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Analyzing distributional properties of interference effects across modalities: chances and challenges

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Abstract In research investigating Stroop or Simon effects, data are typically analyzed at the level of mean response time (RT), with results showing faster responses for compatible than for incompatible trials. However, this analysis provides only limited information as it glosses over the shape of the RT distributions and how they may differ across tasks and experimental conditions. These limitations have encouraged the analysis of RT distributions using delta plots. In the present review, we aim to bring together research on distributional properties of auditory and visual interference effects. Extending previous reviews on distributional properties of the Simon effect, we additionally review studies reporting distributional analyses of Stroop effects. We show that distributional analyses of sequential effects (i.e., taking into account congruency of the previous trial) capture important similarities and differences of interference effects across tasks (Simon, Stroop) as well as across sensory modalities, despite some challenges associated to this approach.

Introduction

Individuals' performance in a task can be impaired by information that is irrelevant for the task's goals. This interference by irrelevant information is typically investigated in interference paradigms such as the spatial compatibility task, also known as Simon task (Simon, 1990; Simon & Small, 1969; for reviews see Hommel, 2011; Lu & Proctor, 1995), and the Stroop task (Stroop, 1935; for a review see MacLeod, 1991). In the Simon task, participants discriminate between task-relevant stimulus attributes (e.g., two colors) of stimuli that appear on the left or the right side of a display, and they respond using spatially aligned response keys (e.g., pressing a right key when the stimulus is blue and a left key when the stimulus is red). Although the stimulus location is task irrelevant, performance is typically impaired when the task-irrelevant stimulus location mismatches the location of the required response (e.g., a blue stimulus that appears on the left), as compared to when stimulus and response locations match (e.g., a blue stimulus that appears on the right). In the Stroop task, participants name the surface color of a color word while trying to ignore its meaning. Typically, participants fail to completely ignore the word meaning, which results in impaired performance in incompatible trials (e.g., the word BLUE printed in red) compared to compatible trials (e.g., the word BLUE printed in blue).

Several variants of the Stroop and Simon task have been developed, including auditory Stroop and Simon variants (e.g., Green & Barber, 1981; Leboe & Mondor, 2007; Simon & Small, 1969) and even tactile variants (e.g., Hasbroucq & Guiard, 1992; Salzer, Aisenberg, Oron-Gilad, & Henik, 2013). Auditory Stroop tasks may be especially useful in research on participants with limited reading ability (e.g., young children, analphabets), and tactile variants can be used to investigate interference when the visual and auditory modalities are not available or appropriate. However, as we will discuss below, it is unclear whether Stroop and Simon interference effects are comparable, or whether Simon and Stroop effects obtained from different modalities are comparable.

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Research investigating Stroop or Simon effects typically focuses on the comparison between compatible and incompatible trials at the level of mean RT, with results showing faster responses for compatible than for incompatible trials. Despite its usefulness, the comparison of mean RT provides limited information as it glosses over the shape of the RT distributions and how they may differ across experimental conditions. Specifically, analyses of mean RT may mask theoretically relevant findings (e.g., reduced variance with increasing RT, see below) that can only be discovered when analyzing the RT distribution. Thus, distributional analyses of interference effects can capture similarities and differences among tasks and experimental conditions, for example, differences in interference effects of different modalities (e.g., auditory vs. visual) or of different tasks (Simon vs. Stroop).

An efficient way of analyzing distributional properties of interference effects is by means of *delta plots* (De Jong, Liang, & Lauber, 1994; Schwarz & Miller, 2012; Speckman, Rouder, Morey, & Pratte, 2008), which map the RT differences between conditions at different RT percentiles. Let A and B be two RT distributions, and P_i (RT) be the ith percentile of a given RT distribution (e.g., the 10th, 20th, 30th,… percentile). The delta-plot maps (on the y axis) the difference between the two RT distributions across percentiles, P_i (A)–P_i (B), against (on the x axis) the average of the two RT distributions across percentiles, $0.5 \times (P_i(A) + P_i(B))$. The slope of the delta plot captures the RT differences between the two conditions across response speed, with positive slopes indicating that the RT differences are larger for slower responses, and negative slopes indicating that RT differences are larger for faster responses. A positive and a negative delta-plot slope is illustrated in Fig. 1 depicting delta plots from visual Stroop and Simon data reported by Pratte, Rouder, Morey, and Feng (2010) (Experiment 1), which show approximately linear trends with positive and negative slopes, respectively. A formal characterization of delta plots and their relationship with the shape of RT distributions is given by Speckman et al. (2008) and Zhang and Kornblum (1997).

In a recent review, Proctor, Miles, and Baroni (2011) discussed studies examining distributional properties of Simon effects. We extend this comprehensive work in reviewing studies examining distributional properties of Stroop effects and in including very recent studies of distributional properties of Simon effects. We will discuss distributional properties of auditory interference effects that—at least for the Simon task—differ remarkably from their visual counterparts, and we will illustrate that examining distributional properties of sequential effects (i.e., taking into account congruency of the previous trial) can be a helpful tool in characterizing similarities and differences of interference effects across tasks (Simon, Stroop) and

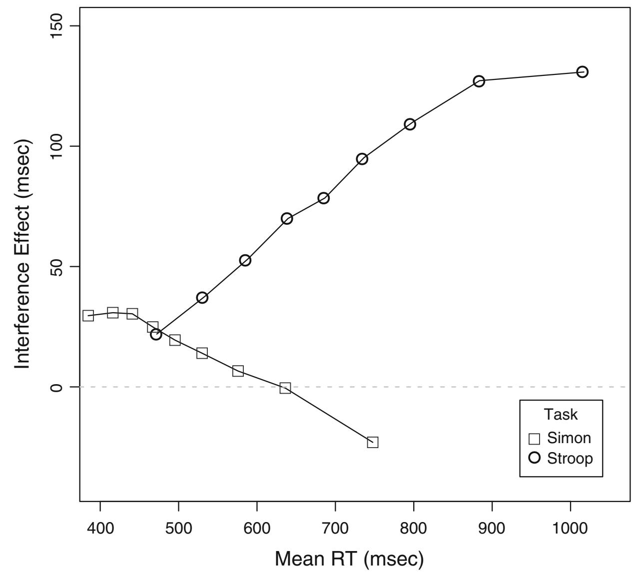

Fig. 1 Delta plots from visual Stroop and Simon data reported by Pratte et al. (2010) (Experiment 1)

sensory modalities. To bring together research on distributional properties of interference effects in different sensory modalities, we will start with characterizing the distributional properties of *visual* Stroop and Simon effects as they represent established and often replicated result patterns. In a second part, we will review effects of sensory modality (visual vs. auditory vs. tactile) on the distributional properties of Simon and Stroop effects. A third part addresses sequential effects (taking into account congruency of the previous trial). Each part will address empirical results, theoretical accounts, and methodological issues and challenges.

Distributional properties of Simon and Stroop effects

In interference tasks, it is very often the case that responses in incompatible conditions have larger mean RT as well as larger RT variances as compared to responses in compatible conditions (Wagenmakers & Brown, 2007). These differences in the RT distributions can be shown to imply that the observed interference effect is larger for slow responses than for fast responses, a pattern that is expressed by a positive delta-plot slope. Therefore, a delta-plot pattern is especially informative when it violates the robust RT regularity of standard deviations increasing proportionally with mean RT, as found for the visual Simon task with horizontally aligned stimuli. For this task, it has been repeatedly shown that interference effects are larger for fast responses than for slow responses (e.g., Burle, Possamaï, Vidal, Bonnet, & Hasbroucq, 2002; De Jong et al., 1994; Liepelt, Wenke, Fischer, & Prinz, 2011; Pratte et al., 2010;

Ridderinkhof, 2002a; for a review see Proctor et al., 2011). As explained below, the atypical result of a larger interference effect for fast responses (i.e., a negative delta-plot slope) in the visual horizontal Simon task turned out to be a seminal finding for developing and testing theories of the Simon effect and demonstrated the usefulness of distributional analyses.

In the visual domain, the most common Simon task variant uses horizontally aligned target stimuli; other variants use vertically aligned stimuli or symbolic stimuli such as arrows and words (Hommel, 2011; Lu & Proctor, 1995). Although all these tasks are typically called Simon tasks, studies examining the distributional properties of Simon effects suggest that visual horizontal Simon tasks differ from other Simon task versions. Specifically, a positive delta-plot slope is typically found in non-horizontally aligned versions, for example in visual Simon tasks with vertically aligned stimuli (Proctor, Vu, & Nicoletti, 2003; Wiegand & Wascher, 2005; but see De Jong et al., 1994; Valle-Inclán & Redondo, 1998).

In the visual modality, the negative-going delta plot of the horizontal Simon effect is not only at odds with the positive slope found in the vertical Simon task, but also contrasts with the clearly positive slope reported for the Stroop effect (Pratte et al., 2010; Sharma, Booth, Brown, & Huguet, 2010; Soutschek et al., 2013). For example, using visual material, Pratte et al. (2010) found a positive slope for the Stroop task in four out of five experiments.

Theoretical accounts

Different explanations have been raised for the finding of negative delta-plot slopes in the horizontal visual Simon task (for an overview of the different accounts, see Proctor et al., 2011; see also van den Wildenberg et al., 2010), but all are based on the assumption that the Simon effect originates from two different pathways, the direct (or unconditional) route and the indirect (conditional) route (e.g., De Jong et al., 1994). In the first pathway, the spatial response is thought to be automatically activated by the stimulus position; this process is assumed to proceed very fast (De Jong et al., 1994; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002). In the second pathway, a more effortful and controlled process is responsible for correct response coding based on relevant stimulus information (see also Ridderinkhof, 2002a). One explanation of the negative delta-plot slope in visual horizontal Simon data is the assumption that the position effect decays spontaneously over time, leading to smaller interference effects for slower responses (Hommel, 1994). Alternatively, it was postulated that the effect is based on an active and selective suppression of the irrelevant response (Ridderinkhof, 2002a, b). Ridderinkhof (2002a) suggested that the suppression process is comparable to active inhibition, initiated in a non-automatic manner and developing over time, leading to negative slopes predominantly for longer RTs. Several findings favor the assumption that negative delta-plot slopes are an indicator of inhibitory or active suppression processes instead of reflecting a spontaneous decay of the position effect (for a discussion of this issue see Proctor et al., 2011; see also Schwarz & Miller, 2012). For instance, neurological studies showed that the declining Simon delta-plot slope is associated with electromyographic activity (Burle et al., 2002) as well as with activity in brain regions associated with inhibition (Forstmann, van den Wildenberg, & Ridderinkhof, 2008). Thus, the negative delta-plot slope in the Simon task appears to be due to an active control mechanism counteracting the influence of the irrelevant position information.

For the vertical Simon task, it has been speculated that there is no automatic activation because vertically aligned stimuli do not directly correspond to the response arrangement (left and right hand; for a discussion of this issue see Proctor et al., 2011), rendering an active suppression of automatically activated responses unnecessary. However, De Jong et al. (1994) as well as Valle-Inclán and Redondo (1998) reported negative delta-plot slopes in a vertical Simon task. Yet, Wiegand and Wascher (2007) demonstrated that the effect found in these studies could be attributed to the fact that variable response mappings were used. They concluded that using a variable response mapping led to a strong association of vertical response location and (left and right) hand. Thus, for the vertical Simon task with fixed response mapping, automatic response activation might be prevented due to the vertical alignment of the stimuli.

The finding of a positive delta-plot slope in Stroop tasks (Pratte et al., 2010; Sharma et al., 2010; Soutschek et al., 2013) is consistent with the typical finding that RT standard deviations increase along with RT means (Wagenmakers & Brown, 2007), and is therefore in accordance with several general process theories (e.g., Ashby & Townsend, 1980; Ratcliff, 1978). However, due to the considerable similarity between Stroop and Simon tasks, the obtained result pattern of positive delta-plot slopes in Stroop tasks is diagnostic in a sense that it cannot be accommodated by the same set of processes used to account for the negative delta-plot slope in the visual Simon task (Pratte et al., 2010).

Methodological issues

As pointed out above, delta plots are particularly informative when they violate the otherwise robust pattern of

RT standard deviation increasing with RT. Such a violation is indicated by a negative delta-plot slope, as has been found in studies investigating the distributional properties of the visual Simon effect with horizontally aligned stimuli (e.g., Burle et al., 2002; De Jong et al., 1994; Liepelt et al., 2011; Pratte et al., 2010; Ridderinkhof, 2002a). However, because the shape of the delta plot does not fully characterize the processes underlying the interference effect, caution is even required when conclusions are drawn on the basis of negative delta plots. Zhang and Kornblum (1997) pointed out that the negative delta-plot slope found in the visual Simon task with horizontally aligned stimuli simply reflects statistical properties of the reaction time distribution that could be explained in different ways (see also Schwarz & Miller, 2012). Thus, even if similar (negative) delta-plot slopes are obtained in different tasks, these similar patterns may still be due to different underlying processes. Therefore, more fine-grained analyses are necessary; for instance, formal models of RT and accuracy such as the diffusion model (Ratcliff, 1978; Voss, Nagler, & Lerche, 2013; Voss, Rothermund, Gast, & Wentura, 2013), or distributional analyses of sequence effects (taking into account congruency of the previous trial; see below).

Ridderinkhof (2002a) noted that the caution of interpreting delta-plot slopes is especially appropriate when interpreting the absolute value of the slope, whereas a relative interpretation of the slope when comparing conditions or groups remains meaningful. In this way, delta-plot slopes have been used in clinical psychological research to compare cognitive control processes in healthy controls with those in Parkinson patients (Wylie, Ridderinkhof, Bashore, & van den Wildenberg, 2010) or patients with attention-deficit/hyperactivity disorder (Ridderinkhof, Scheres, Oosterlaan, & Sergeant, 2005; Soutschek et al., 2013). Similarly, in social psychology, delta-plot slopes have been used to investigate social facilitation processes (results obtained in a social facilitation condition were compared with results from a control condition; Sharma et al., 2010).

Distributional properties across modalities

The visual Simon and Stroop task versions described above are widely used, but several variants of each interference task have been developed (see Hommel, 2011; Lu & Proctor, 1995; MacLeod, 1991), including auditory Simon and Stroop variants (e.g., Cohen & Martin, 1975; Green & Barber, 1981; Hamers & Lambert, 1972; Leboe & Mondor, 2007; Morgan & Brandt, 1989; Shor, 1975; Simon & Small, 1969). In fact, the original Simon task developed by Simon and Small (1969) used auditory material: In this task, participants heard high-pitched or low-pitched tones to which they had to respond with a left or right keypress. Monaurally presented tones produced spatial compatibility effects: Participants classified high- and low-pitched tones faster when the tone was presented at the respective side where the key had to be pressed (e.g., a high-pitched tone, for which participants had to press a left key, presented to the left ear; congruent trials) relative to cases where tone location and key location mismatched (e.g., a high-pitched tone, requiring a left-key response, presented to the right ear; incongruent trials). In addition to visual and auditory task versions, tactile Simon tasks have been developed (e.g., Hasbroucq & Guiard, 1992; Salzer et al., 2013). Salzer et al. (2013) presented horizontally aligned tactile stimuli (continuous or pulsed) on the back of the participants' torso, and participants were required to discriminate between continuous and pulsed vibration with a left or right keypress; in this task, Simon interference was observed.

For the Stroop task, the original version developed by Stroop (1935) presented visual material (and required spoken responses), but variants with auditory stimuli also exist. For example, Green and Barber (1981) developed an auditory Stroop task in which they presented the words "man" or "girl" spoken by a female or male speaker. Participants were instructed to respond to either the gender of the speaker (while ignoring word meaning), or they were instructed to respond to the meaning of the word (while ignoring speaker's gender). Contrary to the classical Stroop task (for which interference effects are typically reliable only when participants are requested to name the surface color but not when they are requested to name the word meaning; MacLeod, 1991), interference effects in this auditory Stroop task were found for both task versions.

As pointed out in the introduction, it may sometimes be advantageous to use auditory interference tasks instead of their visual counterparts (e.g., applying an auditory instead of a visual Stroop variant might be advantageous when children or patients with reading disabilities are tested). However, this presupposes that auditory and visual interference tasks can be used interchangeably. At least for the Simon task, results of distributional analyses suggest instead that different processes underlie visual and auditory Simon effects. For example, Wascher, Schatz, Kuder, and Verleger (2001) compared results of an auditory and a visual Simon task with the help of distributional analyses. In the visual Simon task, target stimuli consisted of the letters A and B that randomly appeared on the left or right side of a computer screen; in the auditory Simon task, high- and low-pitched tones were presented via loudspeakers positioned on the left or right side. Wascher et al. (2001) speculated that result patterns should be similar between tasks if processes underlying auditory and visual Simon effects are comparable. Yet, results of the auditory and the visual Simon effect differed remarkably: A positive delta-plot slope was found for the auditory Simon task, whereas the negative delta-plot slope could be replicated for the visual Simon task. In an additional crossed-hand condition (participants were asked to press a left response key with their right hand and a right response key with their left hand), the pattern of the distributional analysis of the auditory Simon effect was less clear, but there was still no evidence for a decrease of the Simon effect with increasing RT. A positive delta-plot slope in an auditory Simon task was replicated by Proctor and Shao (2010) who also presented high- and low-pitched tones from left- and right-positioned loudspeakers; in contrast to Wascher et al. (2001), this pattern even occurred in a crossed-hand condition.

While the result pattern of distributional analyses is relatively stable for visual horizontal Simon tasks (a negative delta-plot slope) and for auditory horizontal Simon tasks (a positive delta-plot slope), the pattern is less clear-cut for the tactile Simon task reported by Salzer et al. (2013). In Experiments 1 and 2, interference did not decrease with longer RT (in Experiment 1, only left and right tactors, i.e., vibrating tactile actuators, were used; in Experiment 2, vertical neutral upper and lower tactors were administered). Yet, different results were obtained in Experiment 3. In this experiment, a third, centrally positioned neutral tactor was applied. This time, similar to the visual horizontal Simon effect, a negative slope was found.

As elaborated above, for the visual Stroop task, it has been found that interference effects increased with increasing RT (Pratte et al., 2010; Sharma et al., 2010; Soutschek et al., 2013). Similar results were reported for a cross-modal Stroop version with visual targets and auditory distracters (Elliott et al., 2014). To the best of our knowledge, distributional analyses have not yet been reported for auditory Stroop effects; therefore, it is unclear whether a positive delta-plot slope can also be found for the auditory modality (although a positive slope would perhaps be the most likely outcome as negative slopes have consistently only been found for the visual Simon task with horizontally aligned stimuli). To test this assumption, we replicated both versions of the verbal-auditory Stroop task reported by Green and Barber (1981) to analyze the distributional properties of the auditory Stroop effect. Participants heard the word "Mann" (man) or "Frau" (woman) spoken by a male or a female speaker presented via headphones. In the Gender Stroop, participants were instructed to respond to the gender of the speaker while ignoring the spoken word. In the Word Stroop, participants indicated whether the word "man" or "woman" was spoken by simultaneously ignoring the gender of the speaker.[1] The delta plots for the two tasks (see Fig. 2, panel A1) are highly similar and differed neither in slope nor in intercept, $ps > 0.42$.[2] The delta-plot slopes were found to be reliably positive in the Word Stroop ($M = 0.11$, SD $= 0.20$; $t(23) = 2.74$, $p < 0.05$) as well as in the Gender Stroop ($M = 0.15$, SD $= 0.17$; $t(23) = 4.08$, $p < 0.01$), similar to those of the visual Stroop task (Pratte et al., 2010; Sharma et al., 2010; Soutschek et al., 2013) and the cross-modal Stroop version (Elliott et al., 2014).

Theoretical accounts

As explained above, the absence of a negative delta-plot slope in vertical visual Simon tasks is explained by assuming that there is no automatic activation of responses, as vertically aligned stimuli do not directly correspond with the response arrangement (left and right hand), rendering an active suppression of automatically activated responses unnecessary. Yet, in the case of auditory Simon tasks with horizontally aligned stimuli, delta-plot slopes were also found to be positive (Proctor & Shao, 2010; Wascher et al., 2001), although stimuli are presented in a horizontal manner. This suggests that the horizontal arrangement of stimuli alone cannot explain this qualitative discrepancy. To explain the discrepancy in delta-plot slopes in horizontal visual and auditory Simon tasks, Wascher et al. (2001) assumed that the negative delta-plot slope for overall RT in a visual horizontal Simon task might reflect a decay/suppression of a very fast response tendency directed toward the source of activation that should be visually guided (see also Proctor & Shao, 2010): They speculated that the early activation of a corresponding response in visual horizontal Simon tasks might reflect a tendency to reach toward the source of activation; as reaching or grasping should be visually guided, the activation (that is subsequently suppressed or decays spontaneously, leading to negative delta-plot slopes) should be a characteristic of

[1] In the original task, the words "man" and "girl" were used. Here, we used the monosyllabic word "Frau" (woman) instead of "Mädchen" (girl) to maximize comparability with the word "Mann" (man). Participants first practiced the respective task with which they started during a block consisting of 40 trials. Subsequently, participants performed three experimental blocks of this task with 40 trials each. After completion of the first task, participants practiced the second task during one block of 40 trials and then performed three experimental blocks of the second task with 40 trials each. Twenty-four University of Freiburg students (13 women) participated for course credit or as paid volunteers; mean age was 26 years, ranging from 18 to 46 years.

[2] The RT distribution was divided into nine bins; slopes of the individual delta plots were estimated via ordinary least-squares regression (see also Pratte et al., 2010).

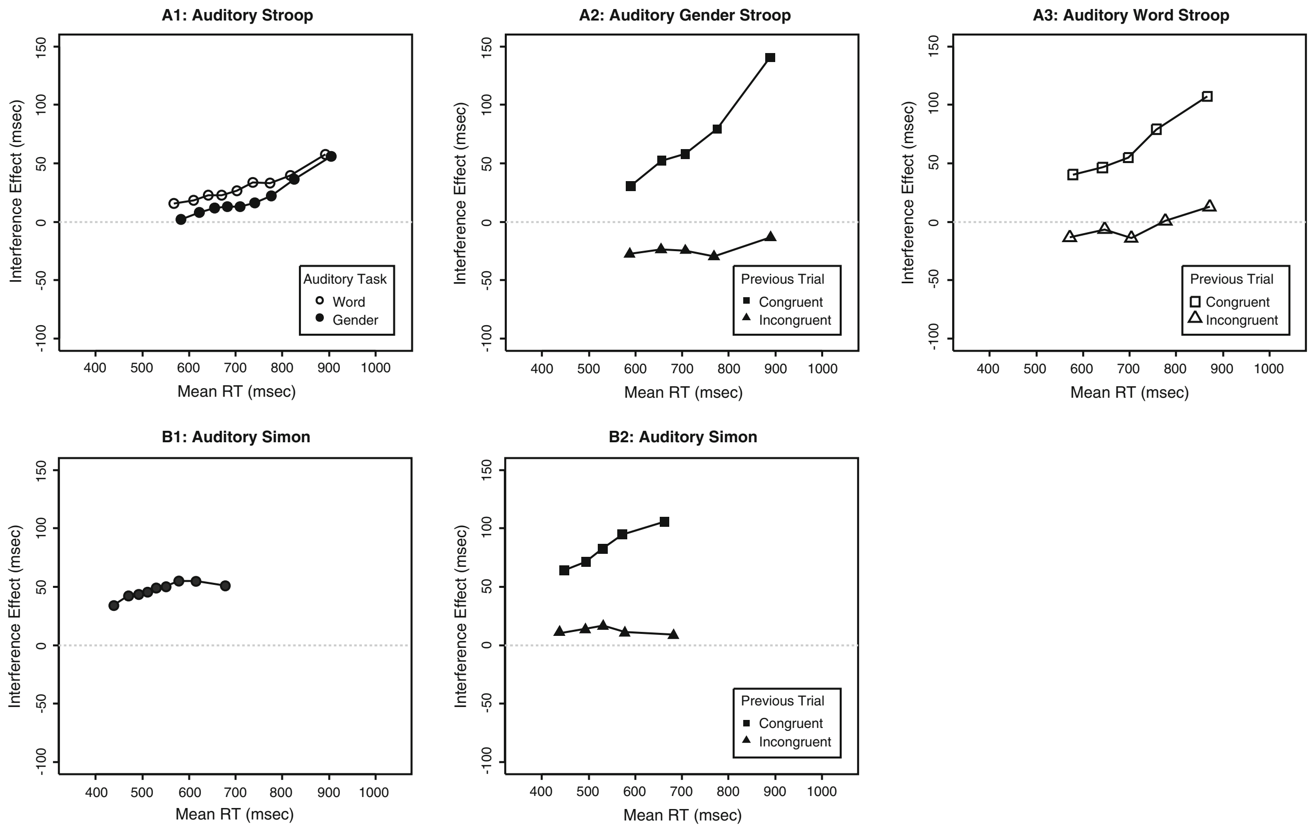

Fig. 2 Delta plots for an auditory Stroop task (panels A1–A3; replication of Green & Barber, 1981; unpublished data) and for an auditory Simon task (panels B1–B2; high- and low-pitched tones had to be discriminated with a left or right keypress; unpublished data). Delta plots are depicted for overall interference effects (panels A1 and B1) as well as separated by previous congruency (panel A2 shows sequential delta plots for the Gender Stroop depicted by the filled symbols in panel A1; panel A3 shows sequential delta plots for the Word Stroop depicted by the open symbols in panel A1; panel B2 shows sequential delta plots for the auditory Simon task in panel B1)

the visual system, and therefore, the pattern of negative delta-plot slopes should be limited to the visual horizontal Simon task. This assumption is consistent with a fundamental difference in neuronal processing of visual versus auditory information.[3] Whereas visual information is processed in a more lateralized manner (the lateral visual information from each eye is projected only to the ipsilateral visual cortex), auditory information is merged early in the information processing stream and projected bilaterally to each auditory cortex (information from both ears is combined subcortically in the left and right nucleus olivaris, and subsequently in the inferior colliculi, before it is projected to the auditory cortex). This is in line with the notion by Neumann, van der Heijden, and Allport (1986) (see also Wascher et al., 2001), that visual and auditory processing differ in many regards, manifested in fundamental differences between visual and auditory spatial attention. For instance, they pointed out that "visual processing takes place 'locally'—with respect to information emanating from a spatially distinct source […]" whereas "Sounds from different sources are not spatially coded at the sensory periphery." [p. 185].

The finding from the tactile Simon task (Salzer et al., 2013) that a negative delta-plot slope was only found in Experiment 3 that featured a third, centrally positioned neutral stimulus location suggests a crucial role of the neutral stimulus. One possibility is that inclusion of this condition may have altered the underlying processes in a qualitative manner (e.g., by rendering the horizontal stimulus dimension salient). Alternatively, the difference may be quantitative; for instance, the different degree of negativity in delta-plot slopes may be due to heightened overall levels of proactive control across studies (as suggested by Salzer et al., 2013). Thus, Salzer et al.'s findings suggest that, in addition to sensory modality, other factors appear to be involved in explaining the negative delta-plot slope in the case of the tactile modality.

Whereas distributional properties are quite heterogenous for different Simon task variants, the result pattern seems to be more stable for Stroop tasks. For visual Stroop tasks, positive delta-plot slopes have been previously reported by Pratte et al. (2010) (see also Sharma et al., 2010; Soutschek

[3] We thank Mike Pratte for pointing out this interrelation.

et al., 2013; for a cross-modal Stroop version, see Elliott et al., 2014). In a replication of the auditory Stroop task of Green and Barber (1981), we found positive delta-plot slopes for both auditory Stroop variants (the Gender and Word Stroop). However, as explained above, a positive delta-plot slope is not diagnostic for a specific theory and therefore, several process theories are consistent with this finding.

Methodological issues

Whereas interference effects in Stroop and Simon tasks are robustly obtained in both visual and auditory modality, it has rarely been investigated whether the processes underlying interference effects observed in visual and auditory tasks are comparable (for notable exceptions, see O'Brien, Williams, Bundy, Lyons, & Mittal, 2008, who examined effects in visual, auditory, and vibrotacile stimulus–response compatibility tasks; Roberts & Hall, 2008, who examined auditory and visual Stroop tasks; and Schumacher, Schwarb, Lightman, & Hazeltine, 2011, who studied auditory and visual Flanker tasks). Neumann et al. (1986) even argued that because of the fundamental difference between auditory and visual information processing, models should be developed within one modality before comparing mechanisms across sensory systems.

For Simon tasks, in light of clear differences at broad levels of analysis, it may be questioned whether conclusions based on visual Simon variants can be generalized to auditory Simon variants—as has been done, for example, in research on the social Simon effect (Sebanz, Knoblich, & Prinz, 2003) which occurs when two participants perform a Simon task together (i.e., each participant responds to only one of the two stimuli). Although the task reduces to a simple go/no-go task for which Simon effects are typically absent or remarkably reduced (Shiu & Kornblum, 1999), a Simon effect is nevertheless observed in the social condition. Whereas social Simon effects have previously been ascribed to shared task representations (Sebanz et al., 2003), a more recent alternative account explains the social Simon effect with a spatial component inherent in the social Simon task (Dittrich, Rothe, & Klauer, 2012; Dolk, Hommel, Prinz, & Liepelt, 2013; Guagnano, Rusconi, & Umiltà, 2010). However, evidence for the alternative account partly comes from auditory Simon tasks (Dolk et al., 2013), and partly from visual Simon variants (Dittrich et al., 2012; Guagnano et al., 2010). As the precise spatial arrangement appears to affect underlying processes in the visual but not in the auditory Simon effect, the results obtained with auditory and visual Simon variants may not be comparable; this fact should be considered in future work. Aside from the social Simon effect, the influence of sensory modality may be underestimated also in other fields (e.g., in emotional influences on conflict processing; Kanske & Kotz, 2012).

Based on the above results of distributional analyses, visual and auditory Stroop tasks appear to be more comparable than visual, auditory, and tactile Simon tasks. Thus, one might argue that processes underlying visual and auditory Stroop variants are at least broadly comparable and therefore it may be appropriate to apply both variants interchangeably, for instance in assessments of cognitive ability in patient populations or healthy controls (e.g., Friedman & Miyake, 2004; Stahl et al., 2013; Sebastian et al., 2013). Yet, in investigations of underlying processes, because of the relatively coarse level at which delta-plot analyses are performed, it appears to be an unwarranted simplification to treat all Stroop-like effects as equivalent (as, for instance, in research on cognitive load or perceptual dilution; e.g., Chen, 2003; De Fockert, Rees, Frith, & Lavie, 2001; Dittrich & Stahl, 2011, 2012; Kahneman & Chajczyk, 1983; Kim, Kim, & Chun, 2005). As we argue below, to compare interference effects across task versions, it might be useful to develop and use more fine-grained distributional analyses, for example by considering sequential effects.

Sequential modulation of distributional properties

Sequential modulation refers to the finding that interference is typically larger in trials following congruent stimuli than in trials following incongruent stimuli (for a review, see Egner, 2007). Such sequential modulation of interference has first been demonstrated for the Flanker task (Gratton, Coles, & Donchin, 1992) and subsequently reported also for other tasks such as the Stroop task (e.g., Jiménez & Méndez, 2013; Kerns et al., 2004; Notebaert, Gevers, Verbruggen, & Liefooghe, 2006) and the Simon task (e.g., Hommel, Proctor, & Vu, 2004; Stürmer et al., 2002; Wühr & Ansorge, 2005). The sequential modulation of interference effects has often been interpreted as the result of cognitive control mechanisms (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Gratton et al., 1992; see below for an alternative explanation in terms of feature bindings proposed by Hommel et al., 2004): Trials evoking a conflict (i.e., incongruent trials) are assumed to activate cognitive control mechanisms that affect performance not only on the current trial but also on subsequent trials.

Ridderinkhof (2002a) used delta plots to examine distributional properties of sequential effects in a visual horizontal Simon task. Separate delta plots were computed for trials following congruent and incongruent stimuli (for the sake of brevity, we will call this a sequential delta plot). Negative slopes were found only for trials following incongruent stimuli, whereas the slope for trials following congruent stimuli was positive (with a negative trend for the last RT bin). This result suggests that theoretically relevant findings (e.g., negative delta-plot slopes) may be masked by the custom of reporting a single overall delta plot that ignores the sequential modulation effect. For example, as explained above, it is still unclear why positive delta-plot slopes are found for auditory Simon effects albeit stimuli are also presented in a horizontal manner (as in the visual horizontal Simon task for which negative delta-plot slopes are found). However, the discrepancy may be quantitative rather than qualitative: Perhaps a negative delta-plot slope can be found for the auditory horizontal Simon variant in sequential delta plots (i.e., a negative delta-plot slope may be found in trials following incongruent stimuli, because cognitive control processes might be specifically elevated), but may be masked by aggregating over trial types. To examine this issue, we conducted an auditory Simon task and analyzed distributional properties of sequential effects. Participants heard high- or low-pitched tones that were presented monaurally via headphones; they had to indicate whether the tone was high or low by pressing one of two spatially aligned response keys, while ignoring the position at which the tone was presented (left ear, right ear).[4] The delta-plot slope for overall RT was found to be positive ($M = 0.09$, $SD = 0.15$; $t(23) = 3.09$, $p < 0.01$), replicating previous results (Proctor and Shao, 2010; Wascher et al., 2001; see also Fig. 2, panel B1). The sequential delta-plot analysis revealed that slopes differed significantly as a function of previous congruency, $t(23) = 2.78$, $p = 0.01$. A positive slope was found in trials following congruent stimuli ($M = 0.19$, $SD = 0.17$; $t(23) = 5.39$, $p < 0.01$), whereas the slope did not differ significantly from zero in trials following incongruent stimuli ($M = 0.04$, $SD = 0.22$; $t(23) = 0.85$, $p = 0.40$); see also Fig. 2, panel B2. Thus, sequential delta plots of an auditory Simon task revealed that the slopes differed as a function of previous congruency: A positive delta-plot slope was found only for trials following congruent stimuli, whereas the slope was zero for trials following incongruent stimuli.

Similar results were obtained for the auditory Stroop task described above, for which we also conducted distributional analyses of sequential effects. In the Gender Stroop (Fig. 2, panel A2), a positive delta-plot slope was only found for trials following congruent stimuli ($M = 0.32$, $SD = 0.30$; $t(23) = 5.13$, $p < 0.01$), whereas the delta-plot slope did not differ significantly from zero in trials following incongruent stimuli ($M = 0.04$, $SD = 0.25$; $t(23) = 0.73$, $p = 0.47$). The difference between slopes for trials following congruent versus incongruent stimuli was significant, $t(23) = 3.21$, $p < 0.01$. For the Word Stroop (Fig. 2, panel A3), a positive delta-plot slope was also found only for trials following congruent stimuli ($M = 0.21$, $SD = 0.25$; $t(23) = 3.96$, $p < 0.01$). Again, the delta-plot slope did not differ significantly from zero in trials following incongruent stimuli ($M = 0.06$, $SD = 0.26$; $t(23) = 1.15$, $p = 0.26$). The difference between the positive slope for trials following congruent stimuli versus the null slope following incongruent stimuli was again significant, $t(23) = 2.36$, $p < 0.05$. In other words, null slopes after incongruent trials were masked by aggregating across previous congruency. This suggests that null or even negative slopes following incongruent trials may similarly be masked by aggregation in other interference tasks and may go undetected by overall delta-plot analyses.

Theoretical accounts

As described above, Ridderinkhof (2002a) found a negative delta-plot slope in a horizontal Simon task only for trials following incongruent stimuli, whereas the slope for trials following congruent stimuli was positive. These and similar results (Hazeltine, Akçay, & Mordkoff, 2011; Wylie et al., 2010) were interpreted as evidence for the assumption that, in Simon tasks, a fast automatic response activation is counteracted by a slower process of active suppression or inhibition. The level of inhibition remains elevated after incongruent trials, leading to smaller subsequent interference effects as well as delta-plot slopes being more negative. This interpretation suggests that both the negative delta-plot slope and the sequential effect result from the same inhibitory control process. At first glance, the pattern of null slopes after incongruent trials found for the auditory Stroop and Simon task might appear inconsistent with Ridderinkhof's (2002a) account because the account predicts initially increasing interference that is actively inhibited only with longer RTs. However, residual inhibition activated in previous incongruent trials might simply affect the shape of the delta-plot, resulting in more negative (i.e., less positive) slopes.

In an another account, Stürmer et al. (2002) also referred to suppression processes, but in contrast to Ridderinkhof's (2002a) activation/inhibition account, they assumed that suppression is characterized by a complete blocking of the unconditional route, that is, the elimination of response activation by irrelevant stimulus location. In contrast to the prediction, by the activation/inhibition account, that initial

[4] Key mapping was counterbalanced across participants. Participants practiced the task in a block consisting of 24 trials. Subsequently, they performed two experimental blocks of 96 trials each. Twenty-four students from University of Freiburg (17 women) participated for course credit or as paid volunteers; mean age was 22 years, ranging from 19 to 34 years.

interference is due to activation by irrelevant location information and is actively inhibited later during the trial, Stürmer et al.'s blocking account suggests the complete absence of interference across the entire RT distribution. This blocking account can well explain the pattern of sequential modulation by previous congruency found for the auditory interference tasks: In trials following incongruent stimuli, response activation by irrelevant stimulus location was completely blocked, manifested in flat delta-plot slopes in those trials. It is unclear, however, how blocking could explain sequential effects in the visual horizontal Simon task, where inverted interference effects are sometimes found (e.g., Burle, van den Wildenberg, & Ridderinkhof, 2005; Pratte et al., 2010). To summarize, it remains to be seen whether two qualitatively distinct types of inhibitory and blocking processes are operating to control interference in Stroop and Simon tasks, or whether different slopes (positive, null, and negative) reflect quantitative differences in the strength of inhibitory processes.

Methodological issues

The finding of systematically different slopes for different subsets of trials demonstrates that sequential delta-plot analyses are useful: Here, they exemplify that interference in auditory Stroop tasks follows regularities similar to those obtained in auditory Simon tasks. Importantly, these findings (see also Ridderinkhof, 2002a) also suggest that delta plots of overall interference effects may mask theoretically relevant findings, in particular negative slopes. By analyzing distributional properties of sequential effects, one could consider the possibility that negative delta-plot slopes may occur also in interference tasks other than the visual Simon with horizontal stimuli, but that evidence for such results may be masked by the custom of reporting a single overall delta plot that ignores the sequential modulation effect. A similar argument was recently made by Burle, Spieser, Servant, and Hasbroucq (2013) who argued that negative delta-plot slopes might be obtained in a visual flanker task in certain trials containing "partial errors" although overall delta-plot slopes in flanker tasks typically have a positive slope (e.g., Davranche, Hall, & McMorris, 2009). Burle et al. (2013) recorded electromyograms of muscles that are involved in response execution and found negative delta-plot slopes in flanker trials that showed subthreshold electromyogram activity in muscles involved in the incorrect response. A positive delta-plot slope was found in all other trials. Presumably, partial-error trials involve online inhibitory control, comparable to trials following incongruent stimuli.

As explained above, sequential modulation of interference effects has often been interpreted as a result of cognitive control mechanisms in a sense that incongruent trials are assumed to activate cognitive control mechanisms that continue to be applied in subsequent trials (Botvinick et al., 2001; Gratton et al., 1992). An alternative explanation invokes S–R binding processes (Hommel et al., 2004). To illustrate, in standard Simon tasks, four different stimuli (or feature combinations) are presented, which are to be classified using two response buttons (e.g., a high-pitched or a low-pitched tone, presented to the left or right ear, has to be discriminated with a left or right response keypress). As a consequence, in the majority of cases, one or more of the features of the previous trial (stimulus and/or required response) are repeated in the current trial, with complete alternations only in a minority of trials. Such feature repetitions have been argued to affect performance and contribute to sequential modulation of interference effects (Hommel et al., 2004; Mayr, Awh, & Laurey, 2003). Specifically, stimulus and response codes are assumed to bind together in trial *N*-1, and this binding is assumed to persist in trial *N* (Hommel, 1998; Hommel et al., 2004). If the entire compound is repeated (or alternated) in trial *N*, improved performance is to be expected; in contrast, in case of a partial repetition, performance is impaired because the features must be un-bounded and re-combined to form a new compound (or because the repeated stimulus feature activates the previous response; Hommel et al., 2004).

The difficulty in explaining distributional properties of sequential effects is that, at least for the classical Simon task, feature repetition is confounded with congruency of the previous trial. To illustrate, following congruent predecessors, congruent trials represent either complete repetitions or complete alternations, resulting in facilitation, whereas incongruent trials following congruent predecessors are always partial repetitions, resulting in impaired performance. An increased interference effect after congruent trials can therefore be accounted for by S–R binding. In contrast, following incongruent predecessors, a congruent trial always represents a partial repetition, whereas incongruent trials represent either complete repetitions or complete alternations; a reduced or eliminated interference effect in this case may thus also be explained in terms of S–R binding. This implies that the sequential delta-plot pattern, which we interpreted above as reflecting cognitive control processes, may instead be accounted for by S–R binding. Importantly, this problem is inherent in many studies of sequential modulation effects (for a discussion of this issue see Egner, 2007). In fact, it may well turn out to be impossible to eliminate because, to avoid confounding both factors, the paradigms to be investigated must be modified; yet, if the required modifications are substantial, this approach incurs the risk that the results obtained with such modified variants may not apply to the original paradigm. Studies using modified designs have found that, when feature repetition is controlled, Simon interference remains to be sequentially modulated by the congruency of the previous trial (e.g., Salzer et al., 2013). To conclude, sequential modulation effects may be alternatively interpreted as resulting from repetition of processes (Mayr et al., 2003) or repetitions of stimulus features and responses (Hommel et al., 2004). Recent work suggests that these alternative explanations should be taken to complement rather than replace the cognitive control account (Jiménez & Méndez, 2013). Methodologically, modifications of the classical interference paradigms are necessary to disentangle these accounts. From a theoretical perspective, however, it is unclear whether such modified approaches will be successful, as both processes may be inseparably intertwined at a more fundamental level (Spapé & Hommel, 2008).

As suggested by the above considerations, the approach of breaking down the overall delta plot into separate plots for congruent and incongruent predecessors may be only a first step: The resulting sequential delta plots may themselves represent a mixture of different underlying distributions, be they manifest (e.g., feature repetition vs. alternation) or latent (e.g., different levels of attentional control). Yet, if one were to analyze even smaller subsets of the data, it may become increasingly difficult to obtain stable estimates of the shapes of RT distributions. To estimate distributional properties even with scarce data, hierarchical analyses may be helpful (see Matzke, Dolan, Logan, Brown, & Wagenmakers, 2013, for an analysis of stop-signal RT distributions).

Concluding remarks

In the present work, we have reviewed distributional analyses of different interference effects (Simon and Stroop), as well as effects of stimulus modality (visual, auditory, tactile) and sequential modulation by previous congruency. In distributional analyses of overall interference effects, negative delta-plot slopes have been consistently found only in visual Simon tasks with horizontally aligned stimuli (see Proctor et al., 2011). In contrast, positive slopes were found for other Simon tasks (e.g., for auditory Simon tasks; Proctor & Shao, 2010; Wascher et al., 2001; but see Experiment 3 of Salzer et al., 2013) as well as for visual Stroop tasks (e.g., Pratte et al., 2010). We found similar positive delta-plot slopes also in auditory Stroop tasks. To summarize, a negative delta plot has been found for Simon but not for Stroop tasks, but neither horizontal alignment nor the visual stimulus modality alone are sufficient to explain this striking pattern.

For Simon tasks, previous work has established negative delta-plot slopes as a marker of active inhibition processes building up over time, thereby reducing Simon interference more strongly for slower responses (Ridderinkhof, 2002a). The level of inhibition is assumed to be elevated after incongruent trials (in line with cognitive control accounts, e.g., Botvinick et al., 2001), leading to smaller subsequent interference effects as well as delta-plot slopes being more negative. Thus, both the negative delta-plot slope in overall RT and the sequential modulation may be explained by the same inhibition process. The advantage of this account over others (e.g., Stürmer et al., 2002) is its relative frugality (different slopes are assumed to reflect differences in the strength of inhibitory processes instead of reflecting different processes). However, despite its usefulness in explaining the negative delta-plot slope in visual horizontal Simon tasks, neither this nor any other account can satisfactory explain why negative delta-plot slopes are obtained only in visual horizontal Simon tasks. For instance, comparing visual and auditory horizontal Simon tasks, Wascher et al. (2001) speculated that the negative delta-plot slope for overall RT in a visual horizontal Simon task might reflect a decay/suppression of a very fast response tendency to reach toward the source of activation that should be visually guided. However, compared visual and auditory Simon tasks (Wascher et al., 2001; see also Proctor & Shao, 2010) also differed in other regards than only in sensory modality (e.g., pitch was the relevant target in auditory Simon tasks, whereas letters were the target stimuli in visual Simon tasks).[5] An examination of highly comparable visual and auditory Simon tasks might help to better understand differences and similarities in distributional properties of auditory and visual Simon effects.

The fundamental differences of distributional properties obtained for auditory and visual Simon effects contrast the homogenous pattern of positive delta-plot slopes obtained for auditory and visual Stroop effects. However, a positive delta-plot slope is consistent with the typical finding that RT standard deviations increase along with RT means (Wagenmakers & Brown, 2007). Thus, the pattern obtained for the Stroop tasks is in accordance with several general process theories (e.g., Ashby & Townsend, 1980; Ratcliff, 1978) and is therefore not suited to test a specific process or theory. Zhang and Kornblum (1997) even argued that this holds true also for negative delta-plot slopes. However, whereas distributional analyses might be too coarse to compare specific theories of underlying processes (Schwarz & Miller, 2012; Zhang & Kornblum, 1997), they may nevertheless yield important insights and point out

[5] Note that a subtle modification such as using letters (A and B) as target stimuli in the visual Simon task might in fact represent a fundamental change to the nature of the task: One may ask whether the visual Simon task used by Wascher et al. (2001) in fact reflected a spatial Stroop task, because the letters A and B might be associated with left and right responses, respectively.

important directions for future research. For example, delta plots may be used in fine-grained analyses of manifest component distributions (e.g., when comparing interference effects following congruent vs. incongruent predecessor trials). Delta-plot analyses may also be helpful in identifying and estimating the contribution of latent processes to the observed RT distribution that is often difficult to extract from noisy RT data (e.g., Matzke & Wagenmakers, 2009).

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