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Decreasing Auditory Simon Effects Across Reaction Time Distributions

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The Simon effect for left–right visual stimuli previously has been shown to decrease across the reaction time (RT) distribution. This decrease has been attributed to automatic activation of the corresponding response, which then dissipates over time. In contrast, for left–right tone stimuli, the Simon effect has not been found to decrease across the RT distribution but instead tends to increase. It has been proposed that automatic activation occurs through visuomotor information transmission, whereas the auditory Simon effect reflects cognitive coding interference and not automatic activation. In 4 experiments, we examined distributions of the auditory Simon effect for RT, percentage error (PE), and an inverse efficiency score [IES = RT/(1 − PE)] as a function of tone frequency and duration to determine whether the activation–dissipation account is also applicable to auditory stimuli. Consistent decreasing functions were found for the RT Simon effect distribution with short-duration tones of low frequency and for the PE and IES Simon effect distributions for all durations and frequency sets. Together, these findings provide robust evidence that left and right auditory stimuli also produce decreasing Simon effect distribution functions suggestive of automatic activation and dissipation of the corresponding response.

Keywords: auditory Simon effect, automatic activation, delta functions, inverse efficiency score, Simon effect distributions

When participants respond to a left or right stimulus with a left or right keypress in a choice reaction task, reaction time (RT) is shorter when the stimuli are mapped to their corresponding responses than when they are not (Shaffer, 1965). This stimulus–response compatibility (SRC) effect is obtained for both visual and auditory stimuli. A similar benefit of spatial correspondence known as the Simon effect occurs when a nonspatial dimension (e.g., color or tone pitch) is relevant and stimulus location is irrelevant (Simon, 1990).

For a Simon task in which visual stimuli occur in left and right locations and responses are made with the hands in a natural, uncrossed placement, the Simon effect decreases across the RT distribution (see Proctor, Miles, & Baroni, 2011, for review). This result is usually attributed to rapid activation of a spatial code corresponding to the stimulus location, which then dissipates (e.g., De Jong, Liang, & Lauber, 1994). Only a few studies have analyzed the Simon effect distribution for auditory stimuli, but those studies have found the effect to remain constant or increase as RT increases (e.g., Proctor & Shao, 2010). In the present study, we performed a detailed examination of the auditory Simon effect for various stimulus conditions, taking percentage error (PE) into account, and obtained evidence that the distribution functions vary in a manner consistent with an activation–dissipation account.

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Automatic Activation and Distribution Analysis of the Visual Simon Effect

Kornblum, Hasbroucq, and Osman (1990) proposed a dual-process model to explain SRC and Simon effects that emphasizes automatic activation of the spatially corresponding response. When the automatically triggered response and the correct response are congruent, responding is facilitated, but when they are incongruent, the response conflict delays response selection. Hommel (1993b) introduced the concept of temporal overlap in producing the Simon effect, for which the idea is that activation of the irrelevant spatial code occurs quickly (due to its being automatic) but then dissipates because it is irrelevant. If the initial burst of activation overlaps in time with activation of the code for the relevant stimulus dimension, a Simon effect occurs. The evidence he provided in support of the temporal overlap hypothesis is that the Simon effect decreased when the relevant discrimination was made more difficult.

De Jong et al. (1994) arrived at a similar conclusion from examining changes in the Simon effect across the RT distribution. They used a Vincentizing procedure (Ratcliff, 1979), in which a group RT distribution is obtained by partitioning each participant's RT on the congruent and incongruent trials into percentile bins (e.g., 10), ranging from shortest to longest, and measuring the Simon effect (the difference) for each bin. The Simon effect decreased as RT increased, which De Jong et al. (1994) attributed, like Hommel (1993b), to an unconditional component that produces automatic priming of the corresponding response. They also postulated a conditional spatial coding component that is locked to the time at which the assigned transformation rule is applied to the relevant stimulus information and thus does not vary across the RT distribution. Many other studies have reported decreasing functions for the visual left–right Simon effect (see Proctor et al., 2011, for a review).

The generality of the hypothesis of diminishing activation has been questioned by the results of studies that have not shown a decline of the Simon effect. Wascher, Schatz, Kuder, and Verleger (2001) varied whether the hands were in an uncrossed or crossed position (for which the right hand operated the left key and the left hand operated the right key), and Wiegand and Wascher (2005) compared the typical uncrossed, horizontal arrangement to a vertical stimulus–response (S–R) arrangement. Only in the case of the uncrossed hand position and horizontal S–R arrangement of stimuli did the Simon effect decrease as RT increased. For the other conditions, the effect increased or remained stable across the RT distribution. Thus, Wascher et al. (2001) proposed two mechanisms underlying Simon effects: *visuomotor information transmission*, which occurs rapidly and dissipates for the normal visual Simon task, and *cognitive coding interference* that occurs for the crossed-hands and vertical versions.

Counter to this distinction, Valle-Inclán and Redondo (1998) reported a decreasing Simon effect function with a vertical S–R arrangement, in which the mapping of stimulus colors to top and bottom response keys varied randomly from trial to trial, being signaled visually prior to onset of the imperative stimulus. Later, Wiegand and Wascher (2007) conducted experiments using vertical arrangements, with the relevant S–R mapping fixed or random. The Simon effect increased slightly across the RT distribution when the S–R mapping was fixed but decreased when the mapping was random. They conducted a third experiment manipulating fixed versus random mapping for the horizontal S–R arrangement. Although both conditions showed decreases in the last half of the distributions, the fixed mapping showed a more substantial increase across the first half, and the two functions fit together in a manner consistent with a single activation–dissipation function. Thus, for both the vertical and horizontal S–R arrangements, the activation and dissipation were evident.

Auditory Simon Effect Distribution

Although the Simon effect was first reported for left–right auditory stimuli (Simon & Rudell, 1967), and the auditory Simon effect is about twice as large as the visual one (Wascher et al., 2001), it has been studied less than the visual Simon effect. The few studies that examined the distribution functions for the auditory Simon effect have not shown the decreasing function obtained with left–right visual stimuli. In Wascher et al.'s (2001) Experiment 2, participants responded with left and right keypresses to 1,000- and 1,500-Hz tones of 200-ms duration, presented from left and right speakers. For both uncrossed- and crossed-hand placements, the Simon effect increased across the RT distribution. These results were replicated in a study by Proctor and Shao (2010) using stimuli of the same tone frequencies.

The finding that the horizontal auditory Simon effect does not decrease across the RT distribution suggests that the effect may have a different basis than the visual Simon effect (Dittrich, Kellen, & Stahl, 2014). This was the explanation given by Wascher et al. (2001), who attributed the auditory Simon effect to cognitive interference rather than visuomotor activation. However, a decreasing component across the last two of five bins was evident in Proctor and Shao's (2010) Experiment 1 (see their Figure 1), as well as for one of the conditions with crossed hands in Wascher et al.'s (2001) Experiment 2 (see their Figure 5B), suggesting that the activation–dissipation account may also apply to the auditory Simon task.

Dissipation of automatic activation in auditory Simon tasks is also supported by Simon, Acosta, Mewaldt, and Speidel's (1976) Experiment 2. In it, participants were asked to respond to the pitch of a 250- or 625-Hz tone of 100-ms duration by pressing a red or green key, labeled by the color of a light-emitting diode placed above the key. Which key was labeled red or green was fixed for one group of participants but varied randomly and previewed 1 s before tone onset for a second group. For four other groups, the key colors also varied randomly from trial to trial, but the color lights came on 0, 150, 250, or 350 ms after the tone onset. For the conditions in which the key colors were not designated before tone onset, response selection to the tone had to be delayed until the key colors appeared. A Simon effect caused by the tone location was obtained for the conditions in which the response keys were labeled prior to or simultaneous with tone onset but not for the other three conditions. This absence of the Simon effect when responses had to be delayed is consistent with the view that activation of the tone's location produced at onset dissipated over time.

Simon et al.'s (1976) study used tones of lower frequency and shorter duration than did the studies of Wascher et al. (2001) and Proctor and Shao (2010) that found mainly nondecreasing distribution functions for the auditory Simon effect. If Simon et al.'s (1976) results reflect dissipation of the activation produced at tone onset, one may expect that low-frequency stimuli of short duration will yield decreasing functions for the Simon effect. There is reason to think that the frequency difference between those studies is crucial, as pitch is among the most prominent perceptual features of sound (Yost, 2009). Also, people are less sensitive to tones below 1,000 Hz than to ones between 1,000 and 4,000 Hz when equating tones for loudness (Suzuki & Takeshima, 2004). This lesser sensitivity suggests that when tone frequency is the relevant dimension in a Simon task, tones in the low-frequency range may take longer to identify than those in the higher range. In contrast, localization should be easier for the low-frequency tones than for the higher frequency ones. For tones below 1,000 Hz, interaural time differences serve as the critical cue for tone localization, whereas for tones between 1,000 and 4,000 Hz, neither interaural time differences nor intensity differences provide good spatial cues (e.g., Casseday & Neff, 1973). A consequence of (a) more difficult identification of the relevant tone pitch and (b) easier determination of the tone location for low-frequency stimuli is that dissipation of the Simon effect should be evident in the distribution function.

The difference in tone durations between Simon et al.'s (1976) study (100 ms) and the Wascher et al. (2001) and Proctor and Shao (2010) studies (200 ms) may also be crucial, as duration is another essential dimension of auditory stimuli (Yost, 2009). Gregg and Brogden (1950a, 1950b) showed that simple RT to an auditory stimulus was affected by duration, increasing as the duration increased from 100 to 400 ms, with response-terminated stimuli tending to yield shorter RT than stimuli that remained on for a fixed duration. Additionally, sequential sampling models of choice reactions assume that responses result from accumulation of information from stimulus onset until a response threshold is reached (e.g., Ratcliff & Smith, 2004), suggesting that the rate of accumulation may change when duration varies (e.g., Ratcliff, 1980).

Distribution Functions for the Simon Effect in Percentage Error

Distribution analyses of PE are often not reported with those of RT, but they provide another gauge of automatic response activation. Ridderinkhof (2002a, 2002b) emphasized this point by plotting visual Simon effect distributions for PE as a function of the RT bin and showing that the PE Simon effect was largest at the early bins and then decreased. Többel, Hübner, and Stürmer (2014) noted these results and said with respect to visual tasks: "Usually, the Simon effect in error rates is relatively large for fast responses and decreases quickly towards zero, as late responses are highly accurate. This effect indicates fast automatic response activation by the location of the stimulus" (p. 47). Többel et al. (2014) compared horizontal and vertical S–R arrangements using distribution functions for PE and RT. The vertical arrangement showed a decreasing PE Simon effect function, leading them to conclude that automatic activation occurred for this function but to a lesser extent than for the horizontal arrangement. The studies of Ridderinkhof (2002a, 2002b) and Többel et al. (2014) for the visual Simon effect show that bin analysis should be performed on PE and RT to describe the time course of the auditory Simon effect.

Ideally, a measure is needed that combines the RT and PE analyses. Townsend and Ashby (1978, 1983) described the inverse efficiency score (IES), for which RT is adjusted by dividing it by 1 − PE (the proportion of correct responses). The IES, which can be regarded as a measure that gauges the average energy consumed by the system over time (Townsend & Ashby, 1983, p. 204), has been used in various areas of cognitive psychology (e.g., Goffaux, Hault, Michel, Vuong, & Rossion, 2005). To analyze the Simon effect across the RT distribution, we implemented this measure in addition to the separate analyses of RT and PE.

Present Study

In the following, we present four experiments for which tone pitch was the relevant stimulus dimension, as in most auditory Simon effect studies. Experiment 1 used tones of 200 and 500 Hz to determine whether tone frequencies below 1,000 Hz would yield a decreasing Simon effect distribution function, as our prior arguments imply. Tone duration was also varied, being 100 ms, 200 ms, or response terminated. With a decreasing function evident in Experiment 1, Experiment 2 compared the distributions for 200-ms duration tones in a low- or high-frequency range, confirming the impact of tone frequency on the auditory Simon effect distribution for RT but not PE or IES. Experiment 3 provided a within-subjects comparison of the 200-ms and response-terminated conditions with low-frequency tones in a more typical Simon task setting. The results showed an order effect for the duration condition, but similar results were obtained in Experiment 4 when participants performed two sessions with one condition or the other. Regardless of the RT distribution pattern, for all conditions in all experiments, the PE and IES distributions showed decreasing functions.

Experiment 1

Experiment 1 was designed to examine the temporal properties of the auditory Simon effect for stimulus tones in the frequency range below 1,000 Hz. For the Simon task, the stimuli were 200- and 500-Hz tones, located to the left or right. Three tone duration conditions were used for different participants: 100 ms, 200 ms, and until the response was made. The first two tone durations are ones used in prior studies, 100 ms by Simon et al. (1976) and 200 ms by Wascher et al. (2001) and Proctor and Shao (2010). Presenting the stimulus until the response is registered has been mainly used for visual stimuli (e.g., Simon et al., 1976; Wühr & Kunde, 2006). We anticipated that activation and dissipation of the corresponding response would be more evident with these low-frequency stimuli than with the higher frequency ones used in prior studies, revealing the dissipation portion of the Simon effect distribution. RT was expected to be shorter for the response-terminated condition (e.g., Gregg & Brogden, 1950a), which should result in it showing more of the early part of the activation function.

Method

Participants. Eighty-four students (29 male, 55 female) participated. All participants in this and the remaining experiments (a) were enrolled in an introductory psychology course at Purdue University and received research credits, (b) reported having normal or corrected-to-normal vision and audition, and (c) were naïve to the purpose of the study. Twenty-eight participants were randomly assigned to each of the three stimulus duration conditions. Six additional participants, two from each condition, were excluded, applying criteria of overall mean RT greater than 800 ms (more than 2.5 *SD* above the mean) or PE greater than 10%.

Apparatus and stimuli. Participants were tested in the apparatus of a driving simulator, but no driving display was used. The participant sat in front of a 76-cm-high table on which an Extreme Competition Controls (ECCI, Burnsville, Minnesota) steering wheel was mounted 10° off vertical and tilted away from the participant. The distance between the seat and the bottom of the wheel was about 25 cm. Instructions, a fixation cross, and a visual response error message were presented on a 2.5 m × 1.9 m (width × height) projector screen in front of the participant. The stimuli were 200- and 500-Hz tones of approximately 55 and 58 dBA, respectively. Each tone was delivered by one of two speakers located in front of the steering wheel desk, to the left and right of the participant, at a 50-cm distance. The response keys were two red buttons on the top half of the wheel, one on the left and the other on the right, on which the thumbs of the respective hands rested while the wheel was gripped by the remaining fingers and held stationary. Responses were a press of one of the buttons with the corresponding thumb. Stimulus presentation, response recording, and data collection were controlled by E-Prime 2.0 software installed on a Dell PC workstation.

Procedure. The three stimulus duration conditions were 100 ms, 200 ms, and response terminated. Participants familiarized themselves with the task by first completing 12 practice trials that were not subjected to analysis. The following 240 experimental trials were separated into two blocks of 120 trials each. Each block included an equal number of congruent and incongruent trials. For congruent trials, the stimulus was presented to the same side as the correct response, whereas for incongruent trials the stimulus was on the opposite side of the response. Participants were told to put their thumbs on the response buttons during the whole experiment and to respond as quickly and accurately as possible.

Each trial began with the presentation of a fixation cross, lasting 50 ms, in the center of the screen. After 500 ms, a tone was presented via the left or right speaker, to which a button-press response was to be made based on the pitch. An intertrial interval of 1,500 ms began immediately after a correct response or following a 1,000-ms visual error message ("Incorrect!") after an incorrect response. If no response was detected within 2,000 ms of stimulus onset (0.2% on average for each experiment), the trial was terminated and an error message ("No response detected! Please respond faster!") was presented for 1,000 ms on the screen. Stimulus pitches and locations were randomized within each trial block.

The mapping between tone pitches and response buttons was counterbalanced between participants: Half the participants in each condition were instructed to respond with the left button for a low pitch tone and the right button for a high pitch tone, and half were instructed to do the opposite. After the first block, participants were instructed to take a break and told that they could start the second block whenever they were ready. The experimenter stayed in the dimly lit room for the practice trials but then left the room for the test trials.

Results

In this experiment and all others, trials with premature responses (RT less than 150 ms) or for which RT was greater than 2.5 *SD* above each participant's overall mean were excluded (2.4% for the 100- and 200-ms conditions; 2.8% for the response-terminated condition). The remaining correct RTs of each participant in each condition were rank ordered from shortest to longest and divided into 10-percentile bins. Ten bins allowed isolation of the 10% fastest responses, which are most likely to be subject to automatic activation, and provided a detailed depiction of the distributions. Mean RTs of congruent and incongruent trials in each bin were calculated for each participant, as were PE and IES [RT/(1 − PE)]. For each measure, a 10 (Bin: 1 to 10) × 2 (Congruency: congruent, incongruent) × 3 (Stimulus Duration: 100 ms, 200 ms, response terminated) analysis of variance (ANOVA), with the first two factors within subjects, was performed. For the bin factor, the reported *p* values for all terms in this and the other experiments are those for the Greenhouse–Geisser correction (Girden, 1992). The means for the conditions are shown in Table 1, and the ANOVA values are shown in Table 2.

Reaction time. Responses were 40 ms faster when stimulus location was congruent with response location than when it was not. This Simon effect was of similar size for the three stimulus durations (see Table 1), as shown by a lack of two-way interaction of Congruency × Duration (see Table 2). Stimulus duration had a main effect, with mean RT decreasing from the shortest to longest durations (*M*s = 578, 521, and 500 ms for the 100-ms, 200-ms, and response-terminated conditions, respectively). Post hoc Bonferroni tests revealed that RT was longer in the 100-ms condition than in the response-terminated condition, $p = .002$, and the 200-ms condition, $p = .036$, with the latter two conditions not differing significantly.

There was a main effect of bin due to the rank ordering of RTs and a Bin × Duration interaction. Of interest are the significant

Table 1
Mean Reaction Time and Percentage Error With Standard Errors for Congruency Between Response Location and Tone Location (Congruent vs. Incongruent) and Simon Effects for Each Condition and Order or Session of Experiments 1–4

Condition	Order or Session	RT (ms) Congruent	RT (ms) Incongruent	RT (ms) Simon effect	PE (%) Congruent	PE (%) Incongruent	PE (%) Simon effect
Experiment 1							
100 ms	N/A	559 (16)	598 (16)	39	0.8 (0.2)	2.2 (0.4)	1.4
200 ms	N/A	501 (16)	541 (16)	40	0.5 (0.2)	1.8 (0.4)	1.3
Response terminated	N/A	480 (16)	521 (16)	41	1.1 (0.2)	4.1 (0.4)	3.0
Experiment 2							
200 and 500 Hz	1	556 (27)	589 (28)	33	0.2 (0.2)	0.9 (0.4)	0.7
	2	546 (27)	569 (28)	23	0.5 (0.2)	1.9 (0.4)	1.4
1,000 and 1,500 Hz	1	540 (25)	578 (27)	38	0.6 (0.2)	1.1 (0.4)	0.5
	2	533 (25)	566 (27)	33	0.3 (0.2)	1.9 (0.4)	1.6
Experiment 3							
200 ms	1	458 (21)	488 (20)	30	0.1 (0.2)	1.8 (0.8)	1.7
	2	360 (21)	391 (20)	31	0.6 (0.2)	3.5 (0.8)	2.9
Response terminated	1	395 (18)	435 (20)	40	0.4 (0.4)	4.6 (0.9)	4.2
	2	346 (18)	388 (20)	42	1.1 (0.4)	4.4 (0.9)	3.3
Experiment 4							
200 ms	1	446 (25)	479 (24)	33	0.8 (0.4)	2.4 (0.9)	1.6
	2	414 (25)	449 (24)	35	0.3 (0.3)	1.9 (0.8)	1.6
Response terminated	1	416 (25)	461 (24)	44	0.9 (0.4)	4.4 (0.9)	3.5
	2	436 (25)	474 (24)	38	1.4 (0.3)	4.9 (0.8)	3.5

Note. RT = reaction time; PE = percentage error; N/A = not applicable. Standard errors are in parentheses. Experiment 2: order manipulation—the 200- and 500-Hz condition was first for Order 1; the other frequency set was first for Order 2. Experiment 3: order manipulation—the 200-ms duration was first for Order 1; the duration order is opposite for Order 2. Experiment 4: session manipulation—Session 1 refers to the first session in each duration condition, and Session 2 was the one performed later.

Table 2
Experiment 1: Analyses of Variance for Reaction Time, Percentage Error, and Inverse Efficiency Score as a Function of Bin (1 to 10) and Congruency (Congruent vs. Incongruent) as Within-Subjects Factors and Stimulus Duration (100 ms, 200 ms, and Response Terminated) as a Between-Subjects Factor

		RT			PE			IES		
Effect	*df*	*F*	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2
Bin	9, 729	**579.01**	**<.001**	**.877**	**15.28**	**<.001**	**.159**	**411.51**	**<.001**	**.836**
Congruency	1, 81	**214.65**	**<.001**	**.726**	**57.32**	**<.001**	**.414**	**192.18**	**<.001**	**.703**
Duration	2, 81	**6.58**	**.002**	**.140**	**8.38**	**<.001**	**.171**	**5.90**	**.004**	**.127**
Bin × Congruency	9, 729	**3.46**	**.021**	**.041**	**20.69**	**<.001**	**.203**	**13.27**	**<.001**	**.141**
Bin × Duration	18, 729	**3.05**	**.048**	**.070**	**1.91**	**.034**	**.045**	**2.69**	**.050**	**.062**
Congruency × Duration	2, 81	<1.0	—	—	**4.79**	**.011**	**.106**	1.04	.360	.025
Bin × Congruency × Duration	18, 729	2.00	.076	.047	**1.99**	**.032**	**.047**	1.18	.301	.028

Note. *df* = degrees of freedom; RT = reaction time; PE = percentage error; inverse efficiency score = IES = RT/(1 − PE). Because the sphericity assumption was violated for terms involving the bin factor (epsilons less than .75), the reported *p*-values are adjusted by Greenhouse–Geisser correction (Girden, 1992). Bold font indicates statistical significance ($p < .05$).

Bin × Congruency interaction, which indicates that the Simon effect varied across the RT bins, and the interaction of Bin × Congruency × Duration (see Figure 1, left panel), which was significant without the Greenhouse–Geisser correction, $F(18, 729) = 2.00$, $p = .008$, $\eta_p^2 = .047$, but slightly greater than .05 with it. The 100- and 200-ms durations showed a decreasing pattern for which the Simon effect was larger at the shorter RT bins than the other bins, with the linear trend being significant for the 100-ms duration, $F(1, 27) = 8.05$, $p < .01$, $\eta_p^2 = .230$, but not the 200-ms duration, $F(1, 27) = 2.73$, $p = .110$, $\eta_p^2 = .092$. In the response-terminated condition, the Simon effect was smallest at the shortest bin, increased in the middle bins, and then decreased over the last three bins, yielding a quadratic trend, $F(1, 27) = 6.65$, $p < .02$, $\eta_p^2 = .198$, but not a linear one, $F < 1.0$.

Response errors. For PE, all terms were significant. As for RT, there were main effects of congruency (Simon effect of 1.9%) and stimulus duration (1.5%, 1.1%, and 2.6% for the 100-ms, 200-ms, and response-terminated conditions, respectively). Post hoc Bonferroni tests revealed that the former two conditions did not differ significantly but did differ from the response-terminated condition (*ps* = .010 and .001, in turn). The bin main effect is due to errors being greatest at the early bins, and its interaction with congruency reflects that the errors were mainly on incongruent trials (see Figure 1, middle panel).

The Simon effect for PE was larger for the response-terminated condition than for the other two durations (interaction of Congruency × Duration), and the effect was largest in the first bin (interaction of Bin × Congruency; see Figure 1, middle panel). The three-way interaction of all variables is a consequence of the difference in Simon effects across the three duration conditions being only in the first bin. Post hoc Bonferroni tests of first bin errors showed a significantly larger PE Simon effect for the response-terminated condition (15.6%) than for the 200-ms duration (5.4%), $p = .001$, with the 100-ms duration (10.4%) being intermediate and not significantly different from either.

Inverse efficiency score. The IES showed results similar to those of the RT analysis (see Table 2), with two notable exceptions. First, the interaction of Bin × Congruency, for which the effect size was .041 for RT, increased to .141 for IES. This difference is due to the IES measure incorporating the higher PE Simon effect of the response-terminated condition for the early bins. Second, the three-way interaction of Bin × Congruency × Stimulus Duration, which was of marginal significance in RT, became clearly nonsignificant in IES (see Figure 1, right panel; note that the *y*-axis scale for IES in this figure and the others is more than twice that of RT due to the larger range of Simon effects for IES). In the RT data, the Simon effect increased across the short RT bins for the response-terminated condition, but it had the

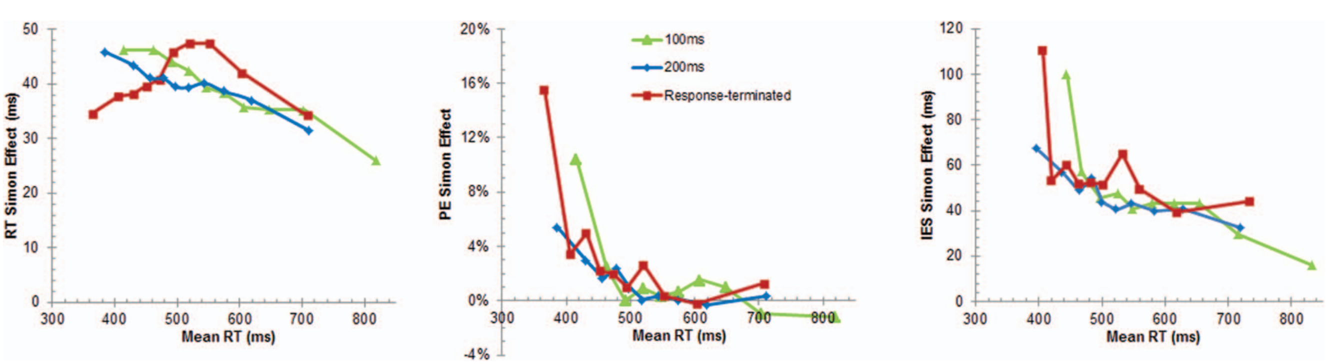

Figure 1. Experiment 1: reaction time (RT; left panel), percentage error (PE; middle panel), and inverse efficiency score [IRS = RT/(1 − PE)] (right panel) Simon effect distributions as a function of mean RT for each bin of the three duration conditions. See the online article for the color version of this figure.

largest decrease in PE across those bins, canceling out the RT pattern in the IES.

Discussion

With the 200- and 500-Hz tones of the present study, decreasing and concave RT Simon effect functions were obtained instead of the increasing functions reported for higher frequency tone sets in prior studies (Proctor & Shao, 2010; Wascher et al., 2001). Only in the response-terminated condition did the Simon effect increase—and there just across the first eight of the 10 RT bins—after which it decreased. The concave and decreasing patterns observed for RT in the current experiment are consistent with an activation–dissipation account, for which the Simon effect should decrease at longer RTs, rather than the cognitive coding interference account of Wascher et al. (2001), which predicts that the auditory Simon effect should not decrease.

The overall PE and the PE Simon effect were considerably larger for the first RT bin than for the others, in accord with Töbel et al.'s (2014) findings for the visual Simon effect. This error pattern implies rapid activation of the congruent response. Moreover, the pattern was most evident for the response-terminated condition, indicating that activation of the congruent response occurred rapidly for it, even though the RT Simon effect was not at its peak in that bin. The larger PE in the first bin and the shorter RT imply that a less strict response criterion was used for the response-terminated condition. The IES measure, which adjusts RT in terms of the error rate, showed similar decreasing functions for all three conditions. Thus, the PE and IES data imply a general activation–dissipation function.

Mean RT was significantly longer for the 100-ms duration than for the 200-ms duration in Experiment 1, and this was paired with a trend toward a higher PE Simon effect for the first bin. This pattern indicates that participants had more difficulty processing the task-relevant tone pitch feature for the 100-ms duration than for the 200-ms duration. Thus, in the remaining experiments, we used only 200 ms as the short duration.

Experiment 2

The 200-ms duration, which was the same as the duration used in Wascher et al.'s (2001) and Proctor and Shao's (2010) experiments, yielded a decreasing RT Simon effect function in Experiment 1 rather than the increasing functions found in those studies. The main difference in the situations is that the tone frequencies of 200 and 500 Hz in Experiment 1 were lower than those of 1,000 and 1,500 Hz in the studies of Wascher et al. (2001) and Proctor and Shao (2010). Thus, in Experiment 2, only the 200-ms duration was used, but with the stimuli in separate trial blocks being from these two frequency sets. Replication of the results of Experiment 1 and those of Wascher et al. (2001) and Proctor and Shao (2010) would be consistent with the hypothesis that activation and dissipation of the corresponding response are more evident in the RT Simon effect distribution for the low-frequency set than for the high-frequency set.

Method

Participants. Twenty-eight new students (nine male, 19 female) participated. Four additional participants were replaced, applying the same criteria as in Experiment 1, three from the condition in which the low-frequency set was conducted first and one from the other condition.

Apparatus, stimuli, and procedure. These were similar to Experiment 1, except as noted. The imperative stimulus duration was 200 ms in all conditions, and tone frequencies were manipulated in two sets: low frequency (200 and 500 Hz) and high frequency (1,000 and 1,500 Hz), with the tones' loudnesses approximately 57 and 60 dBA, respectively.

Each participant performed 240 trials for each frequency set, with the order of high- and low-frequency trial blocks counterbalanced between participants. Each block was separated into two 120-trial halves, with a break between, preceded by practice of 12 trials. For both blocks, the experimenter went through the instructions and practice with the participant but left the room for the test trials.

Results

Using the same criteria as in Experiment 1, 2.8% (200 and 500 Hz) and 2.7% (1,000 and 1,500 Hz) of trials were excluded from analysis. Mean correct RTs and PEs as a function of bin, congruency, and frequency were calculated for each participant. ANOVAs of RT, PE, and IES were conducted, with bin, congruency, and frequency set as within-subjects factors. Also, set order was included as a between-subjects factor because order showed an effect in Experiment 3. The means for the conditions and the values for the ANOVAs are listed in Tables 1 and 3, respectively.

Reaction time. Responses were 32 ms faster if stimulus location was congruent with response location than if it was not (see Table 1). The main effect of frequency set was not significant (see Table 3), but the interaction of Congruency × Frequency set was: The Simon effect was larger for the high-frequency set (36 ms) than for the low-frequency set (28 ms).

RT increased across bins, as predetermined by the rank ordering. The Bin × Frequency interaction was significant: The range of RT across the bins was larger for the low-frequency set (417–795 ms) than for the high-frequency set (443–745 ms; see Figure 2, *x*-axis). Although RT tended to be shorter for the low-frequency set than for the high-frequency set at the first bin, across the remaining bins, RT for the low-frequency set increased progressively relative to that for the high-frequency set, surpassing it from Bin 5 onward. The Bin × Congruency interaction (see Figure 2, left panel) was also significant without the Greenhouse–Geisser correction, $F(9, 234) = 2.24$, $p = .020$, $\eta_p^2 = .079$, but it only approached the .05 criterion after correction (see Table 3).

More importantly, the interaction of Bin × Congruency × Frequency was significant (see Figure 2, left panel), indicating different Simon effect RT distribution patterns for the two frequency sets. Further analysis for each set showed that only the low-frequency set yielded an interaction between bin and congruency, $F(9, 234) = 4.37$, $p = .006$, $\eta_p^2 = .144$—the Simon effect showing a linear decreasing pattern, $F(1, 26) = 6.32$, $p = .018$, $\eta_p^2 = .196$—consistent with Experiment 1. In contrast, the high-frequency set showed no difference in the Simon effect across bins, $F < 1.0$, with a nondecreasing function, similar to prior results with that frequency set. Order did not have any effect.

Response errors. The PE ANOVA also showed main effects of congruency (Simon effect of 1.0%) and bin. Neither the inter-

Table 3
Experiment 2: Analyses of Variance for Reaction Time, Percentage Error, and Inverse Efficiency Score as a Function of Bin (1 to 10), Congruency (Congruent vs. Incongruent), and Tone Frequency Set (200 and 500 Hz vs. 1,000 and 1,500 Hz) as Within-Subjects Factors and Set Order (200 and 500 Hz First vs. 1,000 and 1,500 Hz First) as a Between-Subjects Factor

		RT			PE			IES		
Effect	*df*	*F*	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2
Bin	9, 234	**175.37**	**<.001**	**.871**	**4.29**	**.003**	**.142**	**166.51**	**<.001**	**.865**
Congruency	1, 26	**90.96**	**<.001**	**.778**	**24.27**	**<.001**	**.483**	**96.83**	**<.001**	**.788**
Frequency	1, 26	<1.0	—	—	<1.0	—	—	<1.0	—	—
Order	1, 26	<1.0	—	—	1.56	.223	.057	<1.0	—	—
Bin × Congruency	9, 234	2.24	.087	.079	**5.10**	**.001**	**.164**	**3.69**	**.005**	**.124**
Bin × Frequency	9, 234	**6.26**	**.014**	**.194**	<1.0	—	—	**5.96**	**.014**	**.186**
Bin × Order	9, 234	<1.0	—	—	<1.0	—	—	<1.0	—	—
Congruency × Frequency	1, 26	**4.40**	**.046**	**.145**	<1.0	—	—	3.18	.086	.109
Congruency × Order	1, 26	1.48	.234	.054	3.79	.062	.127	<1.0	—	—
Frequency × Order	1, 26	<1.0	—	—	1.45	.240	.053	<1.0	—	—
Bin × Congruency × Frequency	9, 234	**3.12**	**.035**	**.107**	1.54	.197	.056	<1.0	—	—
Bin × Congruency × Order	9, 234	<1.0	—	—	<1.0	—	—	<1.0	—	—
Bin × Frequency × Order	9, 234	1.75	.197	.063	<1.0	—	—	1.85	.182	.066
Congruency × Frequency × Order	1, 26	<1.0	—	—	<1.0	—	—	<1.0	—	—
Bin × Congruency × Frequency × Order	9, 234	<1.0	—	—	<1.0	—	—	<1.0	—	—

Note. *df* = degrees of freedom; RT = reaction time; PE = percentage error; inverse efficiency score = IES = RT/(1 − PE). Because the sphericity assumption was violated for terms involving the bin factor (epsilons less than .75), the reported *p*-values are adjusted by Greenhouse–Geisser correction (Girden, 1992). Bold font indicates statistical significance ($p < .05$).

action of Congruency × Frequency nor the three-way interaction of Bin × Congruency × Frequency (see Figure 2, middle panel) was significant. However, there was a Bin × Congruency interaction, indicating that the PE Simon effect varied across bins, with the variation being similar for the two frequency sets. The PE Simon effect was highest in the first bin for both sets (see Figure 2, middle panel), being 3.1% for the low-frequency set and 5.3% for the high-frequency set. Again, no terms involving order showed any effect, with only the interaction of Congruency × Order approaching significance.

Inverse efficiency score. Similar to RT and PE, the IES showed main effects of bin and congruency (see Table 3 and Figure 2, right panel). The Bin × Congruency interaction that only approached significance in RT became significant, whereas the three-way interaction of those variables with frequency set disappeared. Thus, when PE was taken into account, a similar distribution function of a decreasing Simon effect was evident for both frequency sets.

Discussion

The results confirmed that tone frequency impacts the auditory RT Simon effect distribution. For the low-frequency set, the Simon effect for RT replicated the decreasing pattern reported for the 200-ms duration in Experiment 1. For the high-frequency set, though, the Simon effect showed a nondecreasing effect function for RT, as in prior studies that used the same stimuli (Proctor & Shao, 2010; Wascher et al., 2001). Thus, only the low-frequency set showed the RT distribution function predicted by an activation–dissipation account.

The overall mean RT, PE, and IES provided no evidence for the hypothesis that tone frequency identification was more difficult for

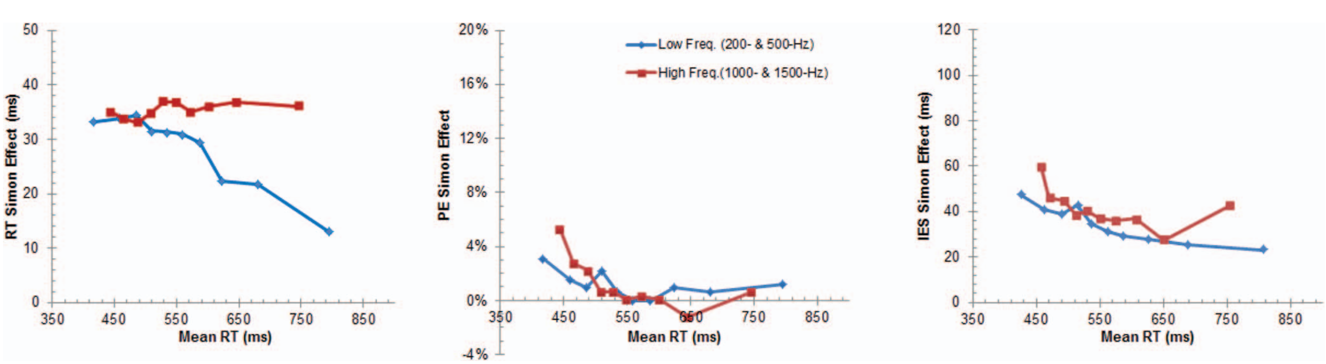

Figure 2. Experiment 2: reaction time (RT; left panel), percentage error (PE; middle panel), and inverse efficiency score [IES = RT/(1 − PE)] (right panel) Simon effect distributions as a function of mean RT for each bin of the high- and low-frequency sets, collapsed across the two sessions. See the online article for the color version of this figure.

the low-frequency set than for the high-frequency set. However, the Bin × Frequency interaction for RT and IES indicates greater identification difficulty for the low-frequency set, as RT was longer for that set than for the high-frequency set over the last half of the RT bins. The extended RT of the later bins likely allowed the decrease of the Simon effect to be evident in the RT distribution.

Though the high-frequency tones did not show a decreasing Simon effect function for RT, the PE data did show a Simon effect of 5.3% in the first bin, which decreased as RT increased. Consequently, the IES measure showed a decreasing Simon effect pattern for the high-frequency set as well as the low-frequency set, suggesting that activation of the corresponding response occurred rapidly and then dissipated for both sets.

Experiment 3

Experiments 1 and 2 were conducted in a driving simulator, and responses were thumb presses of a gaming steering wheel's buttons. To verify the results in a more typical Simon task setting, in Experiment 3 we conducted Simon tasks using tone stimuli presented through a headset and index finger presses on a response box. Tone duration was varied within subjects rather than between subjects as in Experiment 1 to determine whether the Bin × Congruency × Duration interaction, which only approached significance with the Greenhouse–Geisser correction in Experiment 1, would be evident with reduced error variance. Otherwise, both duration conditions were similar to those of Experiment 1 and used the low-frequency tones that yielded the atypical decreasing Simon effect function in that experiment.

Method

Participants. Twenty-eight students (17 male, 11 female) participated. Two participants from each order were replaced with the same criteria as in Experiments 1 and 2.

Apparatus and stimuli. Participants were seated in front of a 76-cm-high table on which an E-Prime response box with a row of five response buttons was placed. Auditory stimuli were presented via a headphone set, whereas instructions and response error messages were presented by a 17-in. (43.2-cm) monitor in front of the subject, with an unconstrained viewing distance of approximately 50 cm. Responses were made by pressing the leftmost or rightmost button on the response box with the corresponding index finger. The same as in Experiment 1, the low pitch tone was 200 Hz and the high pitch tone was 500 Hz. However, the stimulus duration was manipulated in two levels, one of 200 ms and the other until the participant responded.

Procedure. The procedure was similar to Experiment 2 except for the following change. Tone duration (200 ms, response terminated), rather than tone frequency set, was a within-subjects factor. The two durations were used in separate trial blocks, with duration order counterbalanced between subjects. Each duration condition consisted of 240 trials and was preceded by practice of 12 trials.

Results

Using the same criteria as the previous experiments, 2.4% of the trials were excluded for participants who began with the 200-ms duration and 2.3% for those who began with the response-terminated condition. Mean correct RTs and PEs for each participant as functions of bin, congruency, and duration were calculated. The ANOVAs of RT, PE, and IES were conducted similar to Experiment 2, except that stimulus duration (200 ms, response terminated) replaced frequency set as a within-subjects factor and duration order replaced set order as the between-subjects factor. The means for the conditions are shown in Table 1, and the values for the ANOVA are shown in Table 4.

Reaction time. RT was 36 ms shorter if stimulus location was congruent with response location than if it was not (see Table 1). The main effect of stimulus duration was significant: RT was 33 ms shorter in the response-terminated condition than in the 200-ms condition. The Congruency × Duration interaction, not significant in Experiment 1, was significant in Experiment 3, likely because duration was a within-subjects factor in this experiment. Unlike Experiment 2, order not only showed a main effect, reflecting that RT was longer for the order in which the 200-ms duration was first, but also an interaction with duration: RT for the 200-ms duration depended more on order than did that for the response-terminated condition.

There was a main effect of bin, as well as a Bin × Congruency interaction, indicating that the Simon effect varied across bins (see Figure 3, left panel). More interestingly, a four-way interaction of Bin × Congruency × Duration × Order was approximately at the .05 level, suggesting an influence of order on the Simon effect patterns. Further analysis on each order showed that the results when the 200-ms duration preceded the response-terminated condition were the same as in Experiment 1 (see Figure 4, upper left panel): There was an interaction between bin and congruency, $F(9, 117) = 4.25$, $p = .004$, $\eta_p^2 = .246$, and most importantly, a three-way interaction of Bin × Congruency × Duration, $F(9, 117) = 3.97$, $p = .028$, $\eta_p^2 = .234$. The individual analysis for each duration showed a significant linear contrast for the 200-ms duration, $F(1, 13) = 6.55$, $p = .024$, $\eta_p^2 = .335$, but for the response-terminated condition, only the quadratic contrast was significant, $F(1, 13) = 5.72$, $p = .033$, $\eta_p^2 = .305$. In contrast, although the ANOVA on the order for which the response-terminated condition preceded the 200-ms duration showed an interaction between congruency and duration, $F(1, 13) = 6.02$, $p = .029$, $\eta_p^2 = .317$, the three-way interaction involving bin was not significant, $F(9, 117) < 1$, suggesting no difference in the distribution pattern between the two duration conditions (see Figure 4, lower left panel). No other effects were significant or approached significance level.

Response errors. The ANOVA showed a main effect of congruency (3.0%). The effect of duration was significant, with more errors in the response-terminated condition than in the 200-ms condition, and duration interacted with congruency (see Table 1). There was no main effect of order, but the Duration × Order interaction yielded a p value of .093. This interaction trend was similar to that for RT, showing a higher PE for the response-terminated condition than for the 200-ms condition for the order in which the latter was first, but not much difference between the two conditions for the order in which the 200-ms duration was second. The Congruency × Duration × Order interaction showed a trend that was close to the .05 level: This trend reflected a larger PE Simon effect for the 200-ms duration when it was performed after

Table 4
Experiment 3: Analyses of Variance for Reaction Time, Percentage Error, and Inverse Efficiency Score as a Function of Bin (1 to 10), Congruency (Congruent vs. Incongruent), and Tone Duration (200 ms vs. Response Terminated) as Within-Subjects Factors and Duration Order (200 ms First vs. Response Terminated First) as a Between-Subjects Factor

Effect	*df*	RT *F*	RT *p*	RT η_p^2	PE *F*	PE *p*	PE η_p^2	IES *F*	IES *p*	IES η_p^2
Bin	9, 234	**218.10**	**<.001**	**.893**	**13.59**	**<.001**	**.343**	**175.64**	**<.001**	**.871**
Congruency	1, 26	**177.16**	**<.001**	**.872**	**29.58**	**<.001**	**.532**	**120.69**	**<.001**	**.823**
Duration	1, 26	**15.78**	**.001**	**.378**	**22.20**	**<.001**	**.461**	**11.14**	**.003**	**.300**
Order	1, 26	**7.51**	**.011**	**.224**	1.07	.311	.039	**7.45**	**.011**	**.223**
Bin × Congruency	9, 234	**4.97**	**.004**	**.160**	**17.37**	**<.001**	**.401**	**9.84**	**<.001**	**.275**
Bin × Duration	9, 234	<1.0	—	—	<1.0	—	—	<1.0	—	—
Bin × Order	9, 234	1.38	.253	.050	1.40	.243	.051	2.01	.163	.072
Congruency × Duration	1, 26	**6.35**	**.018**	**.196**	**7.80**	**.010**	**.231**	**15.36**	**.001**	**.371**
Congruency × Order	1, 26	<1.0	—	—	<1.0	—	—	<1.0	—	—
Duration × Order	1, 26	**9.00**	**.006**	**.257**	3.04	.093	.105	**7.64**	**.010**	**.227**
Bin × Congruency × Duration	9, 234	1.69	.192	.061	1.05	.396	.039	<1.0	—	—
Bin × Congruency × Order	9, 234	<1.0	—	—	1.09	.359	.040	<1.0	—	—
Bin × Duration × Order	9, 234	<1.0	—	—	1.36	.245	.050	<1.0	—	—
Congruency × Duration × Order	1, 26	<1.0	—	—	4.09	.054	.136	<1.0	—	—
Bin × Congruency × Duration × Order	9, 234	2.97	.057	.103	1.53	.182	.055	1.16	.332	.043

Note. *df* = degrees of freedom; RT = reaction time; PE = percentage error; inverse efficiency score = IES = RT/(1 − PE). Because the sphericity assumption was violated for terms involving the bin factor (epsilons less than .75), the reported *p*-values are adjusted by Greenhouse–Geisser correction (Girden, 1992). Bold font indicates statistical significance ($p < .05$).

the response-terminated condition rather than before it (see Figure 4, right panels).

Bin showed a main effect and interacted with congruency. However, the three-way interaction of Bin × Congruency × Duration was not significant, suggesting a similar distribution pattern for the response-terminated and 200-ms conditions (see Figure 3, middle panel). Further ANOVAs of each bin showed that only the first bin's Simon effect differed significantly across the two durations, $F(1, 26) = 4.74$, $p = .039$, $\eta_p^2 = .154$, with the Simon effect in Bin 1 being 10.2% for the 200-ms duration and 15.2% for the response-terminated condition.

Inverse efficiency score. The IES ANOVA (see Table 4) showed the same pattern of significant effects as the RT ANOVA, with the main difference being that the four-way interaction of Bin × Congruency × Duration × Order that was at the .05 level for RT was not after the adjustment for PE. After adjustment, both durations for both orders showed the decreasing functions illustrated in Figure 3 (right panel), collapsed across order.

Discussion

The RT distribution results showed a similar pattern to those of Experiment 1. For the response-terminated condition, the Simon effect increased over several bins and then decreased, whereas for the 200-ms duration, the RT function was predominantly decreasing. The concave RT distribution pattern of the response-terminated condition, accompanied by a decreasing PE distribution, was evident regardless of whether that condition was tested first or second. In contrast, when the 200-ms condition was performed after the response-terminated condition (rather than first), the mean RT was much shorter, the RT Simon effect distribution flatter, and the PE Simon effect more pronounced at the first RT

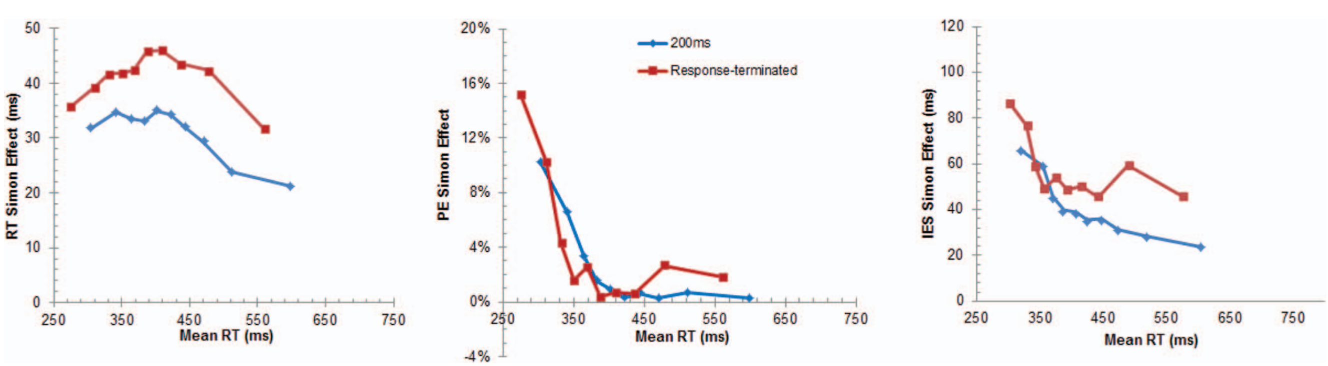

Figure 3. Experiment 3: reaction time (RT; left panel), percentage error (PE; middle panel), and inverse efficiency score [IES = RT/(1 − PE)] (right panel) Simon effect distributions as a function of mean RT for the 200-ms and response-terminated conditions, collapsed across the two sessions. See the online article for the color version of this figure.

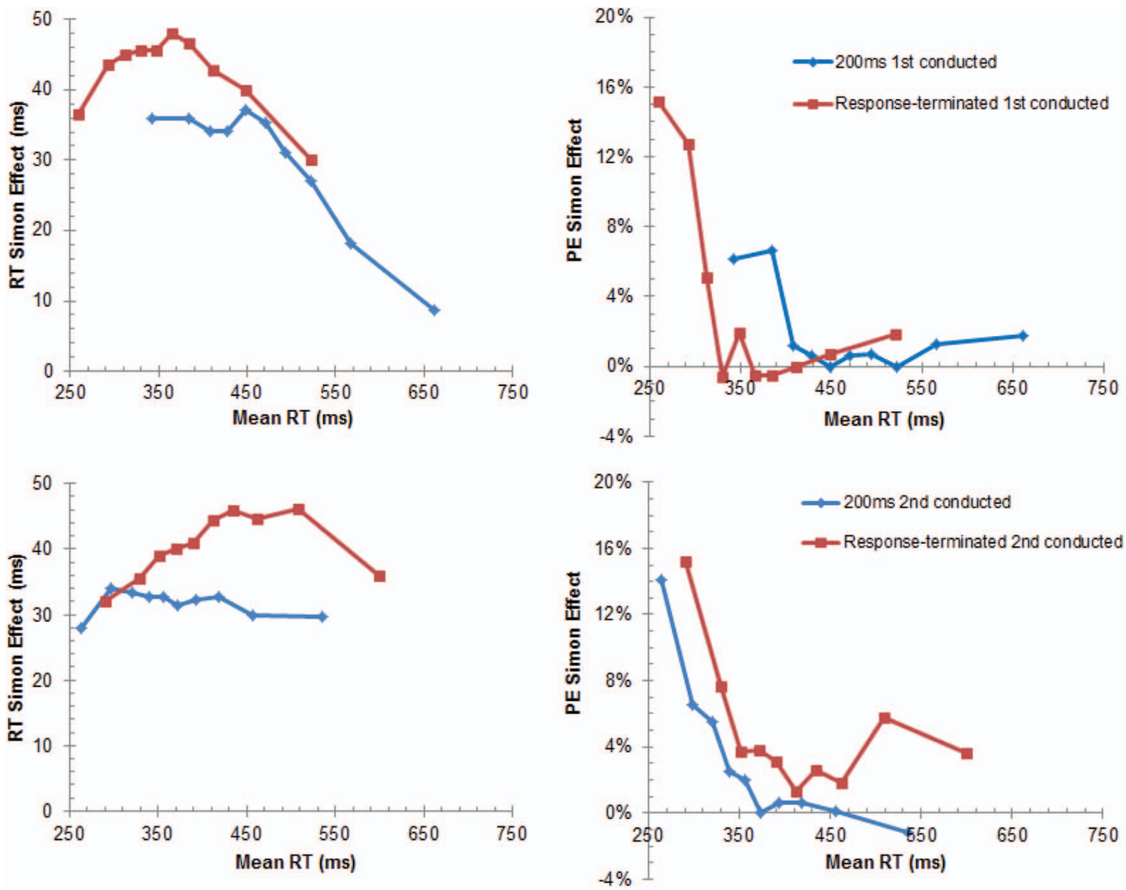

Figure 4. Experiment 3: reaction time (RT; left panels) and percentage error (PE; right panels) Simon effect distributions as a function of mean RT for 200-ms and response-terminated conditions for the first session conducted (top panels) and the second session conducted (bottom panels). See the online article for the color version of this figure.

bin. This pattern suggests that participants may have transferred the speed-oriented, less strict response criterion from the response-terminated condition to the 200-ms condition. Consistent with this possibility, after adjustment of RT by PE, the 200-ms condition showed a decreasing distribution function across the two order conditions.

Experiment 4

Rather than a response criterion change due to experience with the response-terminated duration, practice with the low-frequency tones regardless of duration could be responsible for the flatter RT distribution function (and accompanying PE changes) when the 200-ms duration followed the response-terminated condition in Experiment 3. The aim of Experiment 4 was to evaluate whether the change in RT distributions between the two orders of Experiment 3 was due to practice with the tone frequencies. Like that experiment, this one was designed with two sessions, but the duration condition (200 ms or response terminated) was the same for both sessions for each participant. We expected that the response-terminated condition would show similar results in the two sessions, as it did in Experiment 3. If practice responding to the tones was the determinant of the difference in distribution functions for the 200-ms condition in that experiment, then that condition should show a similar pattern as well.

Method

Participants. Twenty-eight students (14 male, 14 female) participated. Three participants—one from the 200-ms duration condition and two from the response-terminated condition—were replaced on the basis of the same criteria as the prior experiments.

Apparatus, stimuli, and procedure. The apparatus and stimuli were the same as in Experiment 3. The procedure was similar except for the following. Each participant performed two sessions with the same duration condition. Half were tested in both sessions with the 200-ms stimulus duration, and the other half were tested with the response-terminated condition.

Results

Applying the exclusion criteria, 2.7% of the trials for the 200-ms condition and 2.6% for the response-terminated condition were excluded. Mean correct RTs and PEs for each participant, bin, congruency, and session were calculated. ANOVAs of RT, PE, and IES similar to those of Experiment 3 were conducted, with the exception of duration (200 ms, response terminated) being a between-subjects factor and session (first, second) a within-subjects factor. The means and ANOVA values for the conditions are listed in Tables 1 and 5 separately.

Reaction time. Responses were faster on congruent (428 ms) than incongruent (466 ms) trials. The Session × Duration interaction was also significant, indicating an opposite change pattern between sessions for the two duration conditions (see Table 1): RT increased for the second session of the response-terminated condition but decreased for the second session of the 200-ms duration. Bin did not interact significantly with the other factors (see Figure 5, left panel). Because of the predicted patterns outlined in the introduction to Experiment 4 for the two duration conditions, we analyzed each separately.

For the 200-ms duration, the main effect of session was significant, $F(1, 13) = 14.95$, $p = .002$, $\eta_p^2 = .535$. The interactions of Bin × Congruency, $F(9, 117) = 2.03$, $p = .042$, $\eta_p^2 = .135$, and Bin × Congruency × Session, $F(9, 117) = 2.16$, $p = .030$, $\eta_p^2 = .142$, were significant without the Greenhouse–Geisser correction but not after it (*p*s of .153 and .142, respectively). Further analysis for each session showed a significant Bin × Congruency interaction for the first session, $F(9, 117) = 4.39$, $p = .027$, $\eta_p^2 = .252$; linear contrast: $F(1, 13) = 6.70$, $p = .024$, $\eta_p^2 = .333$, but not for the second one, $F < 1$ (see Figure 6, left panels). For the response-terminated condition, only the main effects of bin and congruency were significant; no other effects approached significance, $F\text{s} < 2.34$ (see Figure 6, left panels).

Response error. The ANOVA revealed main effects of congruency (Simon effect of 2.5%) and duration (200 ms: 1.4%; response terminated: 2.9%). The Session × Duration interaction approached the .05 level (see Tables 1 and 5), showing the same pattern as RT: PE increased in the second session for the response-terminated condition but decreased for the 200-ms condition. Bin showed a main effect and two-way interactions with congruency and duration. These were subsumed by a significant three-way interaction of Bin × Congruency × Duration (see Figure 5, middle panel). The Simon effect was largest in the first bin for both durations, being 6.4% for the 200-ms duration and 17.2% for the response-terminated condition. ANOVAs on the Simon effect of each individual bin showed an effect of duration in the first bin, $F(1, 26) = 7.95$, $p = .009$, $\eta_p^2 = .234$, but not the others, $F\text{s} < 2.00$.

Inverse efficiency score. The IES ANOVA was consistent with the RT results except that the interaction of Bin × Congruency, which was not significant for RT, was significant after adjustment for PE (see Figure 5, right panel). The Simon effect decreased significantly across bins when the large bin effect for PE was taken into consideration.

Comparison to Experiment 3. The purpose of Experiment 4 was to evaluate whether practice of 240 trials in the first session, irrespective of the stimulus duration for that session, can account for the flattening of the RT Simon effect distribution for the 200-ms condition in the second session. Thus, we conducted a comparison of the second sessions for the 200-ms conditions of Experiments 3 and 4. For RT, the critical Bin × Congruency × Experiment interaction was not significant, $F < 1.0$, indicating similarly flat functions for the two experiments. This interaction approached the .05 criterion for PE, $F(9, 234) = 2.15$, $p = .081$, $\eta_p^2 = .077$, and exceeded it for IES, $F(9, 234) = 3.45$, $p = .011$, $\eta_p^2 = .117$, reflecting more errors being made on incongruent trials in early bins for Experiment 3 than for Experiment 4.

Discussion

The RT Simon effect distribution analysis of the two identical sessions with the 200-ms duration showed different results: a

Table 5

Experiment 4: Analyses of Variance for Reaction Time, Percentage Error, and Inverse Efficiency Score as a Function of Bin (1 to 10), Congruency (Congruent vs. Incongruent), and Session (First vs. Second) as Within-Subjects Factors and Stimulus Duration (200 ms vs. Response Terminated) as a Between-Subjects Factor

		RT			PE			IES		
Effect	*df*	*F*	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2
Bin	9, 234	**186.85**	**<.001**	**.878**	**12.94**	**<.001**	**.332**	**138.79**	**<.001**	**.842**
Congruency	1, 26	**120.01**	**<.001**	**.822**	**22.08**	**<.001**	**.459**	**82.94**	**<.001**	**.761**
Session	1, 26	<1.0	—	—	<1.0	—	—	<1.0	—	—
Duration	1, 26	<1.0	—	—	**5.76**	**.024**	**.181**	<1.0	—	—
Bin × Congruency	9, 234	1.82	.161	.065	**18.05**	**<.001**	**.410**	**10.35**	**<.001**	**.285**
Bin × Session	9, 234	1.54	.227	.056	<1.0	—	—	1.63	.213	.059
Bin × Duration	9, 234	3.06	.090	.105	**4.81**	**.002**	**.156**	1.93	.174	.069
Congruency × Session	1, 26	<1.0	—	—	<1.0	—	—	<1.0	—	—
Congruency × Duration	1, 26	1.08	.308	.040	2.94	.098	.102	1.80	.191	.065
Session × Duration	1, 26	**5.17**	**.031**	**.166**	4.13	.053	.137	**5.97**	**.022**	**.187**
Bin × Congruency × Session	9, 234	1.43	.244	.052	1.05	.390	.039	1.66	.162	.060
Bin × Congruency × Duration	9, 234	<1.0	—	—	**4.59**	**.002**	**.150**	1.92	.114	.069
Bin × Session × Duration	9, 234	2.03	.164	.072	<1.0	—	—	1.87	.176	.067
Congruency × Session × Duration	1, 26	1.90	.180	.068	<1.0	—	—	1.23	.278	.045
Bin × Congruency × Session × Duration	9, 234	1.02	.387	.038	<1.0	—	—	<1.0	—	—

Note. *df* = degrees of freedom; RT = reaction time; PE = percentage error; inverse efficiency score = IES = RT/(1 − PE). Because the sphericity assumption was violated for terms involving the bin factor (epsilons less than .75), the reported *p*-values are adjusted by Greenhouse–Geisser correction (Girden, 1992). Bold font indicates statistical significance ($p < .05$).

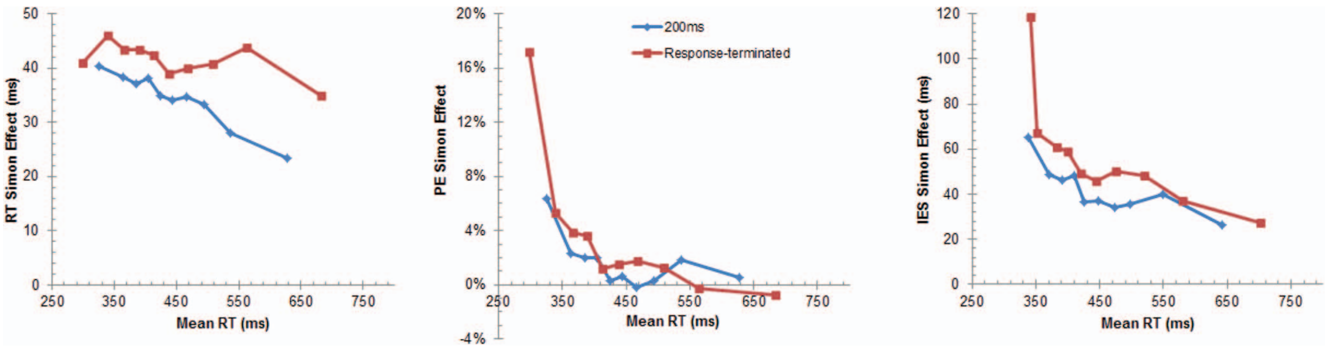

Figure 5. Experiment 4: reaction time (RT; left panel), percentage error (PE; middle panel), and inverse efficiency score [IES = RT/(1 − PE)] (right panel) Simon effect distributions as a function of mean RT for 200-ms and response-terminated conditions, collapsed across the two sessions. See the online article for the color version of this figure.

linear decreasing function for the first session (as in the prior experiments) but a relatively flat function for the second one. The results are similar to those of Experiment 3, in which the decreasing RT Simon effect function became flat when the 200-ms condition was performed after the response-terminated condition. Although a relatively flat pattern was observed for the response-terminated condition, no interaction between bin and session suggested that the RT distribution patterns between sessions were similar, consistent with the results of Experiment 3.

For the second session of the 200-ms duration, the mean RT became shorter, the RT Simon effect distribution flatter, and the PE smaller compared to the first session. This pattern is consistent with a practice account in which performance becomes more efficient as participants become experienced with the task. It was

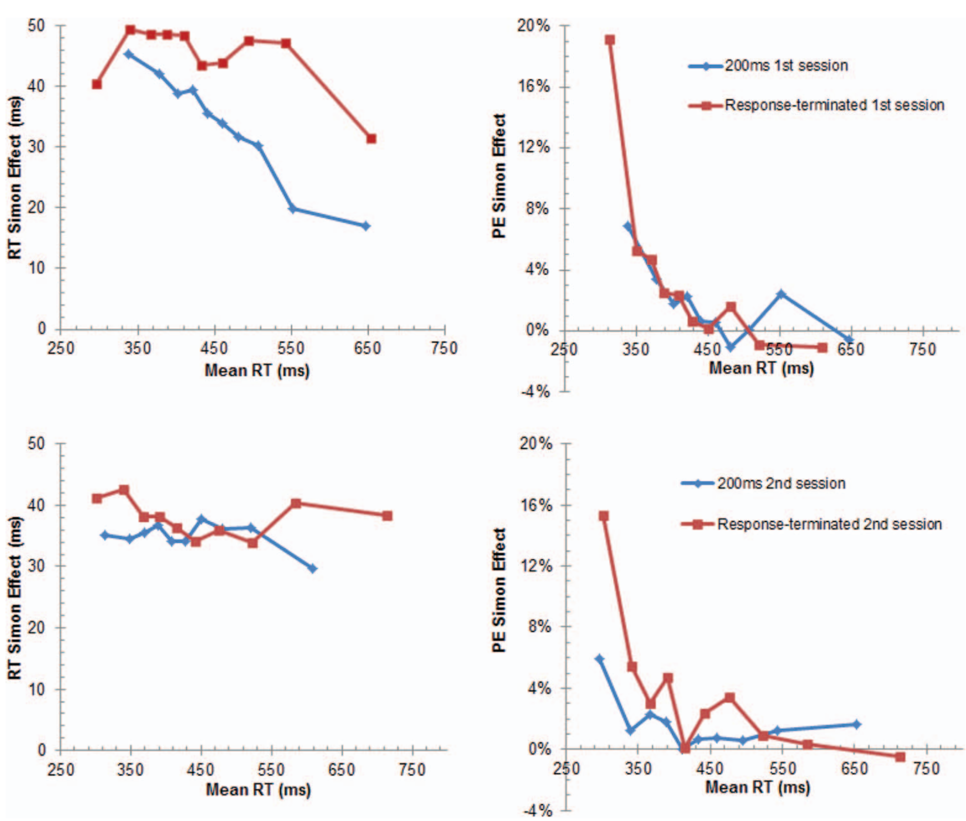

Figure 6. Experiment 4: reaction time (RT; left panels) and percentage error (PE; right panels) Simon effect distributions as a function of mean RT for 200-ms and response-terminated conditions for the first session conducted (top panels) and the second session conducted (bottom panels). See the online article for the color version of this figure.

reflected in the between-experiments comparison that showed no difference in the RT Simon effect functions of the second session across Experiments 3 and 4. However, the smaller PE and IES Simon effects in the early bins for Experiment 4 suggest that part of the change in Experiment 3 was due to participants continuing to apply the less strict response criterion of the response-terminated condition when subsequently responding to the 200-ms duration tones.

General Discussion

The main evidence against an automatic activation–dissipation account of the auditory Simon effect and for an account in terms of cognitive coding interference has been that the distribution functions are nondecreasing rather than decreasing, as for the visual Simon effect (e.g., Dittrich et al., 2014; Wascher et al., 2001). However, our experiments demonstrated reliable decreasing functions for the auditory RT Simon effect with short-duration tones of low frequency and for the PE and IES Simon effect for all durations and frequency sets. These findings provide strong evidence of the types of functions expected if the auditory Simon effect is also due to automatic activation–dissipation of the corresponding response.

Decreasing RT Simon Effect Distribution Functions

Prior studies on the time course of the Simon effect were mainly based on the RT distribution for correct responses (e.g., De Jong et al., 1994; Wascher et al., 2001), which typically shows a decreasing function across the RT bins for visual stimuli but not auditory stimuli (Proctor et al., 2011). We replicated the nondecreasing function for tone stimuli of the same frequencies as those used in prior studies (e.g., Proctor & Shao, 2010) but obtained decreasing auditory RT Simon effect functions for 100- and 200-ms tones of lower frequency.

Decreasing RT Simon effect functions were expected for the low-frequency set as a result of delaying identification of the tone frequency relative to its location. The Bin × Frequency interaction in Experiment 2 revealed that across the RT distribution, responses were slowed relatively more from bin to bin for the low-frequency set than for the high-frequency set, increasing the range of the RT distribution. This greater range, particularly at the long end of the distribution, provided more opportunity for dissipation of the automatic response activation to be observed. That a decreasing function was obtained for the low-frequency set implies that the size of the RT Simon effect across bins is affected by the relative response speed. This implication is in agreement with a diffusion model for conflict (DMC) task proposed by Ulrich, Schröter, Leuthold, and Birngruber (2015), in which RT distribution functions depend on the relative speeds of the automatic and controlled processes.

Decreasing PE Simon Effect Distribution Functions

The automatic activation–dissipation account of the Simon effect also implies that because fast responses are substantially influenced by stimulus location, PE on incongruent trials should be high. Thus, the PE Simon effect distribution provides another measure of the activation–dissipation of the spatially corresponding response, possibly more so than the RT distribution (Ridderinkhof, 2002b; Töbel et al., 2014). Instead of the divergent patterns observed for the RT distribution, a decreasing pattern for the PE Simon effect was evident in all conditions: The effect was largest for the shortest RT bin and then decreased quickly as RT increased, approaching zero. Similarly, Töbel et al. (2014) found a decreasing pattern of the PE Simon effect distribution for visual tasks that yield distinct RT Simon effect distributions, suggesting consistency of the decreasing PE function across sensory modalities.

Within the low-frequency set, a nondecreasing RT Simon effect function was obtained for the response-terminated condition, but this was accompanied by a larger PE Simon effect for the first bin. To confirm that this result pattern can be attributed to a less strict response criterion, we fit the EZ diffusion model (Wagenmakers, van der Maas, & Grasman, 2007) to the overall mean RT and PE of the first sessions in Experiments 3 and 4. The diffusion model distinguishes the drift rate of information accumulation in a random walk from separation of response boundaries or criteria (Ratcliff, 1978). Averaged across the experiments, there was no difference in the drift rate between the two duration conditions, but the boundary separation (a) was smaller for the response-terminated condition ($a = 0.09$) than for the 200-ms condition ($a = 0.11$). The 22% boundary separation difference between the two duration conditions is relatively large. For comparison, it is approximately two thirds of the 36% boundary separation shift obtained by Ratcliff and McKoon (2008) when they fit the diffusion model to conditions with speed instructions ($a = 0.11$) and accuracy instructions ($a = 0.15$) in a two-choice RT task (see their Table 1, Experiment 2).

The above explanation for the distribution differences between the 200-ms and response-terminated conditions is supported by the simulation results of the DMC (Ulrich et al., 2015). These simulations also showed that the size of the RT Simon effect with a negative-going distribution function becomes larger when the separation between the two decision criteria is reduced, as was evident for the response-terminated condition compared to the 200-ms duration in Experiments 3 and 4. The boundary or criterion difference between the two duration conditions may be a consequence of the continued presence of the tone in the response-terminated condition prompting participants to respond, resulting in faster responses at the expense of errors. Alternatively, because the tone was turned off by the participant's response, its offset provides an action effect at that location that could influence performance. Responding is faster when effects are congruent with responses (Hommel, 1993a; Kunde, 2001; Pfister, Heinemann, Kiesel, Thomaschke, & Janczyk, 2012), most likely because people anticipate the effects. Because response–effect congruence or incongruence matches S–R congruence or incongruence for the response-terminated condition of our study, it could increase the tendency to make a quick congruent response.

Inverse Efficiency Score

The IES, which is a handy way to adjust RT to accommodate PE (e.g., Goffaux et al., 2005), also showed a decreasing pattern in all experiments. This result suggests that the absence of a decreasing RT distribution pattern for the auditory Simon effect in other studies seems to be due to lack of consideration of PE. Although it is more comprehensive than RT or PE alone, caution needs to be exercised when interpreting the measure.

Bruyer and Brysbaert (2011) identified three potential problems, none of which seems to be consequential in the present study. First, estimates of corrected RT become less stable when PE is high, as was the case for the first bin of the response-terminated condition (for which the PE Simon effect was greater than 10%). However, the RT Simon effect sizes were similar for the first bin across Experiments 1, 3, and 4 (35–40 ms), implying a stable estimate of the correct RT. Second, the correct responses may include fast guesses. However, the lower bound cutoff in our study would minimize inclusion of fast guesses.

The third problem is that a nonlinear relation is embedded within the IES transform. A given increase in PE will produce a greater percentage increase in RT, with the exact value contingent on the baseline effect size. For example, if PE increases from 10% to 20% versus 20% to 30%, the IES increase will be $0.14 \times$ RT versus $0.18 \times$ RT. However, in our study, PE was less than 5% for each bin in all conditions, with the exception of the first bin. The large Simon effect for the first bin in the IES distribution could be inflated due to the high PE, but another way to look at it is that the PE in the first bin should be weighted more heavily since "the strength of automatic response activation is more reflected in the delta [Simon effect] functions for accuracy" (Töbel et al., 2014, p. 48).

Factors Impacting Bin Analyses

To get detailed depictions of the Simon effect distributions, we divided the trials into 10 bins instead of the five bins used in some studies (such as that of Töbel et al., 2014). Our functions showed that incorrect responses on incongruent trials were most pronounced in the 10% fastest responses. In some conditions, the PE Simon effect of the first bin was more than twice that of the second bin. As can be seen by mentally averaging the first two bins in our figures, the fact that the largest PE Simon effects were obtained on the fastest responses would still be evident with a five-bin analysis, but the prominent effect of the first bin would be diluted. Thus, compared to a five-bin analysis, a 10-bin analysis gives a more detailed depiction of the dynamics of the Simon effect. This detailed depiction comes at the cost of less precise estimates of the true values than for a five-bin analysis due to the fewer trials per bin. However, the consistent patterns across our experiments provide evidence that the estimates of the Simon effect in the 10-bin analysis are sufficiently precise to characterize the distribution.

The RT distribution analysis of our study was based on trimmed data (exclusion of trials with RT less than 150 ms or greater than 2.5 *SD* above a participant's mean for each condition). This method is consistent with that typically applied for analyses of the mean Simon effect (e.g., Theeuwes, Liefooghe, & De Houwer, 2014) and allows our mean Simon effects to be compared directly to those of most other studies. Data trimming in this manner is also common for distribution analyses of the Simon effect, with either a fixed RT cutoff for all participants (e.g., Töbel et al., 2014; Wiegand & Wascher, 2007) or a standard deviation–based cutoff for each participant (e.g., Pellicano, Lugli, Baroni, & Nicoletti, 2009). In our experiments, few trials had RT less than the lower bound (0.02% averaged across all experiments), and thus the lower bound had negligible impact on the early part of the RT distributions. About 2.5% of the trials in each experiment were excluded for longer RT than the upper bound, with this percentage being less for congruent (2.0%) than incongruent (3.0%) trials.

There are two other ways for removing outliers when performing bin analyses that would equate the exclusions for congruent and incongruent trials. First, all RTs can be included, with the 10th bin removed to take care of the outliers (e.g., Wascher et al., 2001). However, this method results in a loss of 10% of the data. Second, for each participant, an exclusion criterion such as 2.5 *SD* above the means for the congruent and incongruent trials separately can be applied (e.g., Gulbinaite & Johnson, 2014). However, in our data, this resulted in an abrupt increase of the Simon effect in the last bin, which again would necessitate removal of the last bin. With the method of removing outliers that we employed, only 2.5% of the trials are removed rather than 10%, and the Simon effect for the last RT bin conforms in most cases with the function for the previous bins. Thus, the Simon effect RT distribution resulting from our trimming method seems to depict the dynamic property of the activation–dissipation process of primary interest more precisely than the other methods while excluding the fewest trials.

Conclusion

Our study conveys the following fundamental messages:

The distribution functions for auditory simon effects conform to predictions of an activation–dissipation account. The activation–dissipation account on which we have focused is only one of several possible explanations for the Simon effect distribution functions (Schwarz & Miller, 2012), but it is the most plausible one. First, the Simon effect was reported initially for auditory stimuli and is larger for those stimuli than for visual stimuli (Lu & Proctor, 1995). This large effect suggests "a natural tendency to react toward the source of stimulation" (Simon, 1990, p. 34) or automatic activation of the corresponding response. Second, the activation–dissipation account is consistent with most explanations of the Simon effect, which attribute it to temporal overlap of the response activations produced by the task-irrelevant stimulus location and the task-relevant stimulus feature (e.g., Hommel, 1993b). Third, empirical data other than distribution analyses are in agreement with the idea that stimulus location produces rapid activation of the corresponding response, which dissipates through passive decay or active suppression (e.g., Hommel, 1993b; Simon et al., 1976). Fourth, Ulrich et al. (2015) demonstrated that the key distribution findings can be simulated by a diffusion model that distinguishes automatic and controlled processes and considers response boundaries or criteria.

Error data need to be taken into account when evaluating rt distribution functions. The extent to which response criteria are biased toward accuracy versus speed will influence the phase in the activation–dissipation cycle during which a response is selected and thus the size of the Simon effect in RT and PE. In all conditions of our study, PE was elevated in the first bin of the RT distribution, and when RT was adjusted in the IES, similar decreasing functions for the auditory Simon effect were evident. Likewise, Töbel et al. (2014) showed that the nondecreasing RT Simon effect function for visual tasks with vertically oriented S–R sets is accompanied by a decreasing PE function. When their mean RT distribution is adjusted with $1 - \text{PE}$ (as estimated from their

Figures 1 and 3), the IES Simon effect shows a decreasing function (IES of 120, 69, 46, 33, and 45 ms for their five quantiles). Error functions have yet to be reported for the nondecreasing RT functions found with horizontally oriented S–R sets when the hands are crossed, but they likely will also be decreasing.

Decreasing RT Simon effect functions are more likely to be evident when processing of the relevant feature is difficult. Relative timing, or temporal overlap, of the activation produced by the irrelevant and relevant stimulus features is crucial to the Simon effect. The RT function is more likely to reflect the later phase of the activation–dissipation cycle when response selection occurs later. In our study, the lengthening of RT for low-frequency tones relative to higher frequency ones in the last half of the RT distribution seems to be a factor in the decreasing RT Simon effect function obtained for the low-frequency tones. For vertical visual Simon tasks, decreasing RT functions have been reported when the relevant S–R mapping varies and is cued on each trial (e.g., Wiegand & Wascher, 2007). This mixing of mappings delays processing of the relevant information because participants must switch between two mappings, but the activation–dissipation function for the location dimension remains unaltered. Thus, the RT Simon effect decreases as the activation dissipates.

Buetti and Kerzel (2008) found evidence of dissipation with a response measure that occurs after RT. Their participants respond by moving the right index finger to one of two response boxes. The RT functions for vertical visual and horizontal auditory Simon tasks showed no decrease, as typical, but the initial movement angle showed a Simon effect (i.e., movement in the direction of the stimulus location) that decreased across the RT bins. Buetti and Kerzel (2008) interpreted their results as "supporting the idea that only a single, common mechanism underlies the Simon effect" (p. 420). Our results based on RT coupled with PE lend further support to the view that auditory and visual Simon effects have a common basis.

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