combined analyses of reaction time (RT) distributions with experimental manipulations of different processing stages (perception, decision, motor execution) in a Simon task to investigate which changes in Simon effects could be explained entirely by fading irrelevant response activation. Consistent with fading activation accounts, the Simon effect on mean RT was usually smaller for conditions with slower responses (Expts. 1–3 but not Expt. 4), and delta plot analyses revealed that it was always smaller for the slower responses within each condition. Critically, however, these analyses also revealed that some experimental manipulations produced upward or downward shifts in the RT delta plots, thus altering the Simon effect on mean RT in ways that could not be explained by fading activation. The results demonstrate the power of combining RT distributional analyses with experimental manipulations to reveal mechanisms contributing to the Simon effect that would not be revealed using only mean RT. We consider alternatives to fading activation accounts of decreasing delta plots and discuss the contribution of different cognitive stages in modulating Simon effects.

Highlights:

- Combined chronometric approach with RT distributional analyses in the Simon task
- Observed interactive mean RT patterns of congruency and stage-specific manipulations
- Observed decreasing RT and PE delta plots for congruency effects in all conditions
- Delta plot analyses reveal influences on congruency effects not evident in mean RT
- Effects of some manipulations on delta plots not explained by fading activation

Keywords: Simon effect; delta plots; information processing; task performance; reaction time

1 Introduction

One central goal of cognitive psychology is to understand the underlying cognitive processes that are used when performing a task. Beginning with Donders (1868/1969), processes are usually investigated by measuring the reaction times (RTs) needed to translate task-relevant informa-

tion (i.e., stimuli) into appropriate motor responses. The idea is that the cognitive processes involved in such perceptual decision-making tasks are manifested through this measure of task performance (e.g., Luce, 1986; Sternberg, 1969a). Researchers attempt to find appropriate experimental conditions to uncover the internal (unobservable) cognitive operations leading to the (observed) task performance (Marr, 1982; Ulrich, 2009; Verbruggen, McLaren, & Chambers, 2014) in order to develop computational models that mimic the complex information processing stream (e.g., Kriegeskorte & Douglas, 2018).

Conflict paradigms are one useful approach to tackle this goal, because the processes intervening between stimuli and responses can be investigated under the presence of both task-relevant and task-irrelevant sources of information. A variety of different paradigms have provided evidence that human performance is affected by task-irrelevant information, as reflected in smaller mean RTs when the two sources

©2020. This manuscript version is made available under the CC-BY-NC-ND 4.0 license. Raw data and MATLAB scripts for the models described by Schwarz and Miller (2012) are available via the Open Science Framework at osf.io/ny4hu. Address correspondence to: Victor Mittelstädt, Department of Psychology, University of Tübingen, Schleichstraße 4, 72076 Tübingen, Germany, email: victor.mittelstaedt@uni-tuebingen.de or Jeff Miller, Department of Psychology, University of Otago, PO Box 56, Dunedin 9054, New Zealand, email: miller@psy.otago.ac.nz.

of information are associated with the same response (i.e., congruent trials) compared to different responses (i.e., incongruent trials; e.g., Eriksen & Eriksen, 1974; Simon & Rudell, 1967; Stroop, 1935). Thus, conflict effects (i.e., differences between incongruent and congruent trials) indicate that activations produced by the irrelevant and relevant information are superimposed during processing. Clearly, understanding how different processes modulate the superimposition of response activations within the information processing stream (and with that the observable conflict effects), is helpful in clarifying the range of effects of irrelevant information on task performance.

The present study applied RT distributional analyses to see how the conflict effect in the Simon task is modulated by experimental manipulations affecting different stages of cognitive processing. The exploration of these manipulation effects at the distributional level can provide further information—beyond what is available from mean RT—about the mechanisms and locus of the Simon effect (e.g., Simon, 1968). This is an important endeavor because the conflict effect observed in the Simon task is often used as a convenient experimental tool in various research areas (e.g., Dreisbach, Fröber, Berger, & Fischer, 2018; Fischer, Plessow, Dreisbach, & Goschke, 2015; Lien & Proctor, 2000; Möckel, Beste, & Wascher, 2015; Rey-Mermet, Gade, & Oberauer, 2018; Schlaghecken, Blagrove, Mantantzis, Maylor, & Watson, 2017; van Driel, Swart, Egner, Ridderinkhof, & Cohen, 2015), and many have recently scrutinized the origin of this effect in empirical studies, which has led to the development of sophisticated models (e.g., McIntosh & Mehring, 2017; Nikouei Mahani, Bausenhardt, Nili Ahmadabadi, & Ulrich, 2018; Ulrich, Schröter, Leuthold, & Birngruber, 2015), although there remain healthy debates (Ellinghaus, Karlbauer, Bausenhardt, & Ulrich, 2018; Hübner & Mishra, 2016; Janczyk & Leuthold, 2018; Salzer, de Hollander, & Forstmann, 2017; Scorolli, Pellicano, Nicoletti, Rubichi, & Castiello, 2015; Servant, White, Montagnini, & Burle, 2016; Valle-Inclán, 1996; Wühr & Heuer, 2018).

1.1 The Simon effect

In one common version of a visual Simon task, participants are required to make a left or right key press response to the color of a stimulus presented on the left or right side of a fixation cross (e.g., Hommel, 1994b; Miller & Rouïast, 2016; Proctor, Miles, & Baroni, 2011; Seibold, Chen, & Proctor, 2016). Despite the fact that stimulus location is irrelevant, responses are faster when the stimulus is on the same side as the required response, compared to when it is on the opposite side (for reviews see, e.g., Hommel, 2011; Kornblum, Stevens, Whipple, & Requin, 1999; Lu & Proctor, 1995; Mewaldt, Connelly, & Simon, 1980; H. Zhang, Zhang, & Kornblum, 1999). Many theoretical accounts are based on two parallel processing routes to account for this so-called *Si-*

mon effect (and other conflict effects; 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; H. Zhang et al., 1999; Zorzi & Umiltà, 1995). According to these dual-route models, activation produced by the relevant stimulus feature is processed by controlled processes via one route and the irrelevant location-based activation is (presumably automatically) processed via another route. The Simon effect arises because task-irrelevant and task-relevant activation superimpose during the decision-making process. This activation superimposition speeds up responses in congruent trials and slows them down in incongruent trials (e.g., De Jong et al., 1994; Ridderinkhof, 2002b).

Interestingly, it is somewhat ambiguous at which point irrelevant activation feeds into the task-relevant processing stream. Specifically, most dual-route models implicitly assume that the superimposition of activation in conflict tasks (including the Simon task) occurs at a decision stage—that is, when selecting the appropriate response (e.g., Botvinick et al., 2001; De Jong et al., 1994)—and this idea is usually also adopted by researchers examining control processes in the Simon task (e.g., Hübner & Mishra, 2016; Wang, Damen, & Aarts, 2018). Similarly, several mathematical models of conflict effects based on dual-route models also assume that the Simon effect arise due to superimposition of decision-level activations (e.g., Cohen, Servan-Schreiber, & McClelland, 1992; Hübner, Steinhauser, & Lehle, 2010; Ulrich et al., 2015). These models usually “simply” assume that total RT is the sum of the time needed by a decision process, during which task-irrelevant and task-relevant activations are superimposed, plus “the residual duration of all processes outside the decision process (e.g., stimulus encoding and response execution)” (Ulrich et al., 2015, p. 153).

On the one hand, a decision locus seems reasonable because many empirical findings suggest that irrelevant activation comes in at the stage in which the response is selected (e.g., Lu & Proctor, 1994; Masaki, Takasawa, & Yamazaki, 2000; Scerrati, Lugli, Nicoletti, & Umiltà, 2017; Treccani, Cubelli, Sala, & Umiltà, 2009). On the other hand, however, it is also possible that irrelevant activation has at least some influence on early and late task-relevant processes—that is, during the process of identifying the stimulus (perceptual level) or when initiating and executing the selected response (motor level). For example, early attempts localized the Simon effect exclusively at a perceptual stage (e.g., Hasbroucq & Guiard, 1991; Stoffels, Van der Molen, & Keuss, 1989). Although the conclusion of a solely perceptual locus was subsequently called into question (e.g., Hommel, 1995b; Lu & Proctor, 1994), early processes might still be involved in conflict resolution—in addition to central processes (e.g.,

Valle-Inclán, 1996).

Furthermore, there is also evidence that the irrelevant location-based activation reaches the motor system (e.g., Leuthold & Schröter, 2006; Stürmer & Leuthold, 2003; Trecani, Cona, Milanese, & Umiltà, 2018), there producing an observable impact of location-based activation on continuous measures of movement times (e.g., Finkbeiner & Heathcote, 2015; Scherbaum, Dshemuchadse, Fischer, & Goschke, 2010). Clearly, these findings do not rule out a decision locus, but it is interesting that some researchers have emphasized that part of the conflict is resolved during response initiation (e.g., Buetti & Kerzel, 2009; Scrollli et al., 2015). Recently, Servant et al. (2016) have even provided direct evidence for the involvement of primary motor cortices in solving the competition between irrelevant and relevant activation in the Simon task by applying sophisticated electroencephalography (EEG) and electromyography (EMG) measurements (see also Coles, Gehring, Gratton, & Donchin, 1992). Thus, the contribution of different task processing stages (i.e., perception, decision, motor) to the emergence of the Simon effect remains unclear. As is discussed next, the somewhat unusual temporal characteristics of irrelevant location-based activation may at least partially contribute to this uncertainty.

1.2 Decreasing delta plots and the fading of irrelevant activation

Critically, there is one particular aspect of performance in the Simon task which seems to distinguish this effect from other conflict effects. Specifically, many studies of the standard Simon task have revealed that the Simon effect is larger for faster compared to slower responses (e.g., Burle, Van den Wildenberg, & Ridderinkhof, 2005; Ellinghaus et al., 2018; Hommel, 1994b, 1995b; Miller & Rouast, 2016; Ridderinkhof, 2002a; Xiong & Proctor, 2016). 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). Specifically, delta plots display the difference between congruent and incongruent mean RTs separately in each of 5–10 bins ranging from the fastest to the slowest RTs. Using five bins, for example, one point on a delta plot would show the difference between the mean of the 20% of fastest RTs in the congruent condition as compared with the mean of the 20% of fastest RTs in the incongruent condition (see, e.g., Schwarz & Miller, 2012, for more detail on the construction of delta plots). These delta plots are usually decreasing, with smaller Simon effects for slower RT bins, and this pattern is not predicted by standard perceptual decision-making models in which RT variance tends to increase with the mean RT (e.g., Hübner et al., 2010; Servant, Montagnini, & Burle, 2014; Wagenmakers & Brown, 2007).

Decreasing delta plots for the Simon effect are usually in-

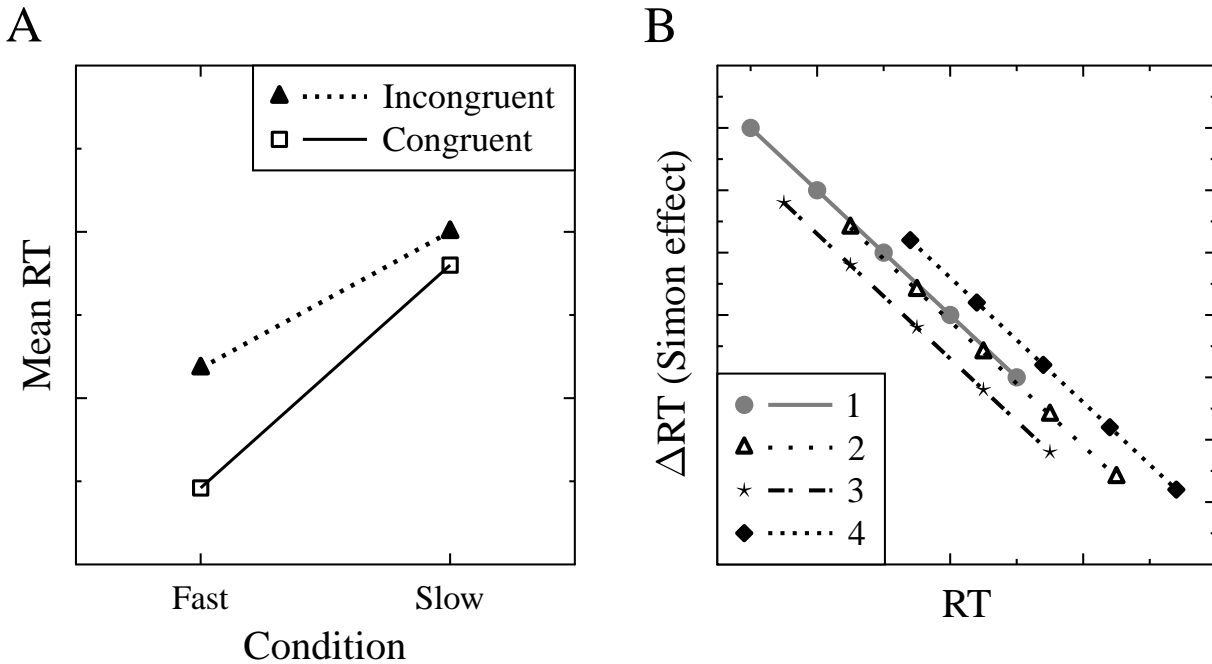
terpreted to mean that the impact of irrelevant location-based activation fades over time (for reviews see, e.g., Dittrich, Kellen, & Stahl, 2014; Pratte, Rouder, Morey, & Feng, 2010; Proctor et al., 2011; Van den Wildenberg et al., 2010). Indeed, a recent activation summation model was able to capture this pattern nicely based on the assumption of fading location-based activation (Ulrich et al., 2015). As will be considered in the General Discussion, there are also alternative accounts of decreasing delta plots (e.g., Schwarz & Miller, 2012; J. Zhang & Kornblum, 1997), but for now we will focus on the idea of fading activation to account for this pattern.

One prediction of the account based on fading irrelevant activation is that the Simon effect should change as a function of processing speed, and this prediction was examined in the seminal work of Hommel (1995b). Specifically, he questioned whether an interaction of the Simon effect with a perceptual manipulation would speak for an influence of irrelevant activation prior to being superimposed with relevant activation (e.g., Hasbroucq & Guiard, 1991). He emphasized that prolonging perceptual processing should reduce the Simon effect because the impact of location-based activation dissipates over time. For example, in a series of studies he provided evidence that manipulations which increase perceptual processing time also tend to decrease the Simon effect on mean RT (Hommel, 1993, 1994a, 1994b, 1995b).

When examining the tendency for increased perceptual processing duration to reduce the Simon effect at the level of mean RT, however, it is ambiguous whether the reduction is just a result of increased fading activation. Instead, changes in perceptual processing time might alter the Simon effect for additional reasons beyond simply affecting the time during which activation fades. For example, it is possible that degraded stimuli trigger weaker location-based activation than non-degraded stimuli. Thus, a reduced Simon effect in a degraded condition might be the combined result of a both lower initial level of irrelevant activation plus more time for that activation to fade out before being superimposed with relevant activation. Another—not mutually exclusive—possibility is that the manipulation prolonging perceptual time might also weaken the activation produced by the relevant stimuli and thereby decrease the rate of task-relevant evidence accumulation (e.g., Servant et al., 2014). In short, the manipulation of perceptual processing time could modulate the Simon effect in numerous ways, so it could be a substantial oversimplification to attribute the decreased Simon effect in a degraded condition entirely to fading activation.

To make this argument more concrete, Figure 1B visualizes three qualitatively different delta plot patterns that could underlie the same interactive mean RT pattern displayed in Figure 1A (i.e., reduced Simon effect in a slow compared to fast processing condition), using idealized linear delta plots

Figure 1. A. Hypothetical interactive mean RT pattern showing reduced Simon effect (i.e., difference between incongruent and congruent trials) in a slow compared to fast experimental condition. B. Schematic depictions of three qualitatively different delta plot shifts of a slow experimental condition (i.e., 2, 3 and 4) compared to a fast experimental condition (i.e., 1) that could underlie the interactive mean RT pattern like that displayed in A. At a given RT, the Simon effect in the slow condition could be the same as (2), smaller than (3), or larger than (4) the Simon effect in the fast condition.



for simplicity. First, compared to the fast condition (Figure 1B1), the decreased Simon effect in a slow condition might simply be due to the increased time for activation to fade, in which case the delta plots of the slow and fast conditions could show the same Simon effects at equal RTs (i.e., overlapping delta plots, Figure 1B2). Second, the Simon effect in the slow condition might be reduced beyond what is explainable by fading activation, thereby additionally shifting the delta plot of the slow condition downward relative to the delta plot of the fast condition (Figure 1B3). Third, the Simon effect in the slow condition might actually be increased when controlling for the extent to which irrelevant activation has faded—that is, the delta plot of the slow condition could be shifted rightward relative to the delta plot of the fast condition (Figure 1B4). Clearly, many other alternative patterns are also conceivable (e.g., nonlinear delta plots, different slopes of delta plots in the fast and slow conditions), but the general point is that interpretations based solely on mean RT cannot discriminate between changes in Simon effects that are simply due to the slower responses (i.e., fading activation) and changes that reflect additional modulations beyond overall response slowing. In a similar vein, manip-

ulating the duration of decision or motor processes (e.g., by changing the number of stimulus alternatives or the response effectors) might also produce additional effects beyond those explainable purely in terms of fading activation (e.g., smaller mean Simon effect with many compared to few stimulus alternatives; Hommel, 1995a; Mewaldt et al., 1980), but examination of mean RTs would not reveal these effects.

The importance of considering the time available for irrelevant location information to dissipate was also demonstrated in a recent study by Mittelstädt and Miller (2018). This study investigated whether the Simon effect decreases if the strength of relevant activation increases relative to that of irrelevant activation. The study used a redundancy gain task in which there were two relevant stimulus dimensions, and it contrasted conditions in which the response was indicated by just one of the relevant dimensions against conditions in which it was indicated by both dimensions (i.e., single vs. redundant trials, respectively). As expected, responses were faster in the redundant compared to the single condition. Contrary to the idea that stronger relevant activations would overwhelm the irrelevant location activations, however, the Simon effect was also larger in the redundant condition—

at least on the level of mean RTs. Critically, the delta plots for the single and redundant conditions overlapped across the whole RT distribution, suggesting that the Simon effect is independent of the strength of the relevant activation when controlling for RT and also, presumably, controlling the time for fading of the irrelevant activation. Thus, the study of Mittelstädt and Miller (2018) demonstrates that decreased mean Simon effects in slower conditions can sometimes be explained in terms of increased time for irrelevant activation to fade. It remains to be seen, however, whether the same is true for the effects of other manipulations.

1.3 The present experiments

In the present study we show how analyses at the level of RT distributions can serve as a valuable tool to control for the fading time-course of irrelevant activation when investigating the effects of individual experimental manipulations. Specifically, we selectively manipulated the duration of task-relevant processing at different stages (perceptual, decision, and motor execution) to produce fast and slow conditions in a standard visual Simon task in which participants were required to respond with their left or right effectors according to the color of a lateralized stimulus. We then compared the corresponding delta plots (i.e., delta plot in the fast compared to the slow condition) to see which effects could be explained entirely by the fading of irrelevant activation and which manipulations had additional effects beyond that of providing more opportunity for such fading. This procedure is also useful in delimiting the process at which activation-superimposition occurs within the information processing stream.

To see how delta plot analyses combined with different experimental manipulations can shed light on effects beyond those explainable by the fading activation account and help identify the locus of the Simon effect, consider the idealized stage diagram in Figure 2A1. As is evident from the descending triangle, fading activation accounts assume that irrelevant location-based activation triggered with stimulus onset is subject to fade-out over time; thus, so too are the facilitatory and inhibitory effects of this activation on the responses required by the relevant stimulus attribute. For the sake of simplicity, we assume that task-relevant processing (i.e., time from stimulus onset to an overt response), takes place at three different stages. First, some early processes take place before the relevant and irrelevant activations are superimposed (e.g., perceptual processes, stage A). These are followed by some other processes during which information superimposition takes place as illustrated by the arrows (e.g., decision processes, stage B), and these are followed in turn by some late processes after information superimposition (e.g., motor processes, stage C). Assuming that the superimposition of relevant and irrelevant information takes place within a single time interval, this idealized conception is essentially def-

initional, since some processes must take place before that interval and others must take place after it.

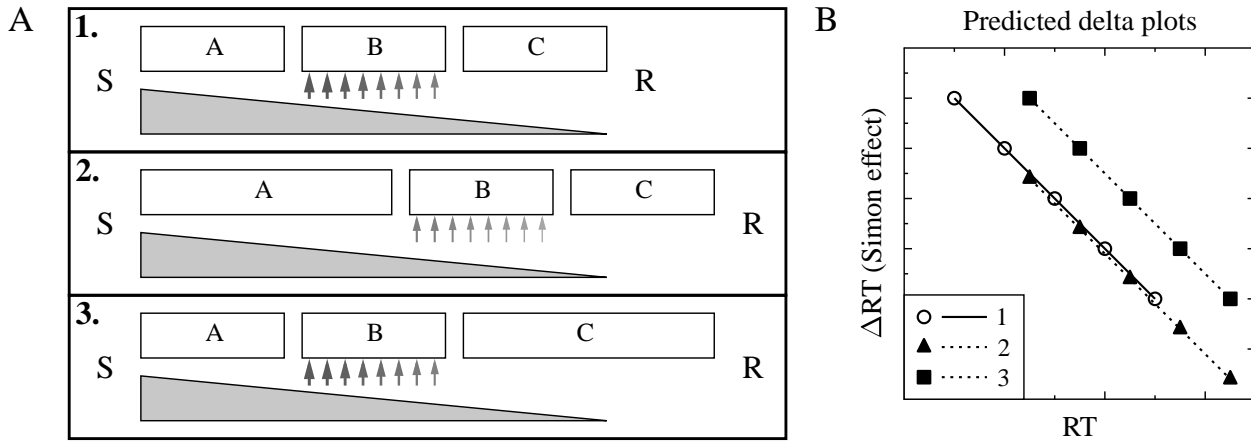
Although Figure 2A1 depicts the duration of stage A as being constant, the standard fading activation account of decreasing delta plots relies on the idea that there is inherent variability in the duration of this stage, as well as the others. Thus, in trials where stage A finishes after a relatively short time, stage B takes place while the irrelevant activation is still relatively strong, so the Simon effect is relatively large. In contrast, in trials where stage A takes a relatively long time, stage B does not take place until the irrelevant activation has diminished, so the Simon effect is relatively small.

Consider now manipulations either delaying early processes preceding the activation-superimposition process (Figure 2A2) or delaying late processes after activation-superimposition has taken place (Figure 2A3). Obviously, any such manipulations would produce main effects on RT measures (e.g., longer RT with slow compared to fast early processes). As is illustrated in Figure 2B, lengthening the processes before superimposition should reduce the Simon effect because the irrelevant activation has more time to fade before it superimposes with relevant activation. Thus, responses in condition 2 will be less influenced by irrelevant activation than responses in condition 1, reducing the Simon effect for these responses. In essence, the Simon effect becomes smaller for the same reason (i.e., fading irrelevant activation) whenever stage A takes longer, regardless of whether it takes longer due to its inherent variability or due to an experimental manipulation. If the Simon effect only decreases in condition 2 because the slowed early processes provide more time for fading, then the delta plot for condition A2 will slide down and to the right along the delta plot for condition A1, resulting in an overlapping delta plot pattern.

Conversely, if the experimental manipulation influences a process after the superimposition of relevant and irrelevant information as illustrated in Figure 2A3, the Simon effect need not be diminished by the experimental manipulation, because the slower condition does not provide more time for irrelevant activation to fade. This means that the delta plot for condition A3 could simply be shifted rightward by the time needed for the extra post-superimposition processing (see Figure 2B). Thus, such a rightward shift of the delta plot in the slow condition would be a sign that there are differences in the speed of processing after the locus of the Simon effect.

Probably the most interesting manipulations, however, are those affecting the stage where activation-superimposition takes place. On the one hand, if a manipulation causes this stage to take more time, there would be more time for fading of the irrelevant activation, and thus a smaller Simon effect. On the other hand, slower processing in this stage is presumably a sign of weaker relevant activation within the stage, and one would expect the Simon effect to be stronger when the

Figure 2. A. Depictions of three idealized task-relevant processing sequences (i.e., 1., 2. and 3.), each with three different stages (i.e., A, B, C) intervening between a stimulus (S) and an overt response (R). The grey-shaded triangles reflect the fading of irrelevant location-based activation after stimulus onset, and the arrows indicate when this facilitatory or inhibitory activation is superimposed with task-relevant activation (i.e., locus of the Simon effect at stage B). Compared to the stage durations in diagram 1, the duration of processing stage A (i.e., before the Simon locus) is prolonged in diagram 2, and the duration of processing stage C (i.e., after the Simon locus) is prolonged in diagram 3. B. Predicted delta plot patterns for the three conditions depicted in the three diagrams on the left.



relevant activation is weaker (Mittelstädt & Miller, 2018). It is not clear how these two counteracting factors would combine to modulate the Simon effect, either at the level of mean RTs or at the level of delta plots. Thus, it seems important to check the effects of such manipulations on the empirical delta plots.

To validate the application of delta plot analyses in revealing additional effects beyond what is expected purely based on fading activation, we used classic stage manipulations for which the corresponding effects have been investigated primarily on a mean RT level. Specifically, in Experiment 1, we manipulated early perceptual processes by varying stimulus discriminability, and in Experiments 2 and 3 we varied the number of alternatives and the strength of S-R pairs within the information processing stream—manipulations which presumably influence the duration of central decision processes (e.g., Sternberg, 1969b). Finally, in Experiment 4 we varied the speed of late motor execution processes by comparing faster and slower response effectors (i.e., hand vs. foot). The decision and motor stage manipulations of Experiments 2 and 4 naturally suggested between-block manipulations, so we also used a between-block manipulation in Experiment 1 to keep the experiments parallel.¹ This procedural choice also allowed us to maintain better consistency with previous literature (e.g., Hommel, 1994b, 1995a; Metzker & Dreisbach, 2009; Mewaldt et al., 1980; Wühr & Biebl, 2011) and to investigate the ef-

fects of stronger manipulations on delta plots because discriminability manipulations, for example, produce larger effects between than within blocks (Van der Schoot, Smulders, Los, & Kok, 2003).

2 Experiment 1

In the first experiment, we manipulated the duration of perceptual processes by lowering the discriminability of the task-relevant stimulus attribute color. Similar manipulations have been applied in previous studies to selectively influence processing within the perceptual stage (e.g., Hommel, 1993; Miller & Pachella, 1976; Pashler, 1984; Schwartz, Pomerantz, & Egeth, 1977). Thus, in different blocks of trials, the discriminability of the colored square was either high or low, and of course RTs were expected to increase in the low discriminability condition. As reviewed in the introduction, there is evidence that the mean Simon effect decreases as the duration of perceptual processing increases—presumably because irrelevant activation fades over time before being superimposed with relevant activation. If fading activation is entirely responsible for the decreased Simon effect, we would expect to observe overlapping delta plots as

¹As we will see, the decision manipulation of Experiment 2 yielded an interesting effect so that we decided to follow up on this finding with another decision stage manipulation for which a within-block manipulation was required.

depicted for conditions 1 and 2 of Figure 2B. Such a finding would be evidence that the decreased mean Simon effect with low-discriminability stimuli is just a by-product of slower responses being influenced by weaker irrelevant activation. Interestingly, however, in contrast to the studies mentioned earlier where mean Simon effects decreased when stimuli were less discriminable (e.g., Hommel, 1993, 1994b), some studies have observed stable Simon effects when decreasing stimulus discriminability (e.g., Baroni, Pellicano, Lugli, Nicoletti, & Proctor, 2012; Servant et al., 2014). The discrepancy of these findings at the level of mean RT level reinforces the idea that it is important to examine the corresponding delta plots.

2.1 Method

2.1.1 Participants. Participants were 60 psychology students (35 female) at the University of Otago and their mean age was $M = 20.1$ years (range from 18 to 33 years).² 51 participants were right-handed and the mean handedness score was $M = 55.1$ as measured by the Edinburg Handedness Inventory (Oldfield, 1971).

All experiments (i.e., Experiments 1–4) were approved by the University of Otago ethics committee and were performed in accordance with the ethical standards described in the 1964 Declaration of Helsinki. All participants were tested in a single session lasting approximately 40 min and they received partial course credit for their participation. All participants had normal or corrected-to-normal vision and gave informed consent before testing.

2.1.2 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 extension (Brainard, 1997). All visual stimuli appeared 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. Stimuli were colored outline squares, which were constructed from lines that were approximately 1.3° in length. For each participant, two stimulus colors were selected randomly from a set of four colors (red, blue, green, yellow), with one each assigned to the left and right hand. Stimuli discriminability was manipulated by varying the thickness and the color saturation (RGB values) of the lines of the squares. Squares of high discriminability had lines that were approximately 0.2° in thickness and that had maximal saturation (i.e., red: RGB[255,0,0], 52 cd/m^2 ; green: RGB[0,255,0], 184 cd/m^2 ; blue: RGB[0,0,255], 17 cd/m^2 ; yellow: RGB[255,255,0], 235 cd/m^2). Squares of low discriminability had lines that were approximately 0.033° in thickness and had much lower saturation (i.e., red: RGB[170,128,128], 65 cd/m^2 ; green: RGB[128,170,128], 90 cd/m^2 ; blue: RGB[128,128,170], 59 cd/m^2 ; yellow: RGB[170,170,128], 100 cd/m^2).³ The stim-

uli appeared to the left or right of the fixation point with a viewing angle of approximately 0.95° for the distance between the center of the screen and the center of the square. Responses were key presses with the left and right index fingers on the “Z” and “/?” keys of a standard computer keyboard.

2.1.3 Procedure. Stimulus discriminability (high, low) was held constant within a block and alternated across blocks. Half of the participants were tested with a block with high stimulus discriminability for the first block. Participants first performed two practice blocks (i.e., one for each discriminability condition), each including 40 trials, and then they were tested in 12 experimental blocks (six for each discriminability). Each of the 12 experimental blocks consisted of 60 randomly ordered trials (720 trials in total), with 15 presentations of each of the four possible stimulus displays (i.e., 2 possible locations \times 2 colors). Participants were instructed to respond as quickly and accurately as possible and to keep their eyes focused on the fixation cross. Instructional screens at the beginning of each block served as reminder and as a short break. At the beginning of each trial, the fixation cross appeared on the screen and after 500 ms a stimulus square was presented to the left or right side of the fixation cross, which remained on the screen. The square remained on the screen until the participant responded, up to a maximum of 2 s.⁴ After each response, feedback was

²Note that demographic data of one participant was missing. Thus, the reported summary values were calculated based on the data of 59 participants.

³Note that luminance could not be measured under exactly the original testing conditions due to relocation of testing rooms.

⁴Due to a technical error, the response deadline was 1 s for half of the participants. Note that there were only 1.0% trials with RTs larger than 1 s for the other half of participants and, more importantly, the crucial findings were virtually identical for participants tested with the two different deadlines. To see whether and how the use of different response deadlines might have modulated the findings observed in the main analyses, we reran all analyses with the between-subjects factor of response deadline (i.e., 1 or 2 s). Specifically, we first conducted ANOVAs on mean RTs and mean PCs with the factors congruency, discriminability, and response deadline. For mean RTs, there was only a marginally significant main effect of response deadline, $F(1, 58) = 3.18$, $p = .080$, $\eta_p^2 = .05$, with faster RTs for the shorter compared to the longer deadline group (458 ms versus 482 ms), and this factor was not involved in any interactions (all $ps > .587$). For mean PCs, the main effect of response deadline was significant, $F(1, 58) = 8.30$, $p = .006$, $\eta_p^2 = .13$, with less accurate responses for the short compared to the long deadline group (92.8% versus 95.1%). Response deadline also interacted significantly with discriminability, $F(1, 58) = 5.50$, $p = .023$, $\eta_p^2 = .09$, reflecting a larger discriminability effect for the short deadline group (2.6% versus 0.9%), with all other $ps > .622$. For the corresponding ANOVA on binned RTs used in computing delta plots, the only additional effect of response deadline was an interaction with bin, $F(9, 522) = 32.72$, $p = .001$, $\eta_p^2 = .36$, reflecting a faster

displayed for 1 s to indicate that the response was correct or for 3 s to indicate that the response was an error. Reaction time was measured from stimulus onset until a response was made.

2.2 Results

Practice blocks were excluded from all analyses. For RT analyses, we excluded error trials (6.1%) and trials with RTs less than 200 ms as anticipations (0.05%).

2.2.1 Reaction times (RTs). Figure 3A shows the mean RTs as a function of stimulus discriminability (low, high) and congruency (congruent, incongruent). A repeated-measures ANOVA with the within-subject factors of stimulus discriminability and congruency revealed significant main effects of discriminability, $F(1, 59) = 71.32, p < .001, \eta_p^2 = .55$, and congruency, $F(1, 59) = 120.50, p < .001, \eta_p^2 = .67$. As can be seen from Figure 3A, the mean RT was shorter with high than low discriminability (446 ms versus 495 ms), and the mean RT was also shorter in congruent than in incongruent trials (459 ms versus 482 ms). Most importantly, there was also a significant interaction reflecting a larger Simon effect with high than with low discriminability (26 ms versus 19 ms), $F(1, 59) = 5.77, p = .019, \eta_p^2 = .09$.

In order to examine the size of the Simon effect across the RT distributions, we constructed delta plots for the RT data separately for trials with high and low stimulus discriminability. Specifically, within each of the four conditions (i.e., high/low \times congruent/incongruent), each participants' RTs were divided into ten bins with equal numbers of trials. Then, we computed the differences between mean RTs of congruent and incongruent trials for each bin separately for both the high and low stimulus discriminability conditions. As can be seen in Figure 3E, the resulting delta plots for the two discriminability conditions were both decreasing and showed similar deltas at each value of RT.

To compare these delta plots, we conducted an ANOVA with the within-subject factors of congruency, discriminability, and bin (i.e., 1 to 10). Not surprisingly, this ANOVA yielded significant main effects of all three factors (all $ps < .001$), as well as a significant interaction between congruency and discriminability ($p = .020$). Furthermore, discriminability interacted significantly with bin ($ps < .001$), indicating that the discriminability effect increases with longer RTs. Replicating previous findings of decreasing delta plots, there was a significant interaction of congruency with bin ($p < .001$), but there was no evidence that this two-way interaction was modulated by discriminability ($p = .276$). Thus, the results suggest that there are similarly decreasing Simon effects in the two discriminability conditions.

In order to further compare the shapes of the two delta plots, we summarized the delta plot for each participant and condition with a linear regression model predicting the delta in each bin from the mean RT in that bin.⁵ The simulation

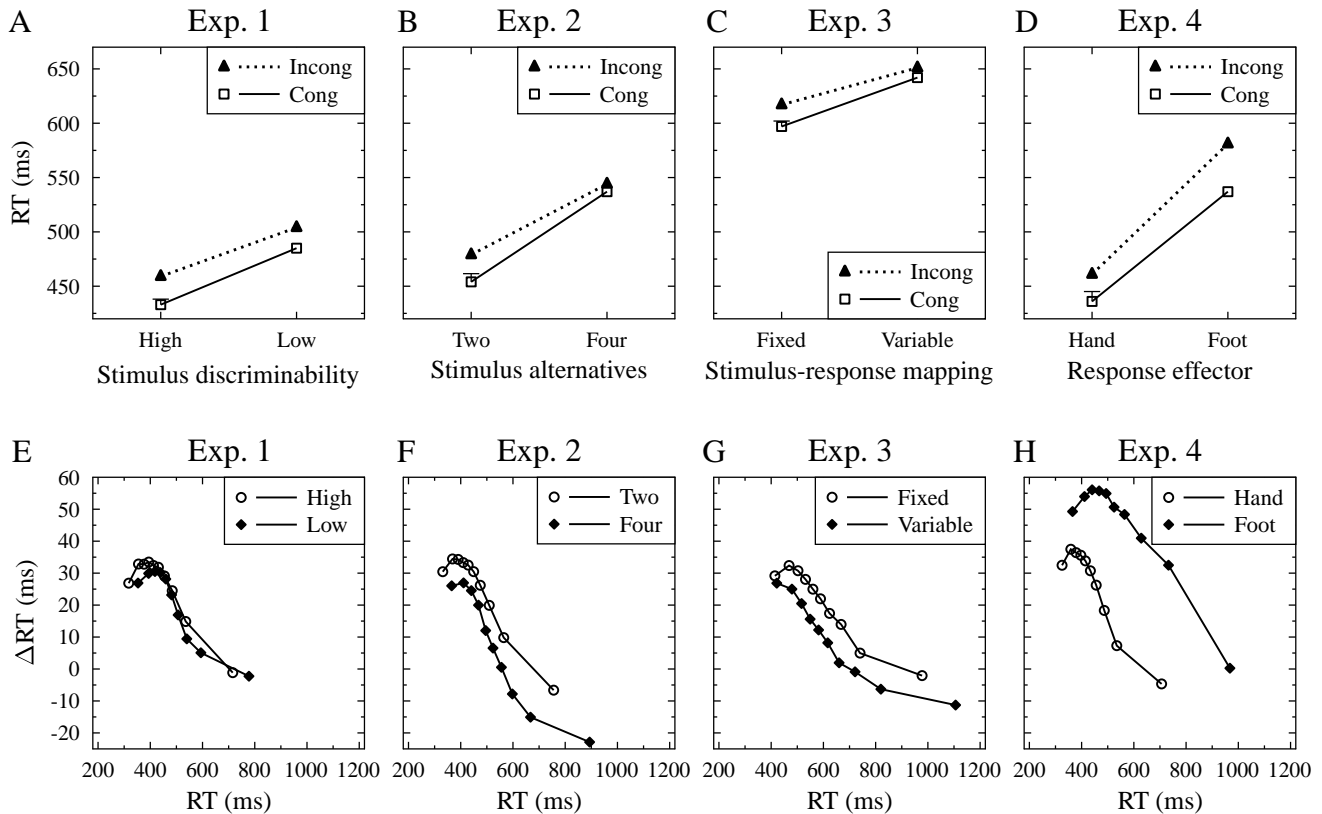
results described in Pratte et al. (2010) indicate that slope estimation based on linear regression models produces very reasonable results (better than other methods) even though some underlying assumptions (e.g., independence) are violated.

The mean slopes were quite similar for the high and low discriminability conditions (i.e., $-.09$ and $-.10$, respectively), and a paired t -test indicated no significant difference between conditions ($p = .776$). To check for an upward or downward shift between the two discriminability conditions (i.e., to compare Simon effects at a common value of RT), we used the regression model for each condition to compute the predicted Simon effect at each participant's individual mean RT. Equating RT in this manner, the predicted Simon effect was only slightly larger for the high discriminability condition (23 ms) than for the low discriminability condition (22 ms), and a paired t -test indicated no significant difference between

decrease of RTs across bins with the shorter deadline. Finally, we conducted ANOVAs with the factors discriminability and response deadline on mean slopes and on predicted Simon effect at the same mean RT, and these analyses yielded no significant effects or interactions involving deadline (all $ps > .288$).

⁵Omitting the first bins improved the linear fits but yielded otherwise similar results for this experiment (and all other experiments), so we report only the results including all bins. Specifically, we conducted the corresponding ANOVAs with the factors congruency, bin (i.e., 2–10) and the experiment-specific manipulation. Furthermore, we fitted lines to only bins 2–10 and then calculated again the corresponding slopes and predicted Simon effects at the same mean RT. The results of analyses examining all bins versus bins 2–10 were extremely similar. In Experiment 1, the three-way interaction was still not significant ($p = .351$), and there was also no significant difference between the slopes of the high ($-.11$) and low ($-.11$) discriminability delta plots ($p = .957$). The predicted Simon effects for the high (24 ms) and low (22 ms) condition did also not differ significantly ($p = .431$). In Experiment 2, the significant three-way interaction of the main analyses was also significant in this analysis ($p = .049$). However, there was again no significant difference between the corresponding slopes (i.e., $-.12$ and $-.13$ for the two and four stimulus alternatives delta plots, respectively), $p = .636$. The predicted Simon effect was again significantly larger with two stimulus alternatives (22 ms) than with four stimulus alternatives (11 ms), $t(63) = 3.76, p < .001, \eta_p^2 = .18$. In Experiment 3, the significant three-way interaction of the main analyses was again not significant ($p = .985$). There was again no significant difference between the slopes of the fixed (-0.08) and variable (-0.06) S-R delta plots ($p = .338$). The predicted Simon effects for the fixed (19 ms) condition was again lower than the one for the variable (10 ms) condition $t(62) = 2.33, p = .023, \eta_p^2 = .08$. In Experiment 4, the three-way interaction was also again not significant ($p = .820$) and the slopes were still quite similar (i.e., $-.14$ and $-.11$ for the hand and foot delta plots, respectively) with no significant difference ($p = .607$). At the same RT, the predicted Simon effect for the hand condition (18 ms) was again significantly smaller than the predicted Simon effect for the foot condition (52 ms), $t(25) = 5.85, p < .001, \eta_p^2 = .58$.

Figure 3. A. Mean reaction time (RT) of Experiment (Exp.) 1 as a function of congruency (congruent, incongruent) and stimulus discriminability (high, low). B. Mean RT of Exp. 2 as a function of congruency and number of stimulus alternatives (two, four). C. Mean RT of Exp. 3 as a function of congruency and S-R mapping (fixed, variable). D. Mean RT of Exp. 4 as a function of congruency and response effector (hand, foot). The error bars in A, B, C, and D indicate 1 *SE* (standard error) based on the pooled error terms of the two main effects and the interaction. E. Delta plots of Exp. 1 showing incongruent minus congruent differences in mean RT within each of 10 RT deciles, plotted against the decile average RTs, separately for each stimulus discriminability condition (high, low). F. Delta plots of Exp. 2 separately for each number of stimulus alternatives condition (two, four). G. Delta plots of Exp. 3 separately for each S-R mapping condition (fixed, variable). H. Delta plots of Exp. 4 separately for each response effector condition (hand, foot).



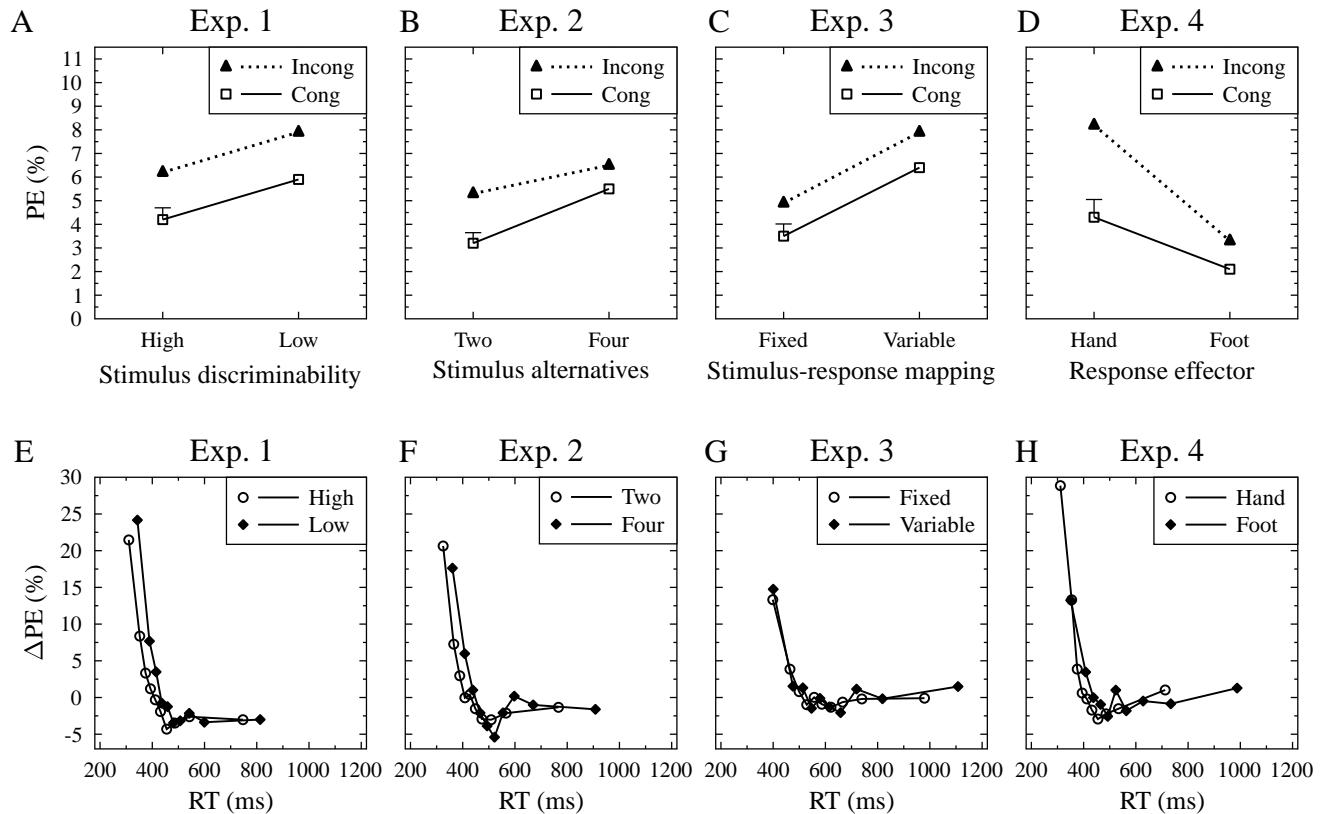
these values ($p = .476$). Thus, these comparisons provide further evidence that the two delta plots followed similar time-courses (reflected in similar slopes) and overlapped (reflected in similar Simon effects at a given RT).

2.2.2 Percentage errors (PEs). Figure 4A shows the mean percentage errors (PEs) in the corresponding conditions. An ANOVA parallel to the one conducted on mean RT also yielded significant main effects of discriminability, $F(1, 59) = 19.75$, $p < .001$, $\eta_p^2 = .25$, and congruency, $F(1, 59) = 23.97$, $p = .010$, $\eta_p^2 = .29$. There were fewer errors for trials with high compared to low stimulus discriminability (5.2% versus 6.9%) and for congruent than incongruent trials (5.1%

versus 7.0%). The interaction between these factors was not significant ($p = .902$), and the Simon effect for high discriminability stimuli (2.0%) was numerically almost identical to the one for low discriminability stimuli (2.0%).

For completeness, we also constructed delta plots for the error rates. For each participant, discriminability condition, and congruence condition, we rank-ordered the individual RTs (including both correct responses and errors) and then computed the error rate within each bin. Figure 4E shows the mean PEs plotted against the mean RT bins separately for the two discriminability conditions. As can be seen in this figure, the Simon effects on PE were mainly restricted to

Figure 4. A. Mean percentage error (PE) of Experiment (Exp.) 1 as a function of congruency (congruent, incongruent) and stimulus discriminability (high, low). B. Mean PE of Exp. 2 as a function of congruency and number of stimulus alternatives (two, four). C. Mean PE of Exp. 3 as a function of congruency and S-R mapping (fixed, variable). D. Mean PE of Exp. 4 as a function of congruency and response effector (hand, foot). The error bars in A, B and C indicates 1 *SE* (standard error) based on the pooled error terms of the two main effects and the interaction. E. Delta plots of Exp. 1 showing incongruent minus congruent differences in mean PE within each of 10 mean RT deciles, plotted against the deciles averages, separately for each stimulus discriminability condition (high, low). F. Delta plots of Exp. 2 separately for each number of stimulus alternatives condition (two, four). G. Delta plots of Exp. 3 separately for each S-R mapping condition (fixed, variable). H. Delta plots of Exp. 4 separately for each response effector condition (hand, foot).



the fastest responses for both high and low discriminability.

2.3 Discussion

The results revealed that the Simon effect on mean RT was smaller in the low compared to the high stimulus discriminability condition—in line with previous studies manipulating early (perceptual) task-relevant processes (e.g., Hommel, 1993, 1994b), and the results also replicated previous findings of decreasing delta plots in the two conditions. More importantly, the delta plots for the two discriminability conditions not only had similar shapes but also approximately overlapped across the whole RT distribution. In terms

of fading activation accounts of decreasing delta plots, this suggests that location-based irrelevant activation followed a similar (fading) time-course regardless of stimulus discriminability and that discriminability did not influence the size of the Simon effect directly, but only by prolonging RT so that the slower responses would be less affected by irrelevant activation. Thus, the comparison of delta plots suggests that relevant activation converges with irrelevant location-based activation at a processing level after the one affected by this perceptual manipulation.

Interestingly, as mentioned in the introduction of this experiment, some studies have reported that the Simon effect

on mean RT is approximately the same size for perceptually intact and degraded stimuli (e.g., Baroni et al., 2012; Servant et al., 2014). Further research will be needed to understand differences in the effects of different perceptual manipulations, but one possibility is that altering the visibility of stimuli in these studies impacted not only task-relevant but also task-irrelevant activation, speed-accuracy trade off criteria, or some other strategic aspect. For example, presenting perceptually degraded stimuli (compared to non-degraded stimuli) might have increased location-based activation if more complete shifts in spatial attention are needed to encode the task-relevant dimension for these stimuli. In that case, decreasing stimulus discriminability would have two counteracting influences on the Simon effect (i.e., stronger irrelevant activation but also more time for that activation to fade). The net result of these effects could be additivity of perceptual difficulty and Simon congruence at the level of mean RT, but inspection of delta plots would show that the Simon effect was actually larger with degraded compared to non-degraded stimuli after controlling for RT, which would produce non-overlapping delta plots.⁶ Another, non-mutually exclusive, possibility is that the use of a between-block manipulation of stimulus discriminability in the current experiment (as in Baroni et al., 2012, in Experiments 2–4 of Hommel, 1993, and in Hommel, 1994a) rather than a within-block manipulation (as in Experiment 1 of Hommel, 1993 and in Servant et al., 2014) may somehow contribute to differences in task-irrelevant and/or task-relevant processing resulting in either additive or interactive effects.

3 Experiment 2

The overlapping delta plots of the previous experiment suggest that our perceptual manipulation only gave task-irrelevant activation more time to dissipate before being superimposed with task-relevant activation, but had no other impacts on task processing relevant to the Simon effect. This pattern is also consistent with a locus of the Simon effect after early perceptual processing (i.e., after the effect of stimulus discriminability). In Experiment 2 we tried to manipulate task-relevant processes somewhat later than the perceptual processes manipulated in Experiment 1—that is, we investigated whether a manipulation of the duration of decision processes would also be explainable entirely by fading activation.

One common way to manipulate decision processes is by varying the number of S-R pairs Hick (1952). The time for a decision increases with the number of stimulus alternatives—presumably mainly increasing the durations of processes after perceptual processes but before the late stages of response execution (e.g., Alegria & Bertelson, 1970; Broadbent & Gregory, 1965; Sanders, 1980; Sternberg, 1969b). Specifically, then, in Experiment 2 two stimulus alternatives were used in half of the blocks (i.e., one color

indicated a left response and another color indicated a right response), whereas in the other half of the blocks four stimulus alternatives were used (i.e., two colors indicated a left response and two colors indicated a right response).

Although the mean Simon effect typically decreases with an increasing number of stimulus alternatives (e.g., Hommel, 1995a; Mewaldt et al., 1980), it remains unclear whether this decreasing Simon effect can be explained entirely by slower responses (similar to the discrimination manipulation). If so, we would expect a delta plot pattern similar to that obtained in Experiment 1—that is, overlapping delta plots with similar shapes for two versus four stimulus alternatives. As illustrated in Figure 2B (i.e., conditions 1 and 2), such a finding would be consistent with a Simon effect arising after decision processes based on the fading activation account. If the manipulation of decision processes has some other influence on the Simon effect (i.e., beyond what can be explained by fading activation), we would expect a different delta plot pattern (e.g., non-overlapping delta plots, see Figure 1). As mentioned in the introduction, the manipulation of decision processes is particularly interesting because of the possibility that irrelevant and relevant activations are superimposed at the decision stage.

3.1 Method

3.1.1 Participants. A fresh sample of 64 students (44 female) from the same pool were recruited to participate in the experiment. Their ages ranged from 18 to 33 years ($M = 19.9$), and their mean handedness score was $M = 57.9$ (56 participants were right-handed). One additional participant was also tested but excluded due to accuracy below 85%.

3.2 Apparatus, stimuli and procedure

The apparatus, stimuli, and procedure were the same as in Experiment 1 except as otherwise described. Stimuli were filled colored squares, which measured 1.9° in length, and these stimuli appeared to the left or right of the fixation point with a viewing angle of approximately 2.9° . The colors pink and cyan were added to the previous four-color set (red, blue, green, yellow). The number of stimulus alternatives (two, four) was manipulated blockwise. In blocks with two stimulus alternatives, participants were required to respond to two randomly selected colors of the six-color set, with one color each assigned to the left and right hand. In blocks with four

⁶Baroni et al. (2012) did present delta plots as a function of their perceptual manipulation. Visual inspection of these plots appear consistent with this interpretation, but no statistical analyses relevant for our purposes were presented. We therefore emphasize caution with respect to our post-hoc theorizing and instead take this as a further illustration of how examining delta plots can shed light on the underlying processes responsible for the Simon effect.

stimulus alternatives, participants had to respond to the remaining four colors, with two colors assigned to the left and two to the right hand. Half of the participants were tested with two stimulus alternatives for the first seven blocks and four stimulus alternatives for the last seven block, whereas the order was reversed for the other half of the participants. The first block of each condition served as practice, and there were thus 12 experimental blocks consisting of 64 randomly ordered trials (768 trials in total). Consequently, there were 16 presentations of each of the four possible stimulus displays in the two-alternative blocks (i.e., 2 possible locations x 2 colors) and 8 presentations of each of the eight possible stimulus displays in the four-alternative blocks (i.e., 2 possible locations x 4 colors).

3.3 Results

Practice blocks (i.e., blocks 1 and 8) were excluded from all analyses. For RT analyses, we excluded error trials (5.1%) and trials with RTs less than 200 ms as anticipations (0.02%).

3.3.1 Reaction times (RTs). Figure 3B shows the mean RTs for the two and four stimulus alternatives conditions plotted separately for congruent and incongruent trials. An ANOVA on these mean RTs revealed significant main effects of number of stimulus alternatives, $F(1, 63) = 69.85$, $p < .001$, $\eta_p^2 = .53$, and congruency, $F(1, 63) = 39.87$, $p < .001$, $\eta_p^2 = .39$. Responses were on average faster with two stimulus alternatives (467 ms) than with four (540 ms), and there was an overall Simon effect of 15 ms (496 ms versus 511 ms). Most important, there was also a significant interaction reflecting a larger Simon effect in blocks with two (25 ms) compared to four (7 ms) stimulus alternatives, $F(1, 63) = 44.57$, $p < .001$, $\eta_p^2 = .41$, replicating earlier findings when stimulus set size was manipulated (e.g., Hommel, 1995a; Mewaldt et al., 1980).

As can be seen in Figure 3F, delta plots were again decreasing in both conditions. We again ran an ANOVA including the factor bin in addition to the factors of number of stimulus alternatives and congruency. All main effects and two-way interactions were significant (all $ps < .001$). In contrast to the previous experiments, however, the three-way interaction was also significant, $F(9, 567) = 2.68$, $p = .005$, $\eta_p^2 = .04$. This effect implies that the decrease of the Simon effect across bins differed quantitatively between the two conditions, even though the delta plots have qualitatively similar shapes (i.e., decreasing; see Figure 3F). Indeed, the mean slope of the individual lines fitted to the two-stimuli delta plot (-.11) was similar to the corresponding mean slope of the four-stimuli condition (-.13), $p = .428$. Interestingly, the delta plot of the four-stimuli condition was shifted downward below the delta plot of the two-stimuli condition. We again computed the individual predicted Simon effects at each participant's mean RT for the two conditions. This analysis also revealed that the average predicted Simon effect was signifi-

cantly smaller with four stimuli (11 ms) than with two stimuli (21 ms), $t(63) = 3.55$, $p = .001$, $\eta_p^2 = .17$.

3.3.2 Percentage errors (PEs). As can be seen from the PE means in Figure 4B, the mean PEs pattern was similar to the one found for mean RTs and all effects were significant in the ANOVA. Specifically, there were fewer errors in blocks with two compared to four stimulus alternatives (4.3% versus 6.0%), $F(1, 63) = 23.67$, $p < .001$, $\eta_p^2 = .27$, and also fewer errors for congruent than for incongruent trials (4.3% versus 5.9%), $F(1, 63) = 21.01$, $p < .001$, $\eta_p^2 = .25$. Furthermore, the Simon effect was smaller with two stimulus alternatives (2.1%) than with four (0.9%), $F(1, 63) = 23.67$, $p = .013$, $\eta_p^2 = .09$. The delta plots for error rates in Figure 4F show a strong decrease in the Simon effect from faster to slower responses.

3.4 Discussion

In Experiment 2, we explored the delta plot pattern produced by manipulating the number of stimulus alternatives—a manipulation which presumably directly affects task-relevant decision processes. The overall pattern of decreasing delta plots with both two and four alternatives is in line with fading activation accounts. More precisely, the two delta plots followed a similar time-course, suggesting that the smaller Simon effect on mean RT in the (slower) four compared to the (faster) two stimulus alternative condition was at least partially the result of irrelevant activation dissipating to a larger degree in the former compared to the latter condition.

On the other hand, the corresponding four-stimulus delta plot was actually shifted downward from the two-stimulus delta plot across the whole RT distribution, which indicates that manipulating the number of alternatives has an additional influence on the Simon effect beyond that explained by the fading activation account—in contrast to the stimulus discriminability manipulation of Experiment 1. Specifically, controlling for RT, the Simon effect was smaller with four stimuli than with two stimuli. One possibility to account for the decrease could be that irrelevant location-based processing and cognitive load compete for limited working memory capacity (e.g., Wühr & Biebl, 2011). Given the higher cognitive load with four alternatives, irrelevant location might have been processed to a lesser degree and thus less irrelevant activation would have been produced. Considering that automatic processing usually involves long-term memory and not capacity-limited working memory (e.g., Logan, 1988; Servant, Cassey, Woodman, & Logan, 2018), possible modulations of the Simon effect due to working memory load in the present study would be in line with findings that speak against automatic (capacity-independent) processing of irrelevant information (e.g., Wyatt & Machado, 2013). It is not clear, however, why increases in working memory load would result in increased conflict effects in the Flanker task

(e.g., Lavie, Hirst, De Fockert, & Viding, 2004), but result in decreased conflict effects in the Simon task (e.g., Wühr & Biebl, 2011). Further studies are needed to explain this discrepancy (for discussion, see Wühr & Biebl, 2011).

Another possibility, which is not mutually exclusive, is related to the idea of a “fan effect” suggested by Metzker and Dreisbach (2009). These authors suggested that irrelevant location activation spreads to all stimulus codes whose responses are associated with presented location, and that this spreading activation is diluted when it spreads to more stimulus codes (cf. Anderson, 1974; Anderson & Reder, 1999), thereby weakening its influence on response processes. Metzker and Dreisbach (2009) presented evidence for such a fan effect in the Simon task from a series of studies in which the same number of stimuli were used in all conditions but the instructed task-set differed between blocks—and with that the number of S-R rules that participants had to remember. For example, with six stimuli, participants were either given instructions mapping them individually to two responses (many-to-one instructions) or they were given a rule mapping two sets of three stimuli to the two responses (one-to-one instructions). The results showed that the mean Simon effect was reduced with the many-to-one compared to the one-to-one instruction. Decreasing delta plots were also observed, but these were presented based on RT bin number rather than actual RT values, so it is not clear whether the Simon effect was reduced with many-to-one instructions when controlling for RT. No doubt, further explanations are also possible, and further research will be useful to explore the reasons for the reduced Simon effect when controlling for RT. In any case, the downward-shifted delta plots observed in this experiment demonstrate how these analyses can go beyond mean RT to establish additional influences on the Simon effect beyond the influence of fading activation.

4 Experiment 3

Increasing the number of stimulus alternatives to prolonged decision processes appears to decrease the Simon effect by more than just giving irrelevant activation extra time to fade out. As noted earlier, one possible explanation of this somewhat surprising result is that the strength of irrelevant location-based activation may have been reduced in the four-stimulus blocks compared to the two-stimulus blocks. For example, the increased working memory load with more stimulus alternatives could have weakened irrelevant location-based processing if this processing also requires working memory capacity. The purpose of Experiment 3 was to investigate the generality of this surprising decision manipulation result by investigating the delta plot effects of a within-block decision stage manipulation—one that seems less likely to influence the strength of irrelevant activation.

Specifically, in this experiment we manipulated decision

processes within blocks in which the number of stimulus alternatives was kept constant. Participants were required to respond to a single, lateralized letter (out of a set of four possible letters), but the letter to response mapping was manipulated. For two of the four stimulus letters the S-R mapping was fixed over the whole experiment, whereas for the other two stimulus letters the S-R mapping reversed for each new block. Thus, these two stimuli conditions allow examination of the effects of the strength of the connection of S-R associations (i.e., higher with fixed compared to variable S-R mapping) on the Simon effect with a decision stage manipulation, which rules out the potential processing differences between blocks (e.g., working memory load) that may have operated in Experiment 2.

4.0.1 Participants. A fresh sample of 63 students (53 female) was recruited from the same pool to participate in the experiment. They ranged in age from 18 to 27 years ($M = 19.78$ years) and 54 were right-handed. One additional participant was also tested but excluded due to accuracy below 85%.

4.1 Apparatus, stimuli, and procedure

The apparatus, stimuli, and procedure were the same as in Experiment 1 except as otherwise described. Stimulus presentation and recording of responses were controlled by E-Prime 2. Each stimulus display consisted of a white letter that subtended approximately 1.4° and that appeared approximately 5.3° to the left or right of the fixation point (measured to the center of the letter). For each participant, four consonants (excluding the letter “Z”) were randomly selected for use as stimulus letters, with two each randomly assigned to left and right hand responses. Critically, for two of the letters the S-R mapping was held constant throughout the experiment, whereas for the other two letters the S-R mapping alternated across blocks (letter-to-mapping condition were randomly assigned). An instructional screen at the beginning of each block indicated the four correct S-R mappings for the block. Participants first performed two practice blocks before they were tested in 10 experimental blocks with 64 randomly ordered trials per block (640 experimental trials in total). Each block consisted of 8 presentations of each of the eight possible stimulus displays (i.e., 2 possible locations x 4 letters). At the beginning of the experiment, participants were informed that the response rules would change every block and that they should pay close attention to the instructional screen at the beginning of each block.

4.2 Results

The first two blocks were considered practice and excluded from all analyses. For RT analyses, we excluded error trials (5.68%) and trials with RTs less than 200 ms as anticipations (0.03%).

4.2.1 Reaction times (RTs). Figure 3C shows the mean RTs as a function of S-R mapping condition (fixed, variable) and congruency (congruent, incongruent). A repeated-measures ANOVA with the within-subject factors of S-R mapping and congruency revealed significant main effects of mapping, $F(1, 62) = 64.15$, $p < .001$, $\eta_p^2 = .51$, and congruency, $F(1, 62) = 21.97$, $p < .001$, $\eta_p^2 = .26$. As can be seen from Figure 3C, the mean RT was shorter for stimuli with fixed than with variable S-R mapping (607 ms versus 647 ms), and the mean RT was also shorter in congruent than in incongruent trials (619 ms versus 634 ms). More importantly, there was also a significant interaction reflecting a larger Simon effect with the fixed than with the variable S-R mapping (20 ms versus 9 ms), $F(1, 62) = 5.77$, $p = .006$, $\eta_p^2 = .12$.

As can be seen in Figure 3G, the resulting delta plots were decreasing for both fixed- and varied-mapping stimuli, with similar time-courses. Interestingly, however, the deltas at each value of a given RT were higher for the fixed compared to the variable S-R mapping condition. An ANOVA including the factor of bin in addition to the factors of S-R mapping and congruency revealed that all main effects and two-way interactions were significant (all $ps < .006$), but the three-way interaction was not significant ($p = .845$). The mean slopes were quite similar for the fixed and variable conditions (i.e., -0.08 and -0.06 , respectively), and a paired t -test indicated no significant difference between conditions $t(62) = 0.64$, $p = .527$, $\eta_p^2 = .01$. Equating RT, the predicted Simon effect was larger for the fixed condition (18 ms) than for the variable condition (11 ms), and a paired t -test indicated that the difference between these values was significant, $t(62) = 2.10$, $p = .040$, $\eta_p^2 = .07$.

4.2.2 Percentage errors (PEs). Figure 4C shows the mean percentage errors (PEs) in the corresponding conditions. An ANOVA parallel to the one conducted on mean RT also yielded significant main effects of the mapping condition, $F(1, 62) = 40.44$, $p < .001$, $\eta_p^2 = .40$, and congruency, $F(1, 62) = 17.59$, $p < .001$, $\eta_p^2 = .21$. There were fewer errors for trials with fixed compared to variable S-R mappings (4.2% versus 7.2%) and for congruent than incongruent trials (5.0% versus 7.2%). The interaction between these factors was not significant ($p = .807$), and the Simon effect in the fixed condition (1.4%) was numerically almost identical to the one for the variable condition (1.5%). As can be seen in Figure 4G, the Simon effects on PE were mainly restricted to the fastest responses for stimuli with both fixed and variable response assignments.

4.3 Discussion

Consistent with the delta plots found in the earlier experiments, decreasing delta plots with similar shapes were found for both the fixed and variable S-R mapping conditions. This is again consistent with the idea that the reduced mean Si-

mon effect for the variable mapping condition is partially the result of slower responses being less affected by fading irrelevant activation. In addition, however, the delta plot for the variable mapping condition was shifted downward relative to the fixed mapping condition, which suggests that this manipulation of the strength of S-R associations had an additional influence on the Simon effect that is not readily explainable by fading activation. Specifically, equating for RT, the Simon effect was reduced when prolonging decision processes in this experiment—as it was in Experiment 2.

The delta plot pattern of Experiment 3—like that of Experiment 2—goes in the opposite direction from what would seem to be predicted if irrelevant and relevant activation were superimposed during the decision stage. Specifically, decision-level task-relevant activation should be reduced by weakening S-R associations. According to activation-superimposition models, this should increase the Simon effect because irrelevant activation would be relatively stronger—at least when controlling for the fading of irrelevant activation. As was mentioned in the discussion of Experiment 2, one possible account of this delta plot pattern is that the S-R mapping manipulation somehow affected the magnitude of irrelevant activation. Yet, it is difficult to see why the strength of location-based activation would vary from trial to trial within a block depending on which stimulus was presented. Clearly, further investigation is needed to determine exactly why the Simon effect is weaker for variable-mapping stimuli even when controlling for RT, but the most crucial point is that the fading activation account would need some elaboration to explain why increasing decision difficulty seems to reduce the Simon effect.

5 Experiment 4

To further validate that the idea that comparing delta plots is useful in identifying sources of the Simon effect, in this experiment we aimed to manipulate late motor execution processes that seem likely to take place after the processing level where irrelevant and relevant activation superimpose. Specifically, in different blocks of trials participants were instructed to respond to the color of the squares with either their hands or their feet. Previous studies have found that hand responses are considerably faster than foot responses (e.g., Miller, 2012, 2016). If the slowing associated with foot responses arises after irrelevant activation has its effect, then the delta plots for hand and foot responses would have similar shapes and would just be shifted rightward, as shown in Figure 2B3. Thus, this processing speed manipulation is expected to produce a delta plot pattern completely different from that seen in the previous experiments. If the slowing associated with foot responses arises after irrelevant activation has its effect, then the delta plots for hand and foot responses would have similar shapes and would just be shifted rightward, as shown in Figure 2B3. Thus, this processing speed

manipulation is expected to produce a delta plot pattern completely different from that seen in the previous experiments.

Consistent with the idea that activation fades before response execution, Miller (2016) found that the mean Simon effects with vertical and horizontal spatial arrangements were similar between hand and foot responses. This earlier study was quite different, however, because it used a four-choice task with different stimuli mapped to each effector and included joint effects of both horizontal and vertical compatibility. Thus, it remains to be seen whether the same pattern can be also observed in a less complex Simon task varying only horizontal compatibility, as in the present experiments.

5.1 Method

5.1.1 Participants. A fresh sample of 26 participants⁷ (22 female) from the same pool participated in the experiment. The range of age was from 18 to 27 years ($M = 20.1$). Mean handedness score was $M = 54.0$ and 22 participants were right-handed.

5.1.2 Apparatus, stimuli, and procedure. The apparatus, stimuli, procedure, and instructions were the same as in Experiment 1 except as otherwise described. An IBM-PC compatible computer running the MS-DOS operating system was used for stimulus presentation and recording of responses under the control of a special-purpose Turbo Pascal program. Stimuli were filled colored squares (1.9° in length) which were presented with a viewing angle of approximately 4.3° to the left or right of the center of the screen at the offset of the fixation cross. Hand responses were again made by key presses (0.6 N) with the left and right index fingers. Foot responses were made by pressing one of two foot pedals (46 N) resting under the balls of the left and right (shoeless) feet. Two colors were used, with one each assigned to the left and right response effector (i.e., hand vs. foot). Response effector alternated blockwise, with the order of effectors counterbalanced across participants. After two practice blocks, participants were tested in 10 experimental blocks consisted of 60 randomly ordered trials (600 trials in total), with 15 presentations of each of the four possible stimulus displays (i.e., 2 possible locations \times 2 colors).

5.2 Results

We followed the same procedure to analyze the data as in the previous experiments. The first two practice blocks were excluded from all analyses. For RT analyses, we excluded 4.5% error trials and 0.11% trials with RTs less than 200 ms as anticipations.

5.2.1 Reaction times (RTs). Figure 3D shows the mean RTs for hand and foot responses plotted separately for congruent and incongruent trials. A repeated-measures ANOVA with the within-subject factors of response effector (hand, foot) and congruency (congruent, incongruent) was

conducted for the RT data. This ANOVA revealed a significant main effect of effector, $F(1, 25) = 126.96$, $p < .001$, $\eta_p^2 = .84$, and a significant main effect of congruency, $F(1, 25) = 56.17$, $p < .001$, $\eta_p^2 = .69$. As expected, hand responses were, on average, faster than foot responses (449 ms versus 559 ms) and responses were also faster for congruent than incongruent trials (521 ms versus 486 ms). Interestingly, the size of the Simon effect was modulated by which response effector was used, $F(1, 25) = 14.06$, $p < .001$, $\eta_p^2 = .36$. Specifically, as can be seen in Figure 3D, the Simon effect was larger with foot than hand responses (44 ms versus 25 ms).

The decreasing delta plots in Figure 3H suggest that the Simon effect follows similar decreasing time-courses for foot and hand responses. To check our assumption based on the visual inspection of Figure 3H, we conducted an ANOVA with the factors of congruency, response effector, and bin. All main effects and two-way interactions were significant (all $ps \leq .001$), but the three-way interaction was not significant ($p = .856$). In addition, we again computed the best-fitting straight lines through the ten data points (i.e., Simon effect values at each RT bin) of the two delta plots separately for each participant. A paired t -test indicated that the mean slope of the line fitted to the hand delta plot (-0.12) was similar to the mean slope of the line fitted to the foot delta plot ($-.10$), $p = .630$. Interestingly, Figure 3H also suggests that the Simon effect for foot responses was on average larger for hand responses even at the same RT (i.e., the foot delta plot is always above the hand delta plot). To check this, we again computed the individual Simon effects as predicted by the two fitted lines at the same individual-participant overall mean RT. With RT equated in this fashion, the average Simon effect predicted for foot responses was significantly larger than the one predicted for hand responses (50 ms versus 18 ms), $t(25) = 5.60$, $p < .001$, $\eta_p^2 = .56$.

5.2.2 Percentage errors (PEs). Mean PEs are shown in Figure 4D. An ANOVA revealed that mean PEs were significantly lower for congruent than for incongruent trials (3.2% versus 5.6%), $F(1, 25) = 15.41$, $p = .001$, $\eta_p^2 = .38$. Furthermore, in contrast to the results for RTs, errors were more frequent for hand than for foot responses (6.2% versus 2.7%) $F(1, 25) = 43.62$, $p < .001$, $\eta_p^2 = .64$, and the Simon effect was larger for hand responses (4.0%) than for foot responses (1.3%), $F(1, 25) = 12.87$, $p = .001$, $\eta_p^2 = .34$. The delta plot for the error rates (see Figure 4H) shows that—as in Experiments 1 and 2—the Simon effect in PE was mainly present for the fastest responses.

⁷We reduced the sample size in Experiment 4 because we expected a considerably stronger main effect of our experimental manipulation than in Experiments 1–3 (e.g., Miller, 2012, 2016).

5.3 Discussion

The main findings of this experiment are that the effector manipulation resulted in a delta plot pattern which shared characteristics with the ones observed in the previous experiments except for one crucial difference. More precisely, the delta plots were again decreasing with similar time-courses (i.e., slopes) for both hand and foot responses. However, the delta plots were clearly non-overlapping—that is, the delta plot of the (slower) foot condition was primarily shifted rightward along the RT axis and as a result, at the level of mean RT, the Simon effect did not decrease as RT increased. This delta plot pattern is in contrast to the overlapping delta plot pattern observed with the discriminability manipulation of Experiment 1 and it is also in contrast to the one found in Experiment 2 and 3 with the number of stimulus alternatives and stimulus-response mapping manipulations (i.e., slow delta plot below fast delta plot). In fact, the empirical delta plots of Experiment 4 closely resembled the delta plots (see Figure 2B) predicted when manipulating late processing stages after the process when activation superimpose. Thus, these findings suggest a locus of the Simon effect before executing responses and thereby demonstrate the usefulness of this method for localizing the Simon effect.

Nevertheless it was somewhat surprising that the Simon effect on mean RTs was actually larger for foot responses than hand responses—that is, the delta plot of the foot condition was not only shifted rightward along the RT axis but also upward along the delta axis. This finding is not predicted by standard fading activation accounts, according to which the Simon effect in a slower condition should be less than or equal to the effect in a faster condition. It is not entirely clear how to account for a larger Simon effect with foot than hand responses, and further research will be needed to pin down the precise explanation for this difference. Since choice responses are more commonly made with the hands than with the feet in everyday life, however, it does not seem surprising that the foot control system would be more vulnerable to the influence of irrelevant activation.

Unfortunately, the higher error rates in the hand compared to the foot condition and the interaction with a larger mean error Simon effect in the hand compared to the foot condition may warrant some caution when interpreting the RT results, since this observed speed-accuracy trade-off (SAT) suggests that the effector manipulation influenced something else in addition to residual motor times. For example, participants might have emphasized accuracy more strongly than speed in the foot condition compared to the hand condition, and the larger RT Simon effect for foot compared to hand responses might be partly a by-product of this change in speed-accuracy emphasis. Contrary to this idea, however, the delta plots of error rates displayed in Figure 4H show that this observed SAT arises mainly due to the fastest responses in the hand condition meaning that the (RT) delta plot comparison

for bins 2–10 is little affected by the SAT. As noted earlier (see footnote 5), excluding the first bin from the analysis produced virtually identical results, and the similarity of these results reinforces the RT finding of an increased Simon effect for foot compared to hand responses. Thus, our overall conclusion is that the Simon effect on RT is truly larger for foot responses than hand responses, even correcting for the observed SAT.

6 General Discussion

In the present study, we selectively manipulated the duration of task-relevant processing at different stages (perceptual, decision, and motor execution) in a standard visual Simon task, and we applied delta plot analyses to disentangle effects that could be explained by the fading time-course of irrelevant activation from other effects produced by these manipulations. The perceptual stage manipulation of Experiment 1 (i.e., stimulus discriminability) and the decision stage manipulations of Experiments 2 and 3 (i.e., number of stimulus alternatives and fixed/variable S-R mapping) revealed that the mean Simon effect was reduced for the slow compared to fast condition. Importantly, the corresponding delta plot pattern of Experiment 1 was fully in line with the prediction of the fading activation account (i.e., overlapping decreasing delta plots with similar shape), but Experiments 2 and 3 showed that prolonging decision processes decreases the Simon effect by more than can be explained by fading irrelevant activation (i.e., the delta plot of the slow condition was shifted down relative to the delta plot of the fast condition). Further support for the applicability of delta plot analyses comes from the motor stage manipulation of Experiment 4 (i.e., response effector). Here, the delta plot of the slow foot responses was shifted rightward relative to that of the faster hand responses, consistent with the pattern predicted when fading irrelevant activation is superimposed with relevant activation at a stage prior to the one affected by the manipulation. In contrast to an account based purely on fading activation, however, the mean Simon effect was increased for the slower foot responses compared to the faster hand responses, as was reflected in an additional upward shift of the delta plot in the foot condition. Overall, these results demonstrate that delta plot analyses provide a useful tool for identifying the contributions of different cognitive stages in modulating the Simon effect, especially because these analyses provide insights that are not readily available from analyses of mean RTs.

6.1 Advantages of going beyond mean RT when investigating Simon effects

In general, many researchers have emphasized that distributional analyses can be very useful in clarifying the underlying causes of patterns observed in mean RTs (e.g., Balota & Abrams, 1995; Balota, Yap, Cortese, & Watson, 2008;

Heathcote, Popiel, & Mewhort, 1991; Ratcliff & Murdock, 1976; Rousselet, Pernet, & Wilcox, 2017; Van Zandt, 2002). The advantages of distributional analyses seem particularly important in the Simon task because of the idea that irrelevant location-based activation dissipates after stimulus onset. As reviewed in the introduction, for example, experimental conditions varying in processing speed may produce different Simon effects simply because one condition allows more time for activation to fade. Looking only at mean RTs, however, it is difficult to investigate which changes of the Simon effect can be explained entirely by this fading. As illustrated in the present experiments, delta plots address such questions rather directly.

To begin with, the results suggest that the time-course of irrelevant activation was not greatly affected by the current experimental manipulations, resulting in similar slopes of the delta plots in all cases. More importantly, the overlapping delta plots in Experiment 1 are fully consistent with the stage conception depicted in Figure 2 in terms of a fading activation account. Thus, these findings also suggest a locus of the Simon effect after an early processing stage. As is also predicted by fading activation, the clear rightward shift of the delta plot associated with slower motor execution processes in Experiment 4 suggests that irrelevant activation has most of its effects on the task-relevant processing stream before the late motor execution stage. This demonstrates not only the robustness of delta plots in measuring the effect of irrelevant activation but also that the method is helpful in delimiting the process at which irrelevant activation is superimposed with relevant activation. Thus, the present study illustrates another technique that may be helpful in localizing the effects of experimental manipulations (i.e., before versus after the Simon effect), thus complementing other techniques for effect localization such as the additive factor method (e.g., Scerrati et al., 2017; Sternberg, 1969a), the locus-of-slack approach within the psychological-refractory period paradigm (e.g., Janczyk, Renas, & Durst, 2018; Klein, Kavyani, Farsi, & Lawrence, 2018; Pashler & Johnston, 1989; Piai, Roelofs, & Schriefers, 2014; Schnur & Martin, 2012), and a variety of psychophysiological and neuroimaging techniques (e.g., Anderson, Zhang, Borst, & Walsh, 2016; Coles, 1989; King & Dehaene, 2014; Meyer, Osman, Irwin, & Yantis, 1988; Ratcliff, Philiastides, & Sajda, 2009; Sternberg, 2004; Sudre et al., 2012).

Importantly, there are also three findings that are difficult to reconcile with an account in which manipulations of task-relevant processing speed influence the Simon effect result solely because of fading activation. First, in addition to the rightward shift there was also an upward shift of the delta plot for foot responses in Experiment 4. One way to account for the larger effect of location-based activation on foot than hand responses is to assume that there are some differences in earlier decision processes between the

blocks using these two response effectors, and—consistent with that idea—there is evidence that the preparation of hand and foot responses involves somewhat distinct brain areas (e.g., Jentzsch & Leuthold, 2002; Miller, 2016). For example, decision-processes involved in selecting foot responses may operate less efficiently than the ones involved in selecting hand responses, and as a result the former processes might be more strongly affected by a given absolute amount of irrelevant activation (for a similar suggestion, see, e.g., Miller, 2016).

Second and third, shift of the delta plots were also revealed by the decision stage manipulations in Experiments 2 and 3. In Experiment 2, delta plot analyses indicated that the decreased Simon effect for four compared to two stimulus alternatives was not simply due to increased fading of irrelevant activation, because the Simon effect was smaller for four alternatives even when controlling for RT. Similarly, in Experiment 3 the Simon effect was reduced for letters with variable rather than fixed S-R mappings, and this reduction was larger than could be explained purely by fading activation. One way to account for these decreases is to postulate that increasing the number of stimulus alternatives or weakening S-R mappings somehow decreases the magnitude of irrelevant activation. As mentioned in the discussion of Experiment 2, for example, irrelevant activation may be weaker when there are more stimuli either because it must spread to more S-R codes with larger stimulus sets (i.e., “fan effect”; Metzker & Dreisbach, 2009) or because the location-based processing responsible for that activation must compete with the relevant stimulus alternatives for limited working memory capacity (Wühr & Biebl, 2011). It seems much harder, however, to explain why irrelevant activation would be weaker for stimuli in the varied mapping condition of Experiment 3 than in the fixed mapping condition, especially since the stimuli in these two conditions were randomly intermixed within each block of trials.

In any case, the idea that the number of stimulus alternatives manipulation in Experiment 2 and the S-R mapping conditions of Experiment 3 primarily influence the size of task-irrelevant location-based activation seems somewhat contradictory to suggestions that relevant and irrelevant activation superimpose at the decision stage (e.g., Lu & Proctor, 1994; Scerrati et al., 2017; Treccani et al., 2009). The RT increases with a) four stimuli relative to two stimuli and b) variable relative to fixed S-R mapping are presumably at least partially the result of weaker S-R associations in the former conditions (Sternberg, 1969b). According to activation-summation models, then, the relative contribution of task-irrelevant activation would therefore be stronger a) with four stimuli than with two, and b) with variable S-R mapping than with fixed, and that would tend to increase the Simon effect with four stimuli and variable mapping—at least when controlling for RT. The observed delta plot pattern actually

goes in the opposite direction from this prediction. Interestingly, as mentioned in the introduction, another manipulation of the strength of task-relevant activation (i.e., redundancy gain; Miller & Reynolds, 2003) also produced no evidence that the Simon effect increased when task-relevant activation was weaker, and this finding was interpreted as evidence that activations are integrated beyond the decision stage (Mittelstädt & Miller, 2018). Similarly, the findings of Experiments 2 and 3 of the present study seem consistent with superimposition of relevant and irrelevant activations at a post-decisional stage. A motor locus of the Simon effect also fits with evidence that S-R compatibility manipulations affect motor as well as decision processes (e.g., Coles et al., 1992; Kato, Kizuka, & Endo, 2004). Note, however, that the clear rightward shift of the delta plot in Experiment 4 suggests that activations are superimposed before the late motor execution processes that differ for hand and foot responses. As mentioned earlier, the larger Simon effect for foot responses could also indicate differential response activation within early motor processes preceding final response execution (e.g., Burtle, Vidal, Tandonnet, & Hasbroucq, 2004). Viewed from the stage conception applied in this study, one might argue that a decision stage is followed by separate response activation and execution stages (e.g., Buetti & Kerzel, 2009; De Jong, Wierda, Mulder, & Mulder, 1988; Ivanoff, 2003; Shiu & Kornblum, 1999), with relevant and irrelevant activations being superimposed in the earlier response activation stage.

6.2 Sequential modulations

So far, effects of experimental manipulations going beyond a fading activation account were exclusively reflected in an offset of the corresponding delta plots (i.e., upward, downward, or rightward shift) leaving the slope of delta plots unaffected. It is well known that the size of the Simon effect decreases following incongruent trials, as compared with following congruent trials (e.g., Finkbeiner & Heathcote, 2015; Hazeltine, Akcay, & Mordkoff, 2011; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002). To account for this decrease, it has been suggested that automatic activation is more strongly suppressed when location information was more recently harmful (e.g., Cona, Treccani, & Umiltà, 2016; Stürmer et al., 2002; Treccani et al., 2018; Wühr & Ansorge, 2005) and that more negative slopes imply stronger inhibitory processes (e.g., Ridderinkhof, 2002b). To examine whether previous trial congruency produced different slopes based on our experimental manipulations, we reanalyzed all results while considering the previous trial's congruency (see Appendix A). However, the condition-specific delta plots after both congruent and incongruent trials followed a similar decreasing time-course, and the effect of previous trial congruency was exclusively reflected in a shift of delta plots (i.e., non-overlapping delta plots). Because the slopes were

generally not modulated by previous trial congruency, this suggests that the fading of irrelevant activation and the processes affected by sequential modulation are independent, as has been previously suggested (e.g., Finkbeiner & Heathcote, 2015; Hazeltine et al., 2011).

6.3 Implications for quantitative models

The decreasing delta plots observed in Simon tasks present a challenge for many formal perceptual decision-making models because these predict that the variance of RT should increase with the mean RT (Luce, 1986), but a number of quantitative models that can account for such decreases have been suggested. Although we have considered the current results in terms of rather general predictions of fading activation models (e.g., Hommel, 1994b; Ridderinkhof, 2002a), it is also worth considering whether specific quantitative models can account for all of the changes in delta plots observed in the present studies. In this section, we consider the predictions of the recently introduced diffusion model for conflict tasks (DMC, Ulrich et al., 2015), which nicely captures decreasing delta plots by assuming that task-relevant activation is superimposed with fading (time-varying) location-based activation. We also consider the predictions of five alternative models that explain decreasing delta plots in other ways. Specifically, Schwarz and Miller (2012) described how such delta plots could be produced by exhaustive models, stage models, mixture models, cascade models, and parallel channel models. For all of these models, it is worth considering whether and how they can accommodate the observed effects on delta plots of the present stage-specific manipulations. As far as we can see, it seems that all models could predict a rightward shift of the delta plot like that shown in the comparison of conditions 1 versus 3 of the figure. This shift is always predicted if the experimental manipulation influences the duration of a late motor stage that takes place after the process responsible for the decreasing delta plot (e.g., condition 1 = hand responses, condition 3 = foot responses)—at least if this manipulation does not greatly increase the motor variance. It is not at all clear, however, whether all models would be capable of producing the overlapping delta plot pattern shown in the comparison of conditions 1 versus 2 of that figure (and also observed in Experiment 1), nor whether they could easily accommodate the downward shifts observed in Experiments 2 and 3 or the upward shift observed in Experiment 4.

In the following, we briefly describe the results of our explorations of the delta plot predictions of the DMC model and the models described by Schwarz and Miller (2012) with respect to the various delta plot patterns observed in the present studies. Using the precise formulations of the models suggested by Ulrich et al. (2015) and by Schwarz and Miller (2012), we explored how effects on different parameter values changed the predicted delta plots, attempting to see

whether each model could simply produce the observed delta plot changes. Appendix B gives details of the models and parameter values, and Table 1 summarizes our results by giving sample parameter values that could account qualitatively for each of the different observed changes in delta plots. Figure 5 illustrates the specific delta plot patterns corresponding to the parameter values of Table 1. No doubt, further elaborations of the models could produce a wider range of delta plots, but this initial examination at least gives some sense of how easily each type of model could produce the observed patterns.⁸

6.3.1 Diffusion model for conflict tasks. The recently introduced DMC model (Ulrich et al., 2015) explains decreasing delta plots by assuming that task-relevant activation is superimposed with fading (i.e., time-varying) location-based activation⁹. Like all models, as noted above, the DMC model can easily account for the rightward shift of the foot versus hand delta plot in Experiment 4 with an increase in the non-decisional (residual) time μ_R .

It is usually assumed that perceptual manipulations change the rate of accumulating evidence toward a decision boundary (e.g., Servant et al., 2014), so we varied these rates in trying to account for the overlapping delta plots observed in Experiment 1. This was not successful, however. If a perceptual manipulation reduces the relevant activation driving accumulation toward a decision boundary (i.e., reduced μ_c), the Simon effect at a given delta plot RT would be actually be larger in the slower condition (for further details, see also Mittelstädt & Miller, 2018). Thus, the overlapping delta plot pattern observed in Experiment 1 cannot be explained within this model simply by reducing the strength of relevant activation in the low-discriminability condition. However, as was mentioned in the discussion of Experiment 1, it seems conceivable that decreasing the discriminability of the task-relevant stimulus dimension might decrease the strength of both relevant and irrelevant activation. Consistent with this idea, decreasing the drift rate μ_c of task-relevant processes and the magnitude of task-irrelevant activation (i.e., by changing the peak of the amplitude A) can produce an overlapping delta plot pattern found in Experiment 1. Furthermore, an overlapping delta plot pattern can be also produced by a suitable combination of a decreased drift rate μ_c and an increased decision boundary b .

The finding of a weaker Simon effect in the slower condition (i.e., Experiments 2 and 3) also contradicts the pattern that would be predicted by DMC if it is assumed that increasing the number of stimulus alternatives or decreasing the strength of S-R associations decreases the rate of evidence accumulation. Specifically, decreasing the drift rate μ_c of task relevant activation would actually shift the delta plot of the slow condition upward—that is, in exactly the opposite direction of the downward shift observed in these experiments. However, as mentioned earlier, it is possible

that irrelevant activation is weaker in the slower conditions, and changing the irrelevant activation strength parameter of the model does allow it to produce a smaller Simon effect at the same RT. A downward shift of the slow compared to the fast delta plot can be also produced by increasing the evidence needed to select a response—that is, by increasing the decision boundary b . Thus, as far as we can see, the DMC model is in principle flexible enough to capture the delta plot patterns obtained in this study, but it would require some specific—yet plausible—assumptions about changes in the strength of irrelevant activation. For example, the manipulations of Experiments 1, 2, and 3 would seemingly have to influence not only task-relevant processes but also the magnitude of irrelevant activation.

Interestingly, the DMC model is also able to produce negative-going delta plots with negative deltas (i.e., reversed Simon effects in late RT bins) by varying parameters of the function describing the time-course of irrelevant activation. As discussed by Ulrich et al. (2015), the irrelevant activation function could in principle slightly undershoot to negative values before swinging back to zero to produce reversed Simon effects. Such negative-going decreasing delta plots have been observed previously (e.g., Ridderinkhof, 2002b) and were also found in the present experiments. The sequential analyses even revealed decreasing delta plots almost exclusively in the negative area (i.e., reversed Simon effects for majority of bins) for which DMC can also account by reversing the direction of the irrelevant activation's effect (e.g., by using $A = -20$ and $\tau = 180$). Although the other models do not have an analogous parameter that specifies the direction of irrelevant activation's effect, it is still possible that other parameter changes could produce also negative decreasing delta plots with these models (see Cascade model section).

6.3.2 Exhaustive models. These models can account for decreasing delta plots by assuming that response execution cannot begin in incongruent trials until both activation of the correct response and inhibition of the incorrect response

⁸For each of these five models, we also explored whether the displayed delta plot pattern could be reproduced to a good approximation when the parameter values displayed in Table 1 were increased or decreased by 10% or 20%. Most delta plot patterns remained qualitatively very similar under these changes in parameters. The overlapping delta plot pattern was not reproduced for the exhaustive and parallel models, however, suggesting that these patterns are particularly sensitive to the exact parameter values.

⁹The crucial idea of the model is that the drift rate of a single Wiener diffusion process toward the correct boundary b is determined at each time point by the superimposed inputs from both a) a temporally constant input of task-relevant processes with drift rate μ_c , and b) a time-varying input of task-irrelevant processes with drift rate $\mu_i(t)$ (for further details, see Ulrich et al., 2015). To examine the predictions of this model we used the MATLAB code provided by Ulrich et al. (2015) and adopted the parameters from their Table 1 and Figure 3.

Table 1

Illustrative parameter values producing delta plot patterns qualitatively similar to those observed in Experiments (Exp) 1–4. (see note next page)

Model & parameter	Observed Delta Plot Pattern			
	Baseline Condition	Overlapping Exp 1	Down Exp 2 & 3	Right/Up Exp 4
<i>DMC</i>				
drift rate μ_c of controlled process	0.50	0.30	0.50	0.50
amplitude A of automatic process	20	17	20	25
decision boundary b	75	75	95	75
residual time μ_R	300	300	300	400
<i>Exhaustive</i>				
ex-Gaussian μ	220	260	240	240
μ of B_i	1.135	1.2	1.45	1.05
<i>Mixture</i>				
p_1	0.40	0.22	0.40	0.40
p_2	0.05	0.04	0.10	0.05
drift rate μ of faster process	0.35	0.30	0.35	0.30
drift rate μ of slower process	0.25	0.20	0.25	0.20
<i>Cascade</i>				
k	20	25	25	25
α_2 congruent	0.05	0.05	0.0425	0.04
α_2 incongruent	0.005	0.005	0.006	0.004
<i>Parallel</i>				
Criterion, k	15	22	12	30
N channels congruent, n_c	20	26	14	39
N channels incongruent, n_i	17	23	13	32

Note. The same parameters were used to produce predicted delta plots in the faster condition (baseline) for all experiments. Parameters were changed in the slower condition as shown to produce delta plot patterns similar to those observed in the different experiments. Parameters of the DMC model have the meanings defined by Ulrich et al. (2015), and its predicted delta plots were computed using simulations of 1,000,000 trials per condition with a stepsize of $t = 1$ ms. Parameters of the other models have the meanings defined by Schwarz and Miller (2012), and the predicted delta plots of these models were computed numerically as described in that article.

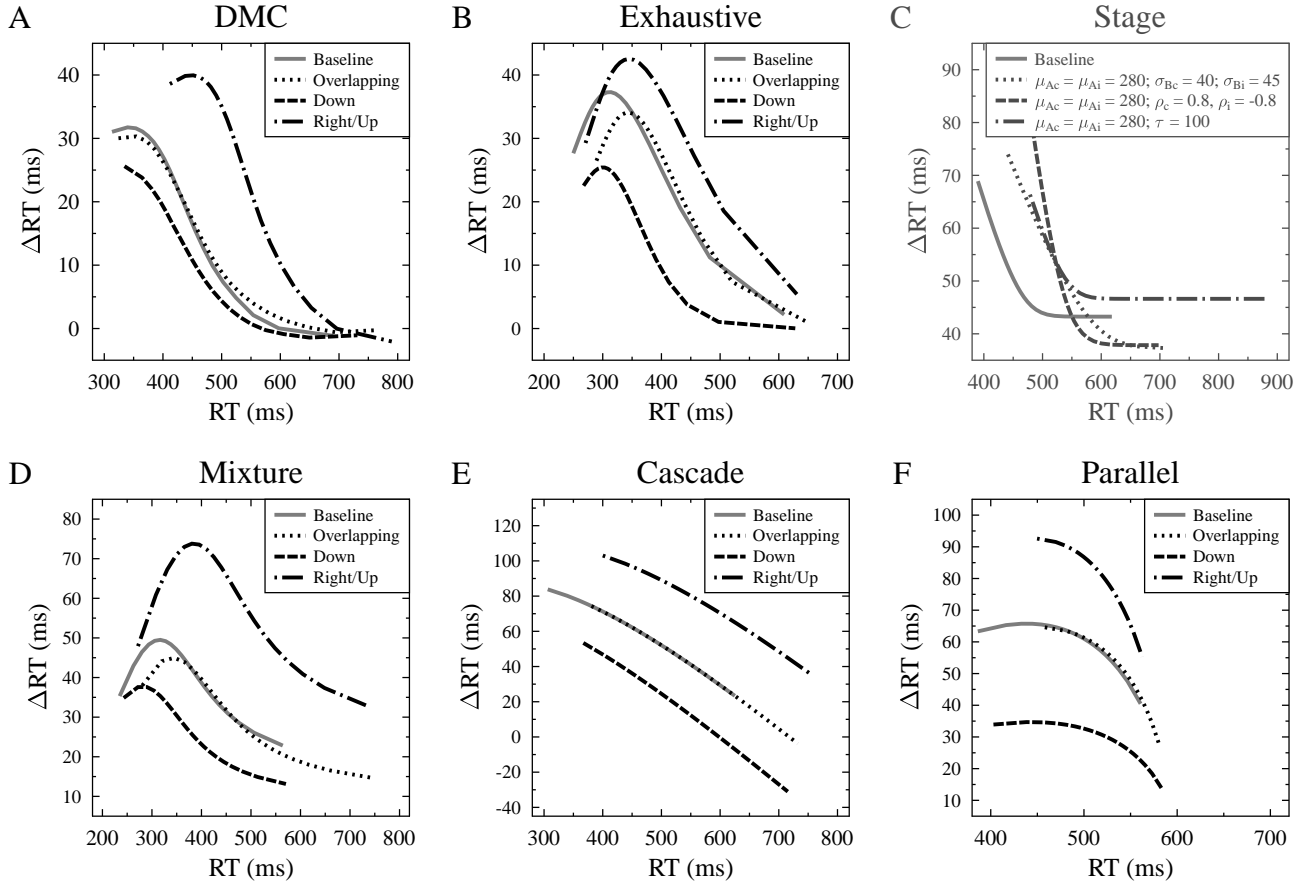
are completed, with these two processes proceeding in parallel (Schwarz & Miller, 2012). The temporal cost of waiting for the inhibition process to finish gradually decreases as the time needed for correct response activation increases, so these models predict larger Simon effects for faster compared to slower responses.

As is summarized in Table 1, this model can account qualitatively for all of the effects on delta plots observed in the present experiments with suitable changes in two parameters in the model of Schwarz and Miller (2012): the mean residual time (i.e., the μ parameter of the ex-Gaussian $A + C$ distribution), and the speed of response inhibition (i.e., the μ parameter of the B_i distribution). Increases in the residual time tend to produce a rightward shift of the delta plot. Separately, slowing and speeding response inhibition tend to increase and decrease, respectively, the delta plot at a fixed

RT. Thus, with suitable combinations of changes in these two parameters, it is possible to produce overlapping delta plots like that found in Experiment 1, downward shifted delta plots like those observed in Experiments 2 and 3, and rightward and upward shifted delta plots like that observed in Experiment 4. In short, exhaustive models are compatible with all three patterns of delta plot effects seen in the present experiments, although it is not entirely clear why the speed of response inhibition would be modulated by all of the present experimental manipulations.

6.3.3 Correlated stage-time models. According to these models, the total RT is the sum of times used by at least two processing stages, and these models are also able to produce decreasing delta plots without the premise of fading irrelevant activation (Schwarz & Miller, 2012). Specifically, decreasing delta plots can arise when the correlation between

Figure 5. Illustrative delta plot patterns produced by parameter variations within the six different models under consideration. The parameters of the DMC, exhaustive, mixture, cascade, and parallel models that produce approximately the observed delta plot patterns are displayed in Table 1. The baseline parameters of the correlated stage-time model were $\rho_c = 0.5$, $\rho_i = -0.5$, $\sigma_{Bc} = 20$, $\sigma_{Bi} = 25$, $\mu_{Ac} = \mu_{Ai} = 200$, and $\tau = 50$, with changes in these parameter values for the other delta plots as indicated in the legend of that panel.



the duration of two stages within the faster condition (i.e., congruent trials) is larger than the corresponding correlation within the slower condition (i.e., incongruent trials). With this model, it was again simple to produce a rightward shift of the delta plot like that found in Experiment 4 by increasing the residual time (e.g., the μ_A parameter in the version of the model described by Schwarz & Miller, 2012). It was not easily possible, however, to produce the overlapping delta plot pattern of Experiment 1, the downward shifted delta plots of Experiments 2 and 3, or the upward shift of Experiment 4. As is illustrated in Figure 5C, modifying other model parameters such as stage time variances or correlations always seemed to alter the slopes of the model's delta plots, in contrast to the rather stable delta plot slopes observed in all of the present experiments. Thus, it does not appear that the patterns of decreasing delta plots observed in our studies can be explained

within stage models purely by the idea of correlated stage times. It should be emphasized that these results only rule out that the idea that stage time correlations are sufficient to explain our results; they do not rule out stage models per se.

6.3.4 Mixture models. Mixture models assume that responses in different trials are generated from one of two different processing modes (e.g., an automatic or controlled mode; Yantis, Meyer, & Smith, 1991). These models can produce decreasing delta plots when the proportion of fast responses is greater in the congruent condition than in the incongruent one—at least when certain conditions are met (see Schwarz & Miller, 2012). This model can also accommodate all of the delta plot patterns observed in the present experiments in a plausible manner. As usual, slowing overall processing (i.e., by reducing the drift rates of the Wald distributions used by Schwarz & Miller, 2012) shift the delta

plot to the right, as observed in Experiment 4. Decreasing the proportions of responses generated in the fast processing mode tends to shift the delta plot downward, as observed in Experiments 2 and 3. Finally, combining these two sets of parameter changes produces the overlapping delta plot pattern observed in Experiment 1.

6.3.5 Cascade models. The underlying idea of cascade models is that early processing stages continuously transmit their activation to later stages until a criterion threshold of evidence is reached at the final output stage, thus producing a response (e.g., McClelland, 1979). Schwarz and Miller (2012) showed that even in a simple two-stage version of such a model, decreasing delta plots would arise when the processing rates in incongruent trials are higher at the first stage and lower at the second stage compared to the corresponding rates in congruent trials. We found that this model could also account for all of the different delta plot patterns observed in these experiments with relatively simple changes in the values of the parameters used by Schwarz and Miller (2012). First, there are at least two ways to produce the overlapping delta plot pattern observed in Experiment 1. On the one hand, this pattern can arise if the response criterion k increases, as is shown in Table 1. On the other hand, this pattern can also arise if the evidence accumulation rates within the first stage decrease in congruent and incongruent trials (i.e., both α_1 parameters). Second, the downward shift of the slow condition delta plot observed in Experiments 2 and 3 can be produced by increasing both the second-stage processing rates and the response criterion (i.e., the k parameter and the α_2 parameters of both congruence conditions). It should be noted, however, that these parameter changes are somewhat counterintuitive, because they involve faster second-stage transmission in the condition with slower responses. Third, the rightward and upward delta plot shift observed in Experiment 4 can arise if the second-stage processing rates (i.e., α_2) decrease and the response criterion k increases. Finally, it should be also noted that the cascade model was the only model other than the DMC model among those considered here that was able to produce negative-going delta plots. Specifically, delta plots could become negative when the response criterion was rather high.

6.3.6 Parallel channel models. The basic idea of these models is that a response is produced when a certain criterion number, k , of parallel processing channels has finished out of a total number of channels, n , where each channel has some probability distribution of finishing times (e.g., Meijers & Eijkman, 1974). In general, Simon effects can be produced simply by increasing the total number of activated channels in congruent compared to incongruent trials—that is $n_c > n_i$ (Schwarz & Miller, 2012). Furthermore, when the number of incongruent channels is only slightly larger than the criterion k , Simon effects can be larger for faster compared to slower responses. These models are also capable of

producing all of the delta plot patterns observed in our experiments by means of changes in the numbers of channels and in the criterion, as is illustrated in Table 1, though rather complex parameter changes are required to produce some patterns. More precisely, slowing down the channels can produce a rightward shift of the delta plot in the slower condition, and combining this with a slight increase in the criterion can produce a rightward and upward shift as observed in Experiment 4. Reducing both the number of channels and the criterion can produce the rightward and downward shift of the slower condition delta plot as observed in Experiments 2 and 3. The pure offset of the slower condition delta plot, as was observed in Experiment 1, seemed the most difficult to produce in a plausible manner. Specifically, to produce a good approximation of this delta plot pattern, it was necessary to slow the channels in the difficult condition—which is plausible—but also to increase the number of channels in this condition—which seems implausible.

6.3.7 Summary. Based on the effects of the present experimental manipulations on observed delta plots, it seems quite reasonable to entertain a variety of models for decreasing delta plots. It was quite easy to reproduce the observed delta plots with simple changes in parameter values for the DMC, exhaustive, mixture, cascade, and parallel models, but some of these changes seem intuitively implausible, especially for the exhaustive, cascade, and parallel channel models. Only the correlated stage-time model seemed particularly strained by the observed delta plot patterns. Though further elaborations of this model might also produce all of the observed patterns, Occam's razor would suggest concentrating for now on the other models as the main competitors to the fading activation account.

6.4 Possible extension to other conflict tasks

Although the present study was designed to illuminate the underlying processes in the standard versions of visual Simon tasks, the basic approach of applying distributional analyses to stage-specific manipulations might also help to understand the mechanisms in other conflict tasks (e.g., Stroop, flanker, and auditory Simon tasks; e.g., Eriksen & Eriksen, 1974; Simon, 1968; Stroop, 1935). For example, it is still unclear whether the processes in the Eriksen flanker task share similarities with the ones at play in the Simon task. Although the observed differences of Simon and flanker effects on a distributional RT level (i.e., decreasing delta plots in the Simon but not the Eriksen task) imply different control mechanisms, these differences could simply reflect a larger temporal overlap from irrelevant to relevant activation (e.g., Burle et al., 2014; Ulrich et al., 2015). Empirical support for this idea comes in particular from a recent study by Hübner and Töbel (2019), in which decreasing flanker delta plots were observed when the relevant central target stimulus appeared sufficiently delayed after the irrelevant flanker stim-

uli. According to Hübner and Töbel (2019), this might indicate that the superimposition of activations happens earlier in the flanker task than in the Simon task. For example, the locus of superimposition could be at an early perceptual level in the flanker task (e.g., White, Ratcliff, & Starns, 2011), whereas the present study reinforces the idea of a locus after perceptual processing has taken place in the Simon task. It may be worthwhile to compare the corresponding decreasing delta plots in a flanker-delay paradigm with a perceptual stage manipulation to see whether this would produce a delta plot pattern different to the overlapping ones found here.

Furthermore, the idea that a single—initially increasing and then decreasing—irrelevant activation function could underlie different conflict effects (e.g., Ulrich et al., 2015) may also explain the fact that in some other versions of the Simon task (e.g., with auditory stimuli or vertical stimulus layouts) both decreasing (e.g., Töbel, Hübner, & Stürmer, 2014; Xiong & Proctor, 2016) and non-decreasing delta plots (e.g., Vallesi, Mapelli, Schiff, Amodio, & Umiltà, 2005; Wascher, Schatz, Kuder, & Verleger, 2001; Wiegand & Wascher, 2005) have sometimes been observed. In any case, the finding of non-decreasing delta plots under many circumstances indicates that accounts based purely on fading activation require some elaboration—as is also indicated by the effects of stage manipulations on delta plots in the present study. Considering that primarily decreasing delta plots have been most consistently found for standard Simon effects, it might also be illuminating to extend the current approach of combining factor manipulations with distributional analyses to situations where the observed delta plots are non-decreasing in some conditions. For example, such an extended approach could help to identify further shared (e.g., Buetti & Kerzel, 2008; Töbel et al., 2014) or distinct (e.g., Vallesi et al., 2005; Vallesi & Umiltà, 2009; Wiegand & Wascher, 2007) mechanisms in vertical compared with horizontal Simon tasks.

6.5 Conclusion

In the present study, we combined distributional analyses (i.e., delta plots) with selective stage-specific manipulations of the task-relevant information processing stream (i.e., perception, decision, motor execution) to investigate which effects could be entirely explained by the fading of irrelevant location-based activation. The results indicate that this approach is useful for detecting effects of stage-specific manipulations that cannot be identified based on mean RT alone. The results of Experiment 1 (stimulus discriminability), Experiment 2 (number of stimulus alternatives), and Experiment 3 (strength of S-R mapping) revealed that the mean Simon effect was larger for the faster compared to the slower condition. Critically, prolonging perceptual processing produced a delta plot pattern consistent with a fading activation account (i.e., overlapping fast and slow delta plots), whereas prolonging decision processes reduced the Simon effect more

than could be explained by fading of irrelevant activation (i.e., the slow delta plot was shifted downward relative to the fast delta plot). The increased mean Simon effect for the slow compared to fast condition of Experiment 4 (foot vs. hand as response effector) was reflected in a both a rightward and upward shift of the delta plot for foot responses. The rightward shift is consistent with a fading activation account in which irrelevant and relevant activation are superimposed before late stages of motor execution, suggesting that this method is also helpful in delimiting the locus of the Simon effect. The upward shift indicates further that the Simon effect is increased for foot responses, which would again require an elaboration of fading activation models. Thus, a chronometric approach combined with fine-grained distributional analyses is a powerful tool to identify further constraints on the cognitive processes intervening between stimuli and responses within perceptual decision-making models of the Simon task.

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Appendix A

Sequential Analyses of Experiments 1–4

In this appendix we describe analyses of performance broken down by trial sequence, specifically analyzing performance on the current trial n depending on the congruency status of the previous trial $n-1$. Tables A1 and A2 show mean RTs and PEs as a function of the current trial congruency, previous trial congruency, and the experiment-specific manipulation, and Figure A1 shows the delta plots for RT and PE broken down according to sequence type. For the sake of brevity, we only report effects and interactions involving the factor of previous trial congruency.

8.1 Experiment 1

The ANOVA on mean RTs revealed a significant main effect of previous trial congruency, $F(1, 59) = 72.45$, $p < .001$, $\eta_p^2 = .22$, with faster responses following congruent trials (463 ms) than following incongruent ones (470 ms), and previous trial congruency interacted significantly with current trial congruency, $F(1, 59) = 268.73$, $p < .001$, $\eta_p^2 = .82$. There was a strong Simon effect on mean RT after congruent trials (51 ms), but a smaller and reversed Simon effect after incongruent trials (-20 ms). This congruency sequential effect (CSE) was not further modulated by the stimulus discriminability condition ($p = .173$).

The corresponding ANOVA on mean PEs pattern indicated that responses were significantly more erroneous after congruent (6.3%) compared to incongruent (5.6%) trials, $F(1, 59) = 7.67$, $p = .007$, $\eta_p^2 = .12$. Previous trial congruency interacted significantly with current trial congruency, $F(1, 59) = 143.75$, $p < .001$, $\eta_p^2 = .71$. The Simon effect on mean PE was also larger after congruent trials (6.3%) compared to after incongruent trials (-2.2%), and a significant three-way interaction revealed that this CSE was slightly larger in the low compared to high stimulus discriminability condition, $F(1, 59) = 4.88$, $p = .031$, $\eta_p^2 = .08$.

Figure A1A shows the corresponding four delta plots (i.e., delta plots of the two discriminability conditions after congruent and incongruent trials) As can be seen in the figure, all of the delta plots were decreasing. Although visual

Figure A1. (see caption next page)

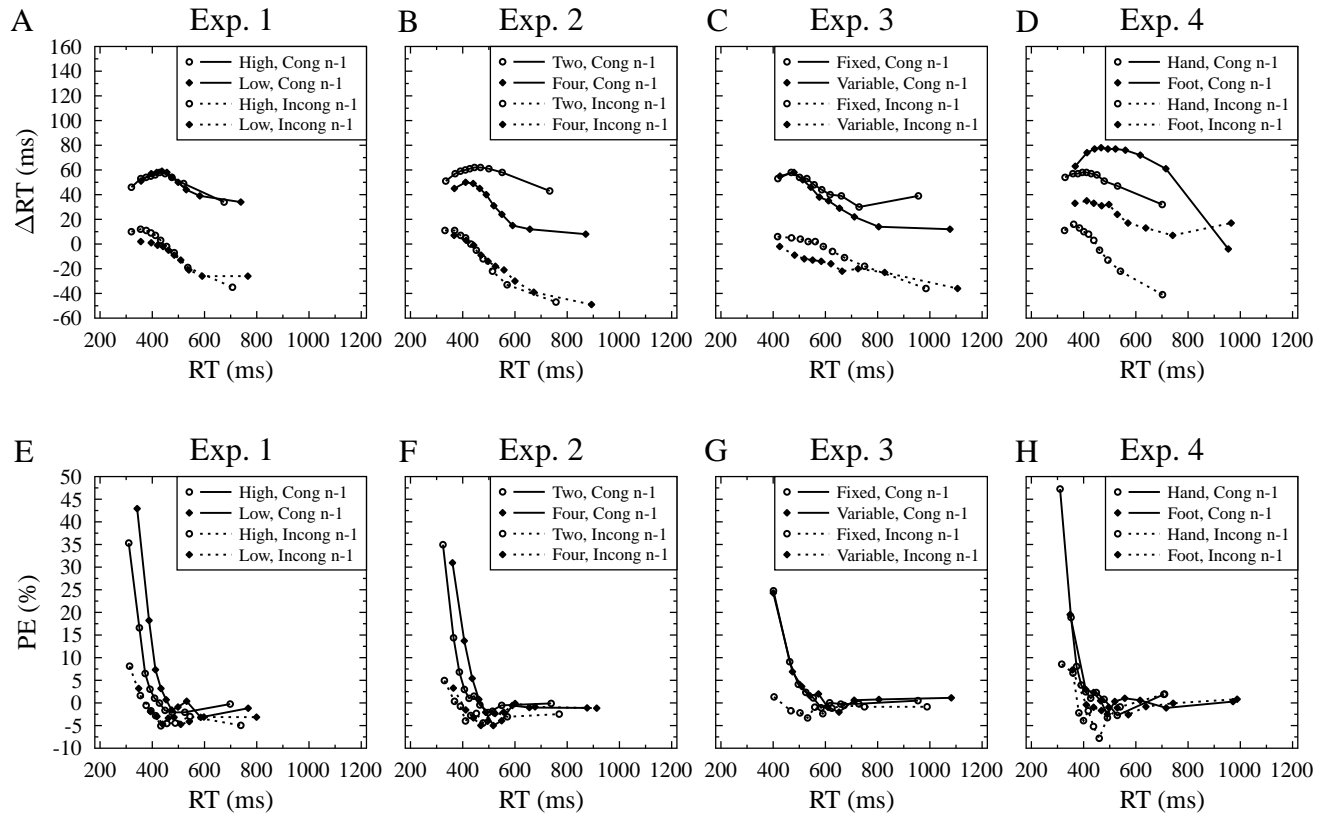


Figure A1. A. Delta plots of Experiment (Exp.) 1 showing incongruent minus congruent differences in mean reaction time (RT) in milliseconds (ms) within each of 10 deciles, plotted against the decile averages, as a function of congruent (Cong n-1) versus incongruent (Incong n-1) previous-trial stimuli, separately for the high versus low stimulus discriminability condition. B. Delta plots of Exp. 2 as a function of congruent (Cong n-1) versus incongruent (Incong n-1) previous-trial stimuli, separately for the two versus four stimulus alternatives. C. Delta plots of Exp. 3 as a function of congruent (Cong n-1) versus incongruent (Incong n-1) previous-trial stimuli, separately for the fixed versus variable S-R mapping condition. D. Delta plots of Exp. 4 as a function of congruent (Cong n-1) versus incongruent (Incong n-1) previous-trial stimuli, separately for hand versus foot responses. E. Delta plots of Exp. 1 showing incongruent minus congruent differences in mean percentage error (PE) within each of 10 deciles, plotted against the decile average RTs, as a function of congruent (Cong n-1) versus incongruent (Incong n-1) previous-trial stimuli, separately for the high versus low stimulus discriminability condition. F. Delta plots of Exp. 2 as a function of congruent (Cong n-1) versus incongruent (Incong n-1) previous-trial stimuli, separately for the two versus four stimulus alternatives. G. Delta plots of Exp. 3 as a function of congruent (Cong n-1) versus incongruent (Incong n-1) previous-trial stimuli, separately for the fixed versus variable S-R mapping condition. H. Delta plots of Exp. 4 as a function of congruent (Cong n-1) versus incongruent (Incong n-1) previous-trial stimuli, separately for hand versus foot responses.

Table A1

Mean reaction time (RT) in milliseconds in Experiments (Exp.) 1, 2, 3, and 4 as a function of the experiment-specific condition (Exp. 1: high vs. low discriminability; Exp. 2: two vs. four stimulus alternatives; Exp. 3: fixed vs. variable S-R mapping; Exp. 4: hand vs. foot effector) and the congruency in the current trial (i.e., Cong n, Incong n) when the previous trial was congruent (i.e., Cong n-1) or incongruent (i.e., Incong n-1).

	Condition	Cong n-1			Incong n-1		
		Cong n	Incong n	Simon n	Cong n	Incong n	Simon n
Exp. 1	High	413	465	52	446	445	-1
	Low	462	513	50	500	490	-10
Exp. 2	Two	433	490	57	473	465	-8
	Four	518	551	32	550	534	-17
Exp. 3	Fixed	579	624	45	613	608	-5
	Variable	621	657	36	658	641	-17
Exp. 4	Hand	419	472	53	453	451	-2
	Foot	522	587	65	550	575	25

Table A2

Mean percentage errors (PE) in Experiments (Exp.) 1, 2, 3, and 4 as a function of the experiment-specific condition (Exp. 1: high vs. low discriminability; Exp. 2: two vs. four stimulus alternatives; Exp. 3: fixed vs. variable S-R mapping; Exp. 4: hand vs. foot effector) and the congruency in the current trial (i.e., Cong n, Incong n) when the previous trial was congruent (i.e., Cong n-1) or incongruent (i.e., Incong n-1).

	Condition	Cong n-1			Incong n-1		
		Cong n	Incong n	Simon n	Cong n	Incong n	Simon n
Exp. 1	High	2.6	8.4	5.8	5.5	3.9	-1.7
	Low	3.6	10.4	6.8	7.8	5	-2.8
Exp. 2	Two	1.5	7.6	6	4.7	3.1	-1.6
	Four	4.4	8.3	3.8	6.4	4.7	-1.7
Exp. 3	Fixed	2.5	6.6	4.1	4.5	3.2	-1.3
	Variable	5.2	9.1	3.9	7.6	6.8	-0.8
Exp. 4	Hand	2.6	11	8.5	5.9	5.1	-0.7
	Foot	1.6	4	2.4	2.6	2.6	0

inspections suggest a similar rate of decrease, an ANOVA including factors of stimulus condition, congruency, previous trial congruency, and bin revealed a significant three-way interaction between the latter three factors, $F(9, 531) = 2.99$, $p = .002$, $\eta_p^2 = .05$. This suggest a stronger decrease of the Simon effect after incongruent trials, which however did not depend on stimulus discriminability as reflected in a non-significant four-way interaction, $p = .433$.

Finally, we fitted lines to the four delta plots and performed the corresponding slope and intercept analyses of the main analyses while considering previous trial congruency. The mean slopes of the two discriminability conditions were descriptively quite similar for both previous trial congruent (i.e., high = $-.03$; low = $-.08$) and previous trial incongruent (i.e., high = $-.14$; low = $-.09$), and an ANOVA on these means (with factors of previous trial congruency and discriminability) revealed no significant effects (all $ps > .099$). The pre-

dicted Simon effects at the individual mean RTs had a similar size for both discriminability conditions after both congruent (i.e., high = 51 ms; low = 51 ms) and incongruent trials (i.e., high = -4 ms; low = -9 ms). The corresponding ANOVA on these predicted mean Simon effects only revealed a significant main effect of previous trial congruency, $F(1, 59) = 254.14$, $p < .001$, $\eta_p^2 = .81$, with all other $ps > .350$. Thus, these analyses suggest overlapping delta plots with similar shapes for the two discriminability conditions after both congruent and incongruent trials.

8.2 Experiment 2

The ANOVA on mean RTs revealed a significant main effect of previous trial congruency, $F(1, 63) = 26.73$, $p < .001$, $\eta_p^2 = .40$, with faster responses following congruent trials (498 ms) than following incongruent ones (505 ms). Previous trial congruency interacted significantly with current

trial congruency, $F(1, 63) = 207.31$, $p < .001$, $\eta_p^2 = .77$, and this two-way interaction was further modulated by the number of stimulus alternatives, $F(1, 63) = 8.21$, $p = .006$, $\eta_p^2 = .12$. After congruent trials, the Simon effect was larger for the two (57 ms) compared to the four (32 ms) stimulus condition, whereas after incongruent trials, there were slightly reversed Simon effects with both two (-8 ms) and four (-17 ms) stimuli.

The corresponding ANOVA on mean PEs revealed a significant main effect of previous trial congruency, $F(1, 63) = 10.45$, $p = .002$, $\eta_p^2 = .14$, and there was also again a significant two-way interaction of previous trial congruency with current trial congruency, $F(1, 63) = 147.98$, $p < .001$, $\eta_p^2 = .70$, as well as a significant three-way interaction between all factors, $F(1, 63) = 5.49$, $p = .022$, $\eta_p^2 = .08$. Mirroring the results of the mean RT analyses, the Simon effect was larger for two (6.0%) compared to four (3.8%) stimuli after congruent trials, whereas after incongruent trials, there was a slightly reversed Simon effect for both the two (-1.6%) and four (-1.7%) stimuli.

Figure A1B shows the delta plots for the conditions with two and four stimulus alternative, separately after congruent and incongruent trials. The corresponding ANOVA including condition, congruency, previous trial congruency, and bin revealed a significant four-way interaction, $F(9, 567) = 3.19$, $p < .001$, $\eta_p^2 = .05$, which was followed up by separate three-way ANOVAs for the previous trial congruent and previous trial incongruent conditions. The three-way interaction was significant after congruent trials, $F(9, 567) = 5.41$, $p < .001$, $\eta_p^2 = .08$, but not after incongruent trials ($p = .957$). As is evident in Figure A1B, with congruent trials there was sharper decrease of the delta plot with four stimuli compared to two stimuli for the intermediate bins.

The corresponding difference in slopes between the conditions with two and four stimulus alternatives was also descriptively present after congruent trials (i.e., two = -.03; four = -.11) but not after incongruent trials (i.e., two = -.16; four = -.14). However, a corresponding ANOVA on these mean slopes revealed only a significant main effect of previous trial congruency, $F(1, 63) = 7.11$, $p = .010$, $\eta_p^2 = .10$. Neither the main effect number of stimulus alternatives ($p = .266$) nor the interaction ($p = .073$) was significant. After congruent trials, the predicted Simon effect at the individual mean RTs was much larger with two stimuli (57 ms) than with four stimuli (35 ms). Interestingly, in contrast to the main analyses, the predicted (reversed) Simon effects after incongruent trials were descriptively similar for both numbers of stimulus alternatives (i.e., two = -13 ms; four = -13 ms). In an ANOVA on these predicted mean RTs, all effects were significant: previous trial congruency, $F(1, 63) = 15.64$, $p < .001$, $\eta_p^2 = .76$, number of stimulus alternatives, $F(1, 63) = 15.64$, $p < .001$, $\eta_p^2 = .76$, as well as the interaction between these factors, $F(1, 63) = 9.72$, $p = .003$, $\eta_p^2 =$

.13.

8.3 Experiment 3

The ANOVA on mean RTs yielded a significant main effect of previous trial congruency, $F(1, 62) = 23.74$, $p < .001$, $\eta_p^2 = .28$, reflecting faster responses following congruent compared to incongruent trials (620 ms vs. 630 ms). Previous trial congruency interacted significantly with current trial congruency, $F(1, 62) = 104.93$, $p < .001$, $\eta_p^2 = .63$. There was a strong Simon effect on mean RT after congruent trials (41 ms), but a smaller and reversed Simon effect after incongruent trials (-11 ms). This congruency sequential effect (CSE) was not further modulated by the S-R mapping condition ($p = .853$).

The descriptive pattern for mean PEs was similar to the one observed for mean RTs. A parallel ANOVA on the PEs also yielded a significant interaction of previous trial congruency with current trial congruency, $F(1, 62) = 78.53$, $p < .001$, $\eta_p^2 = .56$. The Simon effect on mean PE was larger after congruent trials (3.9%) compared to after incongruent trials (-1.0%), and there was no significant three-way interaction ($p = .500$).

Figure A1C shows the delta plots for the two S-R mapping conditions, separately after congruent and incongruent trials. The corresponding ANOVA including condition, congruency, previous trial congruency, and bin revealed no significant four-way interaction ($p = .456$). The corresponding fixed and variable delta slopes after congruent (i.e., fixed = -.05; variable = -.09) and incongruent trials (i.e., fixed = -.09; variable = -.04) were descriptively quite similar, and an ANOVA on these mean slopes yielded no significant effects (all $ps > .142$). The predicted Simon effects at the individual mean RTs were always descriptively larger for the fixed compared to variable mapping condition after both congruent (i.e., fixed = 44 ms; variable = 38 ms) and incongruent trials (i.e., fixed = -7 ms; variable = -15 ms). However, an ANOVA on these predicted Simon effects revealed only a significant main effect of previous trial congruency, $F(1, 62) = 100.44$, $p < .001$, $\eta_p^2 = .62$, and the main effect of S-R mapping was not significant, $F(1, 62) = 3.74$, $p = .058$, $\eta_p^2 = .06$, (with $p = .917$ for the interaction).

8.4 Experiment 4

The ANOVA on mean RTs only yielded a finding that previous trial congruency interacted significantly with current trial congruency, $F(1, 25) = 39.53$, $p < .001$, $\eta_p^2 = .61$. The strong Simon effect after congruent trials (58 ms), was considerably smaller after incongruent trials (11 ms), and this CSE was not further modulated by response effector ($p = .202$).

For the ANOVA on mean PEs, there was a significant main effect of previous trial congruency, $F(1, 25) = 5.14$,

$p = .032$, $\eta_p^2 = .17$, a significant interaction of previous trial congruency with current trial congruency, $F(1, 25) = 45.83$, $p < .001$, $\eta_p^2 = .65$, and a significant three-way interaction among these factors and response effector, $F(1, 25) = 40.94$, $p < .001$, $\eta_p^2 = .62$. After congruent trials, the Simon effect was larger for hand (8.4%) compared to foot (4.4%) responses, whereas after incongruent trials, the Simon effect was virtually absent for both hand (-0.7%) and foot (0.0%) responses.

Figure A1D shows the corresponding delta plots for hand and foot responses, separately after congruent and incongruent trials. The corresponding ANOVA including condition, congruency, previous trial congruency, and bin revealed a significant four-way interaction, $F(9, 225) = 2.36$, $p = .015$, $\eta_p^2 = .09$. Separate ANOVAs after congruent and incongruent trials (i.e., congruency, bin, response effector) revealed that the three-way interaction was not significant after incongruent trials ($p = .367$) and marginally significant after congruent trials ($p = .051$). As can be seen in Figure A1D, the time-course of the delta plots looked quite similar except for the last—presumably noisy—bin.

Further support for similarly shaped delta plots comes from the corresponding analyses slope analyses. Specifically, the ANOVA indicated that neither the main effects ($p > .289$) nor the interaction ($p = .078$) were significant (mean slopes after congruent trials: hand = $-.04$; foot = $-.11$; mean slopes after incongruent trials: hand = $-.20$; foot = $-.06$). In the offset analysis, the predicted Simon effect at the individual mean RTs were larger for foot responses than for hand responses after both congruent trials (i.e., hand = 50 ms; foot = 73 ms) and incongruent trials (i.e., hand = -14 ms; foot = 27 ms). The corresponding ANOVA on these predicted mean Simon effects revealed significant main effects of previous trial congruency, $F(1, 25) = 46.38$, $p < .001$, $\eta_p^2 = .65$, and effector, $F(1, 25) = 30.49$, $p < .001$, $\eta_p^2 = .55$ (with $p = .110$ for the interaction).

8.5 Summary

Overall, the sequential analyses revealed three main findings. First, the reduced mean Simon effects after incongruent trials were only reflected in a downward offset of incongruent delta plots, leaving the decreasing slope unaffected. Second, the mean Simon effects were actually reversed after incongruent trials and the corresponding delta plots were negative in the majority of bins. Third, the delta plot patterns produced by the experimental manipulations in the main analyses were basically identical when taking previous trial congruency into account. The only exception was that the delta plot pattern found in Experiment 2 (i.e., number of stimulus alternatives manipulation) was only found after congruent trials—that is, the delta plot with four stimulus alternatives was below the one with two stimulus alternatives only after congruent trials, whereas the delta plots were over-

lapping after incongruent trials. We do not have an explanation for the difference in these delta plot patterns based on previous trial history.

Appendix B

Additional information for the quantitative models considered in the General Discussion

In this appendix, we present additional mathematical specification of the models that were used to produce the different delta plot patterns shown in Figure 5 (see also Schwarz & Miller, 2012; Ulrich et al., 2015). In addition, we also present here the specific model parameter values which remained unchanged across conditions to produce the experiment-specific delta plot patterns. Varying parameter values are shown in Table 1.

8.6 Diffusion model for conflict tasks

Our implementation of the DMC model closely followed the presentation of Ulrich et al. (2015). RTs for both congruent (RT_c) and incongruent trials (RT_i) were modeled as the sum of $D + R$, where D is the decision time and R is the normally distributed residual time (i.e., with μ_R varied as shown in Table 1 and $\sigma_R = 30$). The decision process was modeled as a single Wiener diffusion process with a standard deviation parameter of $\sigma = 4$. The drift rate of this decision process towards the decision boundary b at each time point t was calculated based on the sum of the drift rate inputs from controlled and automatic processes. The drift rate of the controlled process μ_c was constant over time and positive in all conditions. The drift rate of the automatic process $\mu_i(t)$ varied over time, and it was positive in the congruent condition but negative in the incongruent condition. Specifically, the time-varying drift rate of the automatic process was modeled as having the shape of a gamma density function with shape parameter $a = 2$, scale parameter $\tau = 30$, and peak amplitude A . The drift rate μ_c of the controlled process, the amplitude A of the automatic process, and the decision boundary b were also varied across conditions as shown in Table 1.

8.7 Exhaustive models

The RTs of congruent and incongruent trials were modeled as

$$RT_c = A + B_c + C$$

and

$$RT_i = A + \max(B_c, B_i) + C,$$

respectively. In all conditions, $A + C$ was modeled as an ex-Gaussian random variable with exponential mean $\tau = 10$ and normal standard deviation $\sigma = 10$; the value of the normal mean μ varied across conditions as shown in Table 1. B_c and B_i were modeled as inverse Gaussian random variables. The parameters of B_c were fixed at $\mu_c = 1$, variance $\sigma_c^2 = 100$, and boundary $a_c = 100$. The μ_i of B_i was varied across conditions as shown in Table 1, and its

boundary and variance parameters were fixed at $a_i = 100$ and $\sigma_i^2 = 31.3$.

8.8 Correlated stage time models

RTs for both congruent and incongruent trials were modeled as ex-Gaussian random variables with a common exponential mean τ . The normal components of the two ex-Gaussians, N_c and N_i , were further modeled as sums of two normally distributed stage times A and B, $N_c = t_{Ac} + t_{Bc}$ and $N_i = t_{Ai} + t_{Bi}$. Thus, the means of these stage times (μ_{Ac} , μ_{Bc} , μ_{Ai} , and μ_{Bi}) and their corresponding standard deviations (σ_{Ac} , σ_{Bc} , σ_{Ai} , and σ_{Bi}) are also parameters of the model. Finally, the correlations of the A and B stage times within each condition (ρ_c and ρ_i) are also parameters of the model. As noted by Schwarz and Miller (2012), the overall variance of the normal components N_c and N_i depend critically on the stage time correlations in the congruent and incongruent conditions. As indicated in Figure 5C and its caption, we attempted to produce the observed delta plot patterns by varying these model parameters across conditions: μ_{Ac} and μ_{Ai} , ρ_c and ρ_i , τ , σ_{Bc} and σ_{Bi} . The remaining parameters were fixed at $\mu_{Bc} = 200$, $\mu_{Bi} = 250$, and $\sigma_{Ac} = \sigma_{Ai} = 20$.

8.9 Mixture models

The RTs of congruent and incongruent trials were modeled as the mixtures

$$RT_c = p_1 \times A_f + (1 - p_1) \times A_s$$

and

$$RT_i = p_2 \times A_f + (1 - p_2) \times A_s,$$

respectively. The mixture probabilities p_1 and p_2 correspond to the proportions of fast processes A_f within

each congruency condition, and the values of these probabilities varied across conditions as shown in Table 1. A_f and A_s were modeled as inverse Gaussian random variables with drift rates μ_f and μ_s , respectively, varying across conditions as shown in Table 1. The remaining inverse Gaussian parameters were held constant across conditions (i.e., error standard deviation $\sigma_f = \sigma_s = 1$ and criterion boundary $a_f = a_s = 100$).

8.10 Cascade models

RTs for both congruent and incongruent trials were calculated based on the two-stage stochastic cascade model of Schwarz (2003). Spikes were generated at stage one according to Poisson processes with rates of $\alpha_{1c} = 0.05$ and $\alpha_{1i} = 0.07$ in the congruent and incongruent conditions, respectively. These spikes were transmitted to stage two with rates of α_{2c} and α_{2i} , and the response was initiated as soon as k spikes were collected at the second stage, with these parameters varying across conditions as shown in Table 1.

8.11 Parallel channel models

RTs for both congruent and incongruent trials were calculated based on the time needed to finish processing the first k parallel channels, from a total of n_c (congruent trials) or n_i (incongruent) activated channels, with these parameters varying across conditions as shown in Table 1. Following Schwarz and Miller (2012), we assumed that the finishing times for the different channels followed a uniform distribution from 100–600 ms and that the processing times of different channels were independent.