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BRIEF REPORT

Categorization difficulty modulates the mediated route for response selection in task switching

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Abstract

Conflict during response selection in task switching is indicated by the response congruency effect: worse performance for incongruent targets (requiring different responses across tasks) than for congruent targets (requiring the same response). The effect can be explained by dual-task processing in a mediated route for response selection, whereby targets are categorized with respect to both tasks. In the present study, the author tested predictions for the modulation of response congruency effects by categorization difficulty derived from a relative-speed-of-processing hypothesis. Categorization difficulty was manipulated for the relevant and irrelevant task dimensions in a novel spatial task-switching paradigm that involved judging the locations of target dots in a grid, without repetition of dot configurations. Response congruency effects were observed and they varied systematically with categorization difficulty (e.g., being larger when irrelevant categorization was easy than when it was hard). These results are consistent with the relative-speed-of-processing hypothesis and suggest that task-switching models that implement variations of the mediated route for response selection need to address the time course of categorization.

Keywords task switching · response selection · categorization difficulty · response congruency · asymmetric switch costs

An important aspect of cognitive control is the ability to resolve conflict in ambiguous situations. Conflict resolution is needed particularly in task-switching situations (Kiesel et al., 2010; Vandierendonck, Liefooghe, & Verbruggen, 2010), where a target stimulus might elicit different responses for different tasks, creating ambiguity as to which response is relevant. For example, consider the spatial task-switching paradigm introduced by Meiran (1996), in which subjects categorize the top/bottom or left/right location of a target appearing in a quadrant of a 2 × 2 grid. Responses are typically made with overlapping, spatially compatible category–response mappings, such as pressing a top-right response button for the top and right categories, and a bottom-left response button for the bottom and left categories. In this context, congruent targets are those that require the same response for both tasks (e.g., a target in the top-right quadrant), whereas incongruent targets are those that require different responses across tasks (e.g., a target in the bottom-right quadrant). The ambiguity arising from conflicting responses for incongruent targets leads to response congruency effects: longer response times (RTs) and more errors in incongruent trials than in congruent trials (e.g., Meiran, 1996; Meiran & Kessler, 2008; Monsell, Sumner, & Waters, 2003; Schneider, 2015a, b; Schneider & Logan, 2009). In the present study, I investigated a mechanism for response selection in task-switching situations that can produce response congruency effects.

Previous studies have implicated two mechanisms for generating response congruency effects: mediated and nonmediated routes for response selection (e.g., Kiesel et al., 2007; Meiran & Kessler, 2008; Schneider, 2015a, b; Schneider & Logan, 2009, 2015; Wendt & Kiesel, 2008). Both routes are illustrated in Fig. 1 for Meiran's (1996) spatial task-switching paradigm. The mediated route involves categorizing the target (e.g., a circle in the top-right quadrant) with respect to the task categories (top and right), then activating the response(s) to which those categories are mapped (a top-right button response). The route is mediated because it uses an intermediate categorical representation of the target (Schneider & Logan, 2010). The nonmediated route involves using the target to retrieve a response from memory based on target–response associations formed during task practice (Logan, 1988, 2002). The route is nonmediated because it

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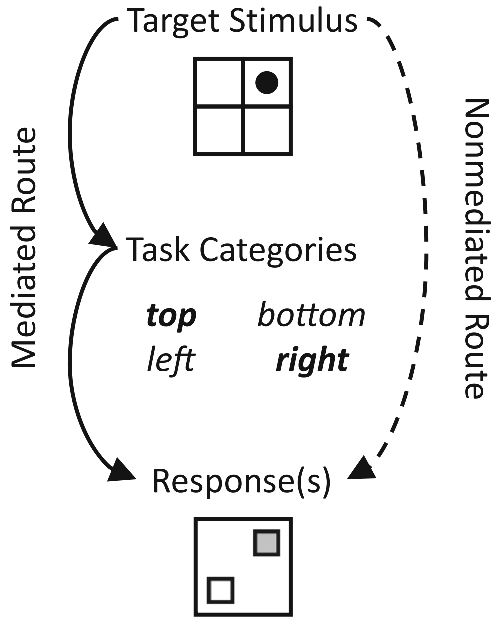

Fig. 1 Illustration of the mediated and nonmediated routes for response selection in a spatial task-switching context

bypasses categorization (see Fig. 1). Given that conflicting responses are activated (mediated route) or retrieved (nonmediated route) by incongruent targets, whereas a unique response is activated or retrieved by congruent targets, response selection is slower and more error-prone in incongruent trials than in congruent trials, producing response congruency effects.

Evidence supporting each route was summarized by Schneider (2015b). The main evidence for the nonmediated route was the finding of inverted response congruency effects when category–response mappings were reversed after training, suggesting that target–response associations were learned and enabled retrieval of responses from memory, even when those associations were no longer valid (Schneider & Logan, 2015; Waszak, Pfister, & Kiesel, 2013; Wendt & Kiesel, 2008). The main evidence for the mediated route was the finding of response congruency effects in situations that precluded retrieval based on learned target–response associations, such as experiments involving nonrepeated targets (Schneider, 2015a, b) or instructed but unpracticed target–response mappings (Liefooghe, Wenke, & De Houwer, 2012).

To elaborate on the last point, Schneider (2015a, b) provided evidence that the mediated route can produce response congruency effects by itself. In those experiments, subjects switched between categorizing the referents of target words as living/nonliving or small/large. Critically, no targets were repeated during each experiment, making the nonmediated route nonfunctional because no target–response associations were available for retrieval of responses from memory. Instead, responses could be selected only by categorizing targets via the mediated route. Response congruency effects were observed in all experiments, implying that the mediated route was sufficient for producing them. A broader implication was that subjects must have engaged in dual-task processing (i.e., categorizing targets with respect to both tasks) in many trials despite being cued to do a single task in every trial, consistent with some task-switching models (Gilbert & Shallice, 2002; Meiran, 2000; Schneider & Logan, 2005, 2009).

If response congruency effects occur because subjects often categorize targets with respect to both tasks, then the effects should be modulated by the difficulty with which targets can be categorized along the relevant and irrelevant task dimensions. This idea is rooted in the relative-speed-of-processing hypothesis (or horse-race model) that has been applied to multiple cognitive phenomena, such as the Stroop effect (Morton & Chambers, 1973; Posner & Snyder, 1975; for a review, see MacLeod, 1991), response inhibition in the stop-signal paradigm (Logan & Cowan, 1984; for a review, see Verbruggen & Logan, 2009), and contingency learning (Forrin & MacLeod, 2017). The crux of the hypothesis is that relevant and irrelevant task processes operate in parallel (or "race" against each other), and irrelevant task processing influences response selection if it finishes before relevant task processing. Applying the hypothesis to the mediated route in task switching, if subjects categorize targets with respect to both tasks (despite being cued to the relevant task), then the irrelevant task category will influence performance only if it is available before the termination of response selection based on the relevant task category. When irrelevant categorization is made harder, category information will become available later in processing, attenuating its effect on response selection. Thus, one would predict that increasing categorization difficulty along the irrelevant task dimension—slowing the availability of irrelevant category information—should produce less interference for incongruent targets and less facilitation for congruent targets, yielding smaller response congruency effects.

Meiran and Kessler (2008) provided mixed evidence in support of this prediction. The control condition of their experiments involved the aforementioned spatial task-switching paradigm (top/bottom and left/right judgments of a target's location in a grid) and yielded response congruency effects. Other conditions involved variants of the paradigm in which target locations could not be categorized along a single dimension for a given task. For example, in the rotated condition of their Experiments 1 and 2, the stimulus display and response configuration were rotated by 45 degrees, and the tasks involved judging target location relative to the inner diagonals of the grid. The rotated condition yielded no response congruency effect for RTs in Experiment 1 (a small effect emerged with practice in Experiment 2), consistent with the notion that categorization difficulty affects the mediated route. However, response congruency effects were still obtained for error rates, complicating interpretation of the RT data. Moreover, a role for the nonmediated route in response selection could not be excluded because the experiments involved repeated targets for which target–response associations could have been learned.

I designed the present experiment to provide unequivocal evidence for the idea that categorization difficulty should modulate response selection via the mediated route. The experiment involved a novel spatial task-switching paradigm in which multiple target "dots" appeared in the quadrants of a 2 × 2 grid (see Fig. 2). Subjects judged whether there were more dots in the left or right half of the grid (left–right task) or more dots in the top or bottom half (top–bottom task) by making a spatially compatible response. An arrow cue in the center of the grid indicated the relevant task in each trial. Overlapping category–response mappings (e.g., top and right categories mapped to one response button; bottom and left categories mapped to another response button) enabled coding of displays as incongruent or congruent.

A feature of the paradigm is that categorization difficulty can be manipulated separately along the relevant (cued) and irrelevant (noncued) task dimensions without changing the basic tasks or categories (cf. Meiran & Kessler, 2008). Categorization was "easy" when there was a large discrepancy in number of dots between halves (7 vs. 2), whereas it was "hard" when there was a small discrepancy (5 vs. 4). The relative-speed-of-processing hypothesis can be applied to this situation to generate two predictions about response congruency effects. First, manipulation of irrelevant categorization difficulty should affect the time when the irrelevant category producing interference or facilitation in response selection becomes available. When irrelevant categorization is easy and occurs quickly, the irrelevant category can influence response selection sooner, leading to the prediction of larger response congruency effects than when irrelevant categorization is hard. Second, manipulation of relevant categorization difficulty should affect the time available for interference or facilitation from the irrelevant category. When relevant categorization is hard and occurs slowly, there is more time for the irrelevant category to influence response selection, leading to the prediction of larger response congruency effects than when relevant categorization is easy. These predictions follow from a relative-speed-of-processing interpretation of dual-task categorization in the mediated route for response selection (see Appendix for additional details). An important aspect of the present experiment is that no dot configurations were repeated for any given subject (analogous to the nonrepeated targets in Schneider, 2015a, b), making the nonmediated route nonfunctional. Thus, the mere observation of response congruency effects, as well as changes in them with categorization difficulty, can be attributed to the mediated route.

Besides the theoretically motivated predictions concerning response congruency effects, there is an empirically driven prediction concerning switch costs—performance differences between task switches and task repetitions. Previous task-switching studies with tasks differing intrinsically in difficulty (e.g., Stroop color-naming and word-reading tasks) have yielded asymmetric switch costs: a larger switch cost for the easy task than for the hard task (e.g., Allport, Styles, & Hsieh, 1994; Allport & Wylie, 2000; Schneider & Anderson, 2010; Yeung & Monsell, 2003). If the manipulation of relevant categorization difficulty in the present study mirrors differences in task difficulty in previous studies, then asymmetric switch costs are predicted, with larger switch costs when relevant categorization is easy than when it is hard.

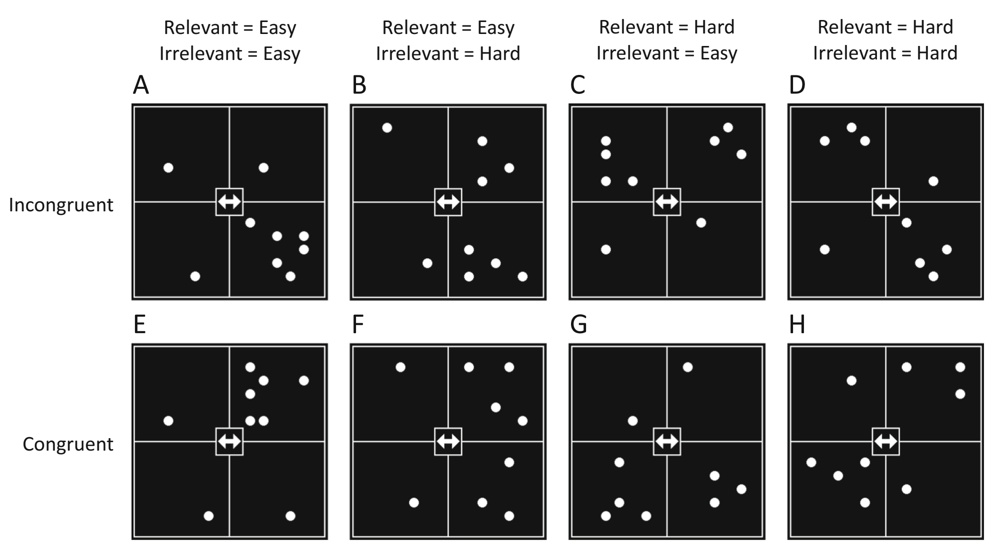

Fig. 2 Examples of actual stimulus displays as a function of response congruency (incongruent or congruent), relevant categorization difficulty (easy or hard), and irrelevant categorization difficulty (easy or hard). For all examples, the relevant category dimension is left–right (as indicated by the central arrow cue) and the irrelevant category dimension is top–bottom. Response congruency is coded assuming the top and right categories are mapped to one response button and the bottom and left categories are mapped to another response button

Method

Subjects

Forty-eight students from Purdue University participated for course credit. Data from two additional subjects were excluded for mean error rates exceeding a predetermined inclusion criterion of 20%. A power analysis indicated that 48 subjects would provide 99% power to detect a response congruency effect equal to the mean effect size (d = 0.64) obtained for nonrepeated targets by Schneider (2015b).

Apparatus

The experiment was conducted with computers that displayed stimuli on monitors and registered responses from Chronos devices (Psychology Software Tools). Stimuli were presented in white on a black background at a viewing distance of approximately 50 cm. The response device was positioned centrally at one of two diagonal orientations (tabletop guidelines enabled consistent positioning), such that the row of response buttons was oriented 45 degrees left or right. Responses were made using the left and right index fingers to press the leftmost and rightmost buttons, respectively, which were designated by red and green light-emitting diodes illuminated near the buttons.

Tasks, Stimuli, and Responses

Spatial categorization tasks were performed on displays such as those shown in Fig. 2. Each display consisted of a 2 × 2 grid (7.5 cm × 7.5 cm) with a central square space (1.0 cm × 1.0 cm) for a cue. Nine dots (filled circles with diameter of 0.35 cm) appeared in pseudo-random locations distributed across the quadrants of the grid. The left–right task, cued by a double-headed arrow pointing left and right (0.9 cm × 0.5 cm), involved pressing a response button to indicate whether there were more dots in the left or right half of the grid. The top–bottom task, cued by a double-headed arrow pointing up and down (0.5 cm × 0.9 cm), involved pressing a response button to indicate whether there were more dots in the top or bottom half of the grid. For half of the subjects (those with the response device oriented 45 degrees left), the top and left categories were mapped to the top-left response button, and the bottom and right categories were mapped to the bottom-right response button. For the other half (those with the response device oriented 45 degrees right), the top and right categories were mapped to the top-right response button, and the bottom and left categories were mapped to the bottom-left response button. Thus, category–response mappings were spatially compatible for all subjects.

Response congruency was defined by the dot configuration and category–response mappings (see Fig. 2, assuming top-right/bottom-left mappings). Congruent displays were associated with the same response across tasks (Fig. 2e–h). For example, Fig. 2e requires pressing the top-right response button because there are more dots in the right than in the left half for the cued left–right task, but the same response would be made for the noncued top–bottom task because there are more dots in the top than in the bottom half. Incongruent displays were associated with different responses across tasks (Fig. 2a–d). For example, Fig. 2a requires pressing the top-right response button because there are more dots in the right than in the left half for the cued left–right task, but the bottom-left response button would be pressed for the noncued top–bottom task because there are more dots in the bottom than in the top half.

Categorization difficulty was defined for the relevant and irrelevant task dimensions by the dot configuration and cue (see Fig. 2, where the cued left–right task is always relevant). Relevant categorization difficulty was based on the difference in number of dots between halves for the relevant (cued) dimension, whereas irrelevant categorization difficulty was based on the difference in number of dots between halves for the irrelevant (noncued) dimension. In both cases, easy and hard displays involved differences of five and one dots, respectively. For example, Fig. 2b is easy for the relevant left–right categorization because there are seven dots in the right half and two dots in the left half, but it is hard for the irrelevant top–bottom categorization because there are five dots in the bottom half and four dots in the top half.

Stimulus displays were pseudo-randomly generated such that each combination of task, response congruency, relevant categorization difficulty, irrelevant categorization difficulty, and correct response occurred twice in random order in each block of 64 trials. Moreover, each combination of task transition (task switch or task repetition), response congruency, relevant categorization difficulty, and irrelevant categorization difficulty occurred at least three times per block. These constraints determined how many dots were displayed in each quadrant in a given trial (there were always nine dots in total). The specific locations of the dots were randomly selected without replacement from an invisible 5 × 5 matrix of evenly spaced, non-overlapping locations within each quadrant. No dot configuration—even for trials in the same condition—was repeated during the experiment for a given subject (i.e., every dot configuration was unique).

Procedure

Subjects sat at computers in individual testing rooms after providing informed consent for a study protocol approved by the Purdue University Institutional Review Board. Instructions were presented onscreen and read aloud by the experimenter. During the instructions, subjects completed six example trials (all incongruent; three trials per task) with accuracy feedback. Afterward, they completed 12 blocks of 64 trials per block without accuracy feedback.

Each trial started with the empty grid displayed for 500 ms. A cue then appeared in the central square space for 500 ms. Finally, nine dots appeared in the quadrants of the grid, and the entire display (grid, cue, and dots) remained until a response was registered. The cue and dots then disappeared immediately (leaving an empty grid) and the next trial commenced. Subjects were instructed to respond quickly and accurately.

Results

The first block and first trial of each subsequent block were excluded. Trials with RTs more than three standard deviations above the mean in each condition for a given subject were excluded as outliers (1.7% of trials). Error trials were excluded from the RT analysis after outlier trimming. Mean RTs and error rates appear as a function of response congruency, relevant categorization difficulty, irrelevant categorization difficulty, and task transition in Table 1. The data were submitted to repeated measures analyses of variance with those variables as factors (summarized in Table 2). Mean RTs and error rates appear as a function of response congruency, relevant categorization difficulty, and irrelevant categorization difficulty in Fig. 3a and c, respectively. Response congruency effects (performance differences between incongruent and congruent trials) for RTs and error rates appear in Fig. 3b and d, respectively.

Response Congruency Effects

Performance was worse in incongruent trials (mean RT of 941 ms and mean error rate of 7.7%) than in congruent trials (898 ms and 3.2%), yielding significant main effects of response congruency. As shown in Fig. 3a and c, performance was impaired when relevant categorization was hard (1152 ms and 8.4%) than when it was easy (687 ms and 2.5%), yielding significant main effects of relevant categorization difficulty. The relevant categorization difficulty effect on RTs was larger when irrelevant categorization was easy (500 ms) than when it was hard (428 ms), resulting in a significant interaction between relevant and irrelevant categorization difficulty. The corresponding interaction was nonsignificant for error rates, but performance was impaired when irrelevant categorization was easy (6.1%) than when it was hard (4.8%), yielding a significant main effect of irrelevant categorization difficulty.

Response congruency effects were modulated by relevant and irrelevant categorization difficulty (see Fig. 3b and d). Response congruency effects were numerically larger when relevant categorization was hard (57 ms and 5.6%) than when it was easy (31 ms and 3.3%), and the interaction between response congruency and relevant categorization difficulty was significant for error rates (p = .115 for RTs). In contrast, response congruency effects were larger when irrelevant categorization was easy (63 ms and 6.6%) than when it was hard (25 ms and 2.3%), yielding significant interactions between response congruency and irrelevant categorization difficulty for both RTs and error rates. In the error data, the difference in response congruency effects for easy versus hard irrelevant

Table 1 Mean response times and error rates

Response congruency	Relevant categorization difficulty	Irrelevant categorization difficulty	Task transition	Response time (ms)	Error rate (%)
Incongruent	Easy	Easy	Task switch	738 (30)	7.9 (0.9)
			Task repetition	653 (25)	3.1 (0.7)
		Hard	Task switch	757 (37)	4.3 (0.7)
			Task repetition	663 (35)	1.2 (0.4)
	Hard	Easy	Task switch	1221 (50)	15.5 (1.7)
			Task repetition	1201 (46)	11.2 (1.6)
		Hard	Task switch	1199 (47)	11.5 (1.4)
			Task repetition	1099 (45)	6.7 (1.0)
Congruent	Easy	Easy	Task switch	688 (28)	0.8 (0.3)
			Task repetition	607 (21)	0.3 (0.2)
		Hard	Task switch	748 (36)	1.4 (0.4)
			Task repetition	645 (29)	0.6 (0.3)
	Hard	Easy	Task switch	1126 (46)	5.6 (0.9)
			Task repetition	1140 (41)	4.5 (0.7)
		Hard	Task switch	1152 (51)	6.3 (0.9)
			Task repetition	1076 (42)	6.0 (1.0)

Standard errors of the means appear in parentheses

Table 2 Summary of analyses of variance

Effect	Response time				Error rate			
	F(1,47)	*MSE*	*p*	η_p^2	*F*(1,47)	*MSE*	*p*	η_p^2
C	20.94	17,618	<.001	.31	53.75	72	<.001	.53
R	473.48	87,414	<.001	.91	53.68	127	<.001	.53
I	0.20	17,976	.656	<.01	32.16	11	<.001	.41
T	36.10	24,527	<.001	.43	60.52	19	<.001	.56
C × R	2.58	12,588	.115	.05	15.56	16	<.001	.25
C × I	7.86	9,018	.007	.14	47.87	18	<.001	.51
C × T	0.96	8,683	.333	.02	45.48	13	<.001	.49
R × I	11.86	20,936	.001	.20	1.08	9	.304	.02
R × T	11.89	8,190	.001	.20	0.26	12	.610	.01
I × T	17.91	6,732	<.001	.28	0.96	9	.331	.02
C × R × I	0.12	6,796	.726	<.01	4.97	11	.031	.10
C × R × T	1.67	7,182	.202	.03	0.25	14	.623	.01
C × I × T	0.16	9,195	.692	<.01	0.20	8	.655	<.01
R × I × T	7.70	7,514	.008	.14	0.44	11	.513	.01
C × R × I × T	<0.01	6,339	.960	<.01	2.92	11	.094	.06

Note. C = response congruency; R = relevant categorization difficulty; I = irrelevant categorization difficulty; T = task transition

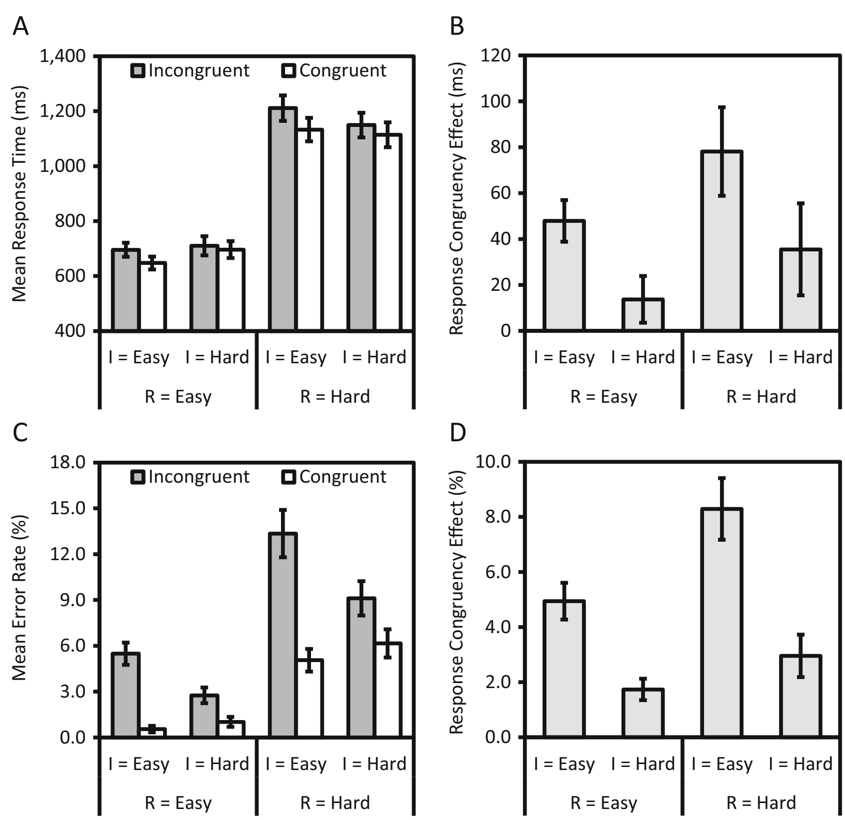

Fig. 3 Mean response times (Panel **a**) and error rates (Panel **c**) as a function of response congruency and relevant and irrelevant categorization difficulty (R and I, respectively). Response congruency effects (performance differences between incongruent and congruent trials) for response times (Panel **b**) and error rates (Panel **d**) as a function of relevant and irrelevant categorization difficulty. Error bars represent standard errors of the means

categorization was larger when relevant categorization was hard (8.3 vs. 3.0%) than when it was easy (4.9 vs. 1.7%), yielding a significant interaction between response congruency, relevant categorization difficulty, and irrelevant categorization difficulty.

Task Transition Effects

Performance was worse for task switches (954 ms and 6.7%) than for task repetitions (886 ms and 4.2%), reflecting switch costs that yielded significant main effects of task transition. Switch costs in error rates were larger for incongruent trials (4.2%) than for congruent trials (0.7%), yielding a significant interaction between response congruency and task transition. The corresponding interaction was nonsignificant for RTs, but switch costs were modulated by relevant and irrelevant categorization difficulty (see Table 1). Switch costs were larger when relevant categorization was easy (90 ms) than when it was hard (45 ms), yielding a significant interaction between relevant categorization difficulty and task transition. In contrast, switch costs were smaller when irrelevant categorization was easy (43 ms) than when it was hard (93 ms), yielding a significant interaction between irrelevant categorization difficulty and task transition. The switch cost asymmetry based on relevant categorization difficulty was present predominantly when irrelevant categorization was easy (switch costs of 83 vs. 3 ms when relevant categorization was easy versus hard) than when it was hard (98 vs. 88 ms), yielding a significant interaction between relevant categorization difficulty, irrelevant categorization difficulty, and task transition. No other effects were significant (see Table 2).

Discussion

My goal in the present study was to gain insight into the mediated route for response selection in task-switching situations. Given that response congruency effects can be produced by the mediated route only if targets are categorized with respect to both tasks, I conjectured that the effects should reflect the difficulty with which targets can be categorized. Based on the relative-speed-of-processing hypothesis used to explain other cognitive phenomena, I derived predictions for the modulation of response congruency effects by categorization difficulty (see Appendix). I tested the predictions in an experiment involving a novel spatial task-switching paradigm in which the categorization difficulty of the relevant and irrelevant task dimensions was manipulated.

The experiment produced empirical findings with methodological and theoretical implications. Response congruency effects were obtained for RTs and error rates despite no repetition of dot configurations, conceptually replicating earlier findings with nonrepeated targets (Schneider, 2015a, b) and generalizing them from semantic categorization tasks performed on words to spatial categorization tasks performed on dots. The mere observation of response congruency effects in a context in which the nonmediated route was nonfunctional provides further support for the mediated route as a viable explanation of the effects. It also indicates that subjects must have categorized targets with respect to both tasks in many trials (despite being cued to do a single task in every trial), which is consistent with theoretical views of task switching that afford dual-task processing (e.g., Gilbert & Shallice, 2002; Meiran, 2000; Schneider & Logan, 2005, 2009) and inconsistent with those that do not (e.g., Mayr & Kliegl, 2000; Sohn & Anderson, 2001). Critically, response congruency effects varied systematically with categorization difficulty (see Fig. 3b and d), consistent with predictions based on the relative-speed-of-processing hypothesis. Supporting the first prediction, response congruency effects were significantly larger for RTs and error rates when irrelevant categorization was easy than when it was hard. Supporting the second prediction, response congruency effects were larger (significantly for error rates) when relevant categorization was hard than when it was easy.

These findings suggest there is merit to the relative-speed-of-processing interpretation of dual-task categorization in the mediated route. Building on earlier work by Meiran and Kessler (2008), the results indicate that the functionality of the mediated route is sensitive to categorization difficulty, especially in relation to the opportunity for the irrelevant category to influence response selection. When the irrelevant category is available sooner (by making irrelevant categorization easy), or when the irrelevant category can affect response selection for longer (by making relevant categorization hard), then larger response congruency effects are produced. This refined characterization of irrelevant-task categorization has implications for task-switching models that implement variations of the mediated route for response selection (e.g., Gilbert & Shallice, 2002; Meiran, 2000; Schneider & Logan, 2005, 2009). For example, in Schneider and Logan's model, the target categories for the relevant and irrelevant tasks become available simultaneously, as soon as the target has been encoded. Moreover, the strength with which a target is associated with a category is typically a free parameter that is common to all targets in the same category (cf. Logan & Schneider, 2010). To explain the present results, the model would need to be elaborated by addressing the time course of categorization for each task dimension and by allowing targets to provide varying strengths of evidence for different associated categories.

Besides the influence of categorization difficulty on response congruency effects, overall RTs (collapsed across task transition) were shorter when relevant categorization was easy than when it was hard, indicating that the difficulty manipulation was effective. However, switch costs in RTs were twice as large when relevant categorization was easy than when it was hard, replicating common switch cost asymmetries (e.g., Allport et al., 1994; Allport & Wylie, 2000; Schneider & Anderson, 2010; Yeung & Monsell, 2003). Interestingly, the asymmetry was most pronounced when irrelevant categorization was easy. These findings suggest that the present experimental paradigm might be useful for refined exploration of asymmetric switch costs by allowing parametric adjustment of task difficulty.

Finally, the present study complements research on attentional modulation of response selection in task switching. For example, recent studies have revealed that response congruency effects become larger with an increasing proportion of congruent trials (Braverman & Meiran, 2015; Bugg & Braver, 2016; Schneider, 2015a). Similar proportion congruent effects have been interpreted as evidence of top-down attentional control of response selection, especially in contexts where bottom-up control via item-specific learning can be excluded (Bugg & Crump, 2012). Given the well-established link between attention and categorization (Logan, 2002; Nosofsky, 1986), a direction for future research would be to see whether the categorization difficulty effects obtained with the present paradigm are sensitive to attentional manipulations, potentially revealing more about the mediated route for response selection in task switching.

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Appendix

The purpose of this appendix is to explain in more detail how the relative-speed-of-processing hypothesis can be applied to the present experimental context to generate the two predictions that were tested. For a response congruency effect to be produced by the mediated route, the irrelevant task category has to be available before the termination of response selection based on the relevant task category. A simplified way of investigating this contingency is to compare the relative finishing times of relevant and irrelevant categorization, focusing on how often irrelevant categorization finishes before relevant categorization in different conditions.

Inspired by representations of the horse-race model of response inhibition for the stop-signal paradigm (e.g., Fig. 2 in Logan & Cowan, 1984; see also Verbruggen & Logan, 2009), Fig. 4 provides a graphical representation of the relative-speed-of-processing hypothesis applied to each combination of relevant and irrelevant categorization difficulty.[1] Each panel shows a normal distribution of relevant categorization finishing times and a constant irrelevant categorization finishing time. Panel A depicts the condition in which both categorizations are easy and take the same time on average, as indicated by the overlapping triangle and circle that correspond to the mean finishing times for relevant and irrelevant categorization, respectively. Given that relevant categorization has a distribution of finishing times, sometimes it finishes before irrelevant categorization (unshaded area of the distribution), resulting in no influence of the irrelevant category (i.e., no response congruency effect). However, relevant categorization sometimes finishes after irrelevant categorization (shaded area of the distribution), enabling the irrelevant category to influence response selection (producing a response congruency effect). For the normal distribution assumed for relevant categorization finishing times, irrelevant categorization finishes earlier on 50% of the trials (shaded area = 0.5). For ease of exposition, I will refer to the trials on which the irrelevant category can influence response selection as "influence" trials; therefore, the shaded area corresponds to the proportion of influence trials. It seems reasonable to assume that as the proportion of influence trials increases, the response congruency effect will get larger. For a condition with 50% influence trials, the result might be a medium-sized response congruency effect.

Panels B–D of Fig. 4 depict the other three combinations of categorization difficulty, each of which involves at least one categorization that is hard. A change in categorization difficulty from easy to hard is represented by a rightward shift in finishing times. I arbitrarily assumed a shift that resulted in a mean finishing time for hard categorization at the 90th percentile of the easy categorization finishing time distribution. Panel B depicts the condition in which relevant categorization is easy and irrelevant categorization is hard, which is why their mean finishing times (represented by the triangle and circle, respectively)

[1] In the horse-race model of response inhibition, the race is between a GO process for a primary task and a STOP process for response inhibition. When the GO process finishes before the STOP process, a response is emitted. When the STOP process finishes before the GO process, the response is suppressed. Adapting the model to the present context, relevant and irrelevant categorization processes are analogous to GO and STOP processes, respectively, except that irrelevant categorization modulates responding instead of suppressing it.

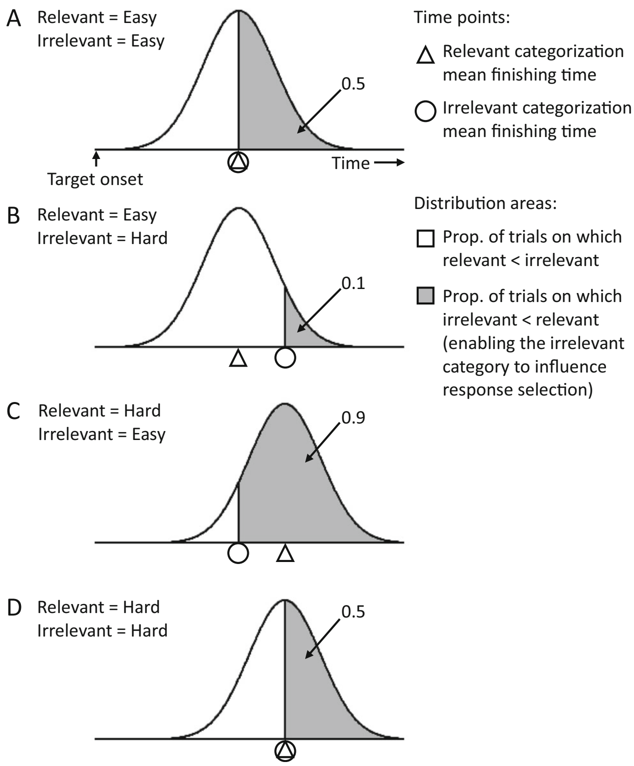

Fig. 4 Graphical representation of the relative-speed-of-processing hypothesis applied to relevant and irrelevant categorization in the mediated route for response selection as a function of categorization difficulty (see text for explanation). Prop. = Proportion

are shown at different time points. In this condition, irrelevant categorization rarely finishes before relevant categorization (shaded area = 0.1), resulting in few influence trials and a small response congruency effect. Panel C depicts the opposite condition, in which relevant categorization is hard and irrelevant categorization is easy. In this condition, irrelevant categorization often finishes before relevant categorization (shaded area = 0.9), resulting in many influence trials and a large response congruency effect. Panel D depicts the final condition, in which both categorizations are hard. This situation is similar to when both categorizations are easy (shaded area = 0.5), resulting in a medium-sized response congruency effect.

The two predictions given in the main text can be derived from the mean proportions of influence trials in different conditions (i.e., the shaded areas in Fig. 4). The first prediction—a larger response congruency effect when irrelevant categorization is easy than when it is hard—is reflected by a larger mean proportion of influence trials when irrelevant categorization is easy (0.7; mean of 0.5 and 0.9 in Panels A and C) than when it is hard (0.3; mean of 0.1 and 0.5 in Panels B and D). The second prediction—a larger response congruency effect when relevant categorization is hard than when it is easy—is reflected by a larger mean proportion of influence trials when relevant categorization is hard (0.7; mean of 0.9 and 0.5 in Panels C and D) than when it is easy (0.3; mean of 0.5 and 0.1 in Panels A and B). Thus, both predictions follow from a relative-speed-of-processing interpretation of dual-task categorization in the mediated route.

The graphical representation in Fig. 4 and the associated numerical examples involve simplifying assumptions to facilitate visualization and communication of the relative-speed-of-processing hypothesis. One assumption is that irrelevant categorization finishing time is constant, which is likely false.[2] Another assumption is about the magnitude of the rightward shift of finishing times when categorization difficulty changes from easy to hard. To investigate whether these assumptions affect the basic pattern of predictions, I conducted simulations of a basic horse-race model in which (1) irrelevant categorization had a distribution of finishing times with the same shape and variability used for relevant categorization, and (2) the mean finishing time for hard categorization involved less extreme shifts to the 80th and 70th percentiles of the easy categorization finishing time distribution. In each simulated trial, I randomly sampled finishing times for relevant and irrelevant categorization, then compared them to see which process finished first. For all simulated scenarios, the mean proportion of influence trials was still larger when irrelevant categorization was easy than when it was hard, consistent with the first prediction. It was also still larger when relevant categorization was hard than when it was easy, consistent with the second prediction. Thus, the predictions seem to hold under altered assumptions.

There are additional assumptions regarding the shape of the distribution of finishing times (it need not be normal) and the variability of the distribution (which could be smaller or larger than assumed, and need not be the same for relevant and irrelevant categorization). I have not explored the vast space of possibilities involving alterations of these assumptions, in part because they should ideally be investigated in the context of a computational model of task switching. The goal of this Appendix was to demonstrate proof of concept, showing how the two predictions tested in the present experiment can be derived from the relative-speed-of-processing hypothesis.

[2] This is analogous to the assumption of a constant stop signal reaction time (i.e., the covert latency of the STOP process) in the horse-race model of response inhibition (Logan & Cowan, 1984). The consequences of violating this assumption have been investigated in simulations (e.g., Band, van der Molen, & Logan, 2003).

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