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Generalizing attentional control across dimensions and tasks: Evidence from transfer of proportion-congruent effects

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Three experiments investigated transfer of list-wide proportion congruent (LWPC) effects from a set of congruent and incongruent items with different frequency (inducer task) to a set of congruent and incongruent items with equal frequency (diagnostic task). Experiments 1 and 2 mixed items from horizontal and vertical Simon tasks. Tasks always involved different stimuli that varied on the same dimension (colour) in Experiment 1 and on different dimensions (colour, shape) in Experiment 2. Experiment 3 mixed trials from a manual Simon task with trials from a vocal Stroop task, with colour being the relevant stimulus in both tasks. There were two major results. First, we observed transfer of LWPC effects in Experiments 1 and 3, when tasks shared the relevant dimension, but not in Experiment 2. Second, sequential modulations of congruency effects transferred in Experiment 1 only. Hence, the different transfer patterns suggest that LWPC effects and sequential modulations arise from different mechanisms. Moreover, the observation of transfer supports an account of LWPC effects in terms of list-wide cognitive control, while being at odds with accounts in terms of stimulus–response (contingency) learning and item-specific control.

Keywords: Congruency effect; Transient conflict adaptation; Sustained conflict adaptation; Proportion-congruent effect; Gratton effect; Transfer.

To achieve our goals in a complex and dynamic environment, our information-processing system must be selective. Attention is the key to selectivity. Attention biases the processing system to efficiently find and process relevant information, and attention sometimes inhibits the processing of irrelevant information (e.g., Desimone & Duncan, 1995; Posner, 1980; Tipper, 2001; Wühr & Frings, 2008). Researchers typically study the selectivity of attention in so-called *filtering* tasks (cf. Luck & Vecera, 2002, for a review). In these tasks, participants have to respond to a relevant stimulus feature (e.g., colour), and the congruency between an irrelevant stimulus feature and either the relevant stimulus feature or the response is varied. The impact of irrelevant information on behaviour (i.e., the size of the *congruency* effect) reflects the selectivity of processing in this task.

The Stroop and the Simon task are popular filtering tasks. In a Stroop task (Stroop, 1935)

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participants name the ink colour of a word that spells either a congruent or an incongruent word. Responses are faster to congruent items (e.g., the word RED in red ink) than to incongruent items (e.g., the word RED in blue ink)—an observation called the Stroop effect (see, MacLeod & MacDonald, 2000, for a review). In a Simon task (Simon & Rudell, 1967), participants press a left or a right key to the colour of a stimulus that appears to the left or right of fixation. Responses are faster when stimulus and response locations correspond (congruent condition) than when they do not correspond (incongruent condition)—an observation called the Simon effect (see, Proctor & Vu, 2006, for a review). The fact that participants typically produce the correct response in Stroop and Simon tasks, even in incongruent conditions, indicates that selective attention is quite effective. The occurrence of Stroop and Simon effects, however, indicates that selection is not perfect, and many authors attributed this lack in selectivity to the automatic nature of processing conceptual and spatial information (e.g., MacLeod & MacDonald, 2000; Proctor & Vu, 2006). However, fluctuations in the level of processing irrelevant information presumably also reflect flexible adjustment of control settings.

To investigate the flexibility of selective attention, researchers studied whether the lack of selectivity in filtering tasks varies with the usefulness of irrelevant information. For example, it was investigated whether the proportion of congruent items in a block of individual trials affects the size of Stroop interference. In fact, Stroop effects are larger with a high proportion of congruent items than with a low proportion of congruent items (e.g., Lindsay & Jacoby, 1994; Logan, 1980; Logan & Zbrodoff, 1979; Lowe & Mitterer, 1982). A low proportion of congruent items (i.e., a high proportion of incongruent items) sometimes even leads to the reversal of Stroop interference—that is, faster and more accurate responses for incongruent than for congruent conditions (e.g., Logan, 1980; Logan & Zbrodoff, 1979). Similar results were observed for the Simon task: Simon effects are large with a high proportion of congruent displays, and Simon effects are small, or even inverted, with a low proportion of congruent displays (e.g., Hommel, 1994; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002). In the following, we refer to the effect of a list-wide manipulation of the proportion of congruent trials on the size of the congruency effect as the *list-wide proportion congruent (LWPC) effect* (see Bugg & Crump, 2012, for a review).

Flexible control assumes that the cognitive system modulates attention to the relevant stimulus dimension and/or the nominally irrelevant stimulus dimension, depending on the proportion of congruent items (e.g., Lindsay & Jacoby, 1994; Logan, 1980; Lowe & Mitterer, 1982). According to this hypothesis, control mechanisms register the frequency of conflict within a list (or block) of trials and correspondingly adapt the attentional weights for the processing of relevant and/or irrelevant stimulus dimensions (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001). As a result, with a high proportion of congruent trials (low-conflict lists), participants might decrease attention to the relevant dimension and/or increase attention to the irrelevant dimension. This attentional set aids performance on congruent trials, but impairs performance on incongruent trials, thus increasing congruency effects. In contrast, with a low proportion of congruent trials (high-conflict lists), participants might increase attention to the relevant dimension and/or decrease attention to the irrelevant dimension. This attentional set impairs performance on congruent trials, but aids performance on incongruent trials, thus decreasing congruency effects.

More recently, it has been suggested that LWPC effects may reflect more basic processes of learning new stimulus–response (S–R) associations rather than flexible attentional modulation. This account in terms of *S–R (contingency) learning* assumes that, during the course of the experiment, participants learn and use S–R associations between the nominally irrelevant word and the most frequent response to this word (e.g., Melara & Algom, 2003; Schmidt, 2013; Schmidt & Besner, 2008; Schmidt, Crump, Cheesman, & Besner, 2007). For example, consider a two-item stimulus set for a Stroop task involving the words RED and GREEN in red and green colour. In the mostly congruent list, the word RED, for example, is more often combined with the congruent colour red than with the incongruent colour green. In contrast, in the mostly incongruent list, the word RED is more often combined with the incongruent colour green than with the congruent colour red. After some practice, participants might use these contingencies to predict the specific response associated with each irrelevant stimulus. Using the word to predict the (mostly congruent) response in mostly congruent lists facilitates performance on congruent trials, but impairs performance on incongruent trials, increasing congruency effects. In contrast, using the word to predict the (mostly incongruent) response in mostly incongruent lists impairs performance on congruent trials, but facilitates performance on incongruent trials, decreasing congruency effects.

An important difference between both accounts is that S–R (contingency) learning critically rests on different frequencies of individual stimuli, whereas the notion of flexible control does not. Hence, a straightforward empirical test for the existence of flexible control is to look for a *transfer* of LWPC effects from a set of frequency-biased items to a set of frequency-unbiased items. In fact, a handful of studies tested for such transfer effects and obtained mixed results (e.g., Blais & Bunge, 2010; Bugg & Chanani, 2011; Bugg, Jacoby, & Toth, 2008; see Bugg & Crump, 2012, for review). For example, Bugg et al. (2008) combined a pair of frequency-biased Stroop stimuli with a pair of frequency-unbiased Stroop stimuli. The two biased items (e.g., the words GREEN and WHITE) were 75% congruent in a mostly congruent list and 75% incongruent in a mostly incongruent list. In contrast, the two unbiased items (e.g., the words BLUE and RED) were 50% congruent and 50% incongruent in both conditions. Results showed no LWPC effect for the unbiased items (see, Blais & Bunge, 2010, for similar findings). These findings seriously question the notion of flexible control as an explanation for LWPC effects. Rather, contingency learning might be sufficient to explain both item-specific and list-wide effects.

The results from two other transfer studies, however, suggest that it might be premature to dismiss flexible control as an account for LWPC effects (Bugg & Chanani, 2011; Funes, Lupiáñez, & Humphreys, 2010b). Bugg and Chanani (2011) used picture–word Stroop stimuli and increased the number of frequency-biased items from two to four. The rationale was that increasing the number of items might decrease the usefulness (and probability) of contingency learning. For example, contingency (S–R) learning is more likely with a two-item set because a mostly incongruent item is most often paired with a single (incongruent) response. In contrast, in a four-item set, a mostly incongruent item is equally often paired with three incongruent responses. Results revealed an LWPC effect for the two unbiased items, consistent with a flexible control account.

Still, the transfer effects demonstrated by Bugg and Chanani (2011) might have resulted from transfer of sequential effects. In particular, congruency effects are typically larger after congruent trials than after incongruent trials—a finding called the *Gratton* effect (after Gratton, Coles, & Donchin, 1992, who were the first to describe this effect). The sequential modulation was observed for the Simon effect (e.g., Stürmer et al., 2002; Wühr, 2004) and for the Stroop effect (e.g., Kerns et al., 2004). Some authors attribute sequential modulations of congruency effects to cognitive mechanisms concerned with the detection and regulation of cognitive conflict (e.g., Botvinick et al., 2001; Gratton et al., 1992; Stürmer et al., 2002; see, Egner, 2007, for a review).

Sequential modulations of congruency effects can explain the LWPC effect because, with a high proportion of congruent trials, most trials N have congruent predecessor trials $N - 1$ that increase the congruency effect observed in trials N (e.g., Schmidt & Besner, 2008). In contrast, with a high proportion of incongruent trials, most trials N have incongruent predecessor trials $N - 1$ that decrease the congruency effect observed in trials N.

Sequential effects could therefore explain transfer of LWPC effects from frequency-biased items to frequency-unbiased items if the sequential modulation also transferred from biased to unbiased items. Bugg and Crump (2012, p. 12) dismiss this hypothesis by arguing:

> Such an explanation may be less likely to account for LWPC effects on congruency-matched items or neutral items, however, when such items do not share overlapping features (relevant or irrelevant) with the items that establish the bias of the list. . . .

However, several studies demonstrated sequential modulations of congruency effects between items that did not share (relevant or irrelevant) features in the Stroop task (e.g., Duthoo & Notebaert, 2012) and in the Simon task (e.g., Wühr, 2005). In fact, the literature suggests that sequential modulations of congruency effects can occur between different items (i.e., complete alternations) as long as these items share the relevant stimulus dimension (e.g., Egner, 2007; Notebaert & Verguts, 2008) and/or the source of conflict (e.g., Funes, Lupiáñez, & Humphreys, 2010a). Both conditions were met in the study by Bugg and Chanani (2011).

Stronger support for flexible control was provided by Funes et al. (2010b) where transfer of LWPC effects in the absence of transfer of sequential effects was demonstrated. In their task, participants responded to upward- or downward-pointing arrowheads by pressing a left or right key. In half of the trials, stimuli appeared at horizontal locations, creating a Simon-like situation where incongruent S–R relations produced response conflict. In the other half of the trials, stimuli appeared at vertical locations, creating a Stroop-like situation where incongruent S–S relations produced stimulus conflict. Hence, the source of conflict varied between horizontal and vertical stimulus locations, but the participants' task (i.e., the stimuli and responses) remained the same. Most importantly, the authors manipulated the proportion of congruent Simon-like trials (being either 75% or 25% in different blocks), but kept the ratio between congruent and incongruent Stroop-like trials equal.

The results of Funes et al. (2010b) revealed transfer of the LWPC effect from frequency-biased (Simon-like) items to unbiased (Stroop-like) items, but no transfer of the Gratton effect from Simon-like trials to Stroop-like trials. In particular, Stroop-like interference was larger in a context of mostly congruent Simon-like trials than in a context of mostly incongruent Simon-like trials. In contrast, sequential modulations of congruency effects occurred for repetitions of Simon-like and Stroop-like trials, but not for alternations of trial types. Funes et al. concluded that the LWPC effect and the Gratton effect arise from different mechanisms. According to their analysis, transfer of LWPC effects provides evidence for flexible control (in this case, increasing attention to stimulus shape over location) that is sensitive to the frequency of conflict, but independent from individual stimuli. In contrast, their failure to observe transfer of Gratton effects suggests that these effects are bound to repetitions of the source of conflict (see also Funes et al., 2010a).

The purpose of our research was to further investigate transfer in order to better understand flexible control. Funes et al. (2010b) demonstrated that flexible control adjusts the relative processing weights of relevant or irrelevant information. Because both the relevant and the irrelevant dimension were identical for biased and unbiased items, this study could not (and was not intended to) dissociate modulations of attention to relevant information from modulations of attention to irrelevant information. In the present series of experiments, we tested the role of attention to the relevant dimension in obtaining transfer of control. Experiment 1 mixed trials of a horizontal and vertical Simon task. Both tasks involved different stimulus (and response) sets, but relevant stimuli varied on the same dimension (colour). Experiment 2 had the same design, except that the relevant stimuli now varied on different dimensions (colour and shape). Finally, Experiment 3 mixed trials of a Simon task with manual responses and trials of a Stroop task with vocal responses, with both tasks sharing the relevant stimulus dimension (colour). Importantly, for each experiment, we tested not only for transfer of the LWPC effect, but also for transfer of sequential

(Gratton) effects from frequency-biased items to frequency-unbiased items. Finding transfer of LWPC effects would provide strong evidence for flexible control if this transfer was independent from sequential modulations. Moreover, if transfer of LWPC effects would only occur when the two tasks share the relevant dimension (as in Experiments 1 and 3), this would suggest that flexible control mainly modulates attention to the relevant stimulus dimension.

EXPERIMENT 1

Previous studies revealed that the LWPC effect can transfer from frequency-biased items to unbiased items within the same task—that is, when both sets of items shared relevant stimuli and responses (e.g., Funes et al. 2010b). Experiment 1 went one step further and tested whether the LWPC effect would also transfer between two tasks that involve different stimuli and different responses. Therefore, in Experiment 1, our participants performed a horizontal and a vertical variant of the Simon task, respectively, in separate trials. In the horizontal Simon task, participants pressed a left key to a green stimulus and a right key to a red stimulus, and the imperative stimulus appeared at a left or a right location. In the vertical Simon task, participants pressed an upper key to a blue stimulus and a lower key to a yellow stimulus, and the imperative stimulus appeared at an upper or lower location. Hence, we independently manipulated horizontal congruency in the horizontal Simon task, and vertical congruency in the vertical Simon task.

For one group of participants, we manipulated the proportion of congruent trials in the horizontal Simon task (between blocks) and kept constant the proportion of congruent trials in the vertical Simon task. For a second group of participants, we manipulated the proportion of congruent trials in the vertical Simon task (between blocks) and kept constant the proportion of congruent trials in the horizontal Simon task. We expected reliable Simon effects for both Simon tasks, and we expected a LWPC effect for the biased Simon task (the "inducer" task). The question was whether different proportions of congruent trials in the inducer Simon task would also affect the size of the Simon effect in the unbiased "diagnostic" task, providing evidence for transfer of the LWPC effect across tasks.

We also investigated whether sequential modulations (i.e., Gratton effects) would occur not only within tasks, but also between tasks. On the one hand, this was possible because the tasks shared the relevant stimulus dimension (colour; Notebaert & Verguts, 2008). On the other hand, previous research suggests that horizontal and vertical Simon tasks might involve different sources of conflict (e.g., Wiegand & Wascher, 2005), and therefore transfer of Gratton effects might not occur (e.g., Funes et al., 2010a, 2010b).

Method

Participants

Forty-six student volunteers (38 female, 8 male; 44 right-handers, 2 left-handers) with a mean age of 23 years (range 19–37 years) participated for course credit. Twenty-four participants (18 female, 6 male) were assigned to Condition 1 where we manipulated the proportion of congruent trials in the horizontal Simon task; 22 participants (20 female, 2 male) were assigned to Condition 2, where we manipulated the proportion of congruent trials in the vertical Simon task.

Apparatus and stimuli

Participants sat in a dimly lit room in front of a 17-inch colour monitor, with an unconstrained viewing distance of approximately 50 cm. A computer program written in ERTS language (BeriSoft, Frankfurt am Main, Germany) controlled stimulus presentation and collected responses. All responses were keypresses with the index finger of the right hand on the number pad of a standard keyboard (keys 2, 4, 5, 6, and 8). A plus sign, presented at screen centre, served as a fixation. The visual stimuli were filled squares that appeared to the left, to the right, above, or below the fixation point. The square measured 1 cm × 1 cm. The distance between the fixation point and the inner edge of the square stimulus was 5 cm. The square appeared in blue, green, red, or yellow colour. The two colours requiring a left or right response only appeared at the left or right screen location; the two colours requiring an upper or lower response only appeared at the upper or lower screen location. In other words, participants performed the horizontal and the vertical Simon task in separate trials.

Procedure

At the beginning of the experiment, the instructions appeared on the screen, and participants could read them at leisure. The instructions told participants to start each stimulus presentation (i.e., each trial) by pressing the central key (5) and then to press the appropriate lateral key to stimulus colour as quickly as possible, while ignoring stimulus location. The instructions also informed participants about the relevant S–R mapping, with each of the four colours mapped onto one of the four response keys. A Latin square was used to counterbalance the mapping of colours to key locations across participants.

Each trial started with a screen message asking participants to press the central key in order to start the next stimulus presentation. This keypress triggered the presentation of the fixation point for 1500 ms. Five hundred ms after the onset of fixation, the imperative stimulus (i.e., the coloured square) appeared at one of the four peripheral locations and remained there for 1000 ms. Hence, the fixation point and the imperative stimulus disappeared simultaneously. A blank period of one second followed stimulus offset. The computer registered responses for a period of two seconds after stimulus onset. If the participant pressed the correct key within one second, the programme proceeded to the next trial without delay. If the participant had pressed an incorrect key, or if the reaction time (RT) of a correct response exceeded one second, a corresponding error message (i.e., "Wrong response!" in the former case; "Respond more quickly!" in the latter case) appeared at screen centre and remained for 1.5 seconds.

There were three short practice blocks at the beginning of the experiment. In the first block, participants practised the horizontal Simon task for 12 trials. In the second block, participants practised the vertical Simon task for 12 trials. In the third block, participants practised both tasks in random order for 16 trials. The experimental phase consisted of 10 blocks with 40 trials each. Blocks 1–5 and Blocks 6–10 differed with respect to the proportion of congruent trials in the "inducer" task. Half of the participants performed in Condition 1 with the horizontal Simon task as inducer task and the vertical Simon task as diagnostic task. The other half of the participants performed in Condition 2 with the vertical Simon task as inducer task and the horizontal Simon task as diagnostic task. For one half of the participants in each condition, the inducer task involved 80% congruent and 20% incongruent trials in Blocks 1–5, but 20% congruent and 80% incongruent trials in Blocks 6–10. The opposite applied to the other half of the participants in each condition. Participants could take short breaks between blocks. The whole experiment took 30–40 minutes.

Design

The experiment had a 2 (proportion) × 2 (task) × 2 (congruency) mixed design. The variable *proportion* coded the proportion of congruent trials in the inducer task (80% or 20%) in a block of trials. The variable *task* coded the type of task (inducer task vs. diagnostic task) in a trial. Finally, *congruency* coded the relationship between stimulus and response location (congruent vs. incongruent) in a trial.

Results

The response deadline of 1000 ms excluded less than 3.0% of the trials in both tasks. Figure 1 shows mean RTs in both tasks (inducer task, diagnostic task) as a function of the proportion of congruent trials in the inducer task.

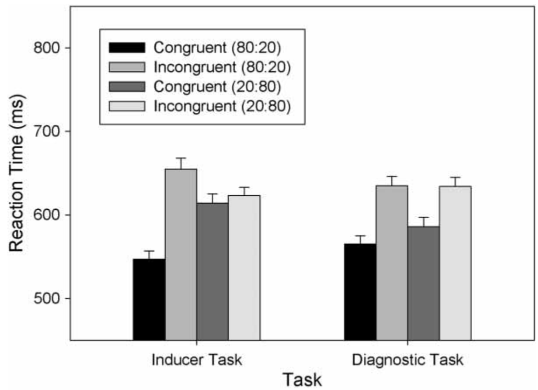

Figure 1. *Mean reaction times (RTs) observed in Experiment 1 as a function of task (inducer task vs. diagnostic task), stimulus–response (S–R) congruency (congruent or incongruent), and the proportion of congruent trials in the inducer task (80% or 20%). The ratio of congruent to incongruent trials in the diagnostic task was always 50:50. Error bars represent standard errors between participants.*

RT data

We entered RTs of correct responses into a three-factorial analysis of variance (ANOVA) with proportion, task, and congruency as within-subject variables. The analysis revealed significant main effects for proportion, $F(1, 45) = 7.50$, $MSE = 2609.74$, $p < .01$, $\eta_p^2 = .14$, and congruency, $F(1, 45) = 164.77$, $MSE = 1921.17$, $p < .001$, $\eta_p^2 = .79$, but not for task, $F(1, 45) < 1.0$. The main effect of proportion reflected shorter RTs in mostly congruent blocks than in mostly incongruent blocks (600 vs. 615 ms). The main effect of congruency reflected shorter RTs with congruent than with incongruent trials (578 vs. 637 ms). The significant two-way interaction of Proportion × Congruency, $F(1, 45) = 109.46$, $MSE = 742.67$, $p < .001$, $\eta_p^2 = .71$, indicated a LWPC effect: Simon effects were larger in mostly congruent blocks than in mostly incongruent blocks (differences = 88 vs. 29 ms). The two-way interactions of Task × Proportion, $F(1, 45) = 1.62$, $MSE = 591.08$, $p = .21$, $\eta_p^2 = .04$, and Task × Congruency, $F(1, 45) < 1.0$, were not significant. However, the three-way interaction of Proportion × Task × Congruency was significant, $F(1, 45) = 66.90$, $MSE = 553.47$, $p < .001$, $\eta_p^2 = .60$, suggesting that the LWPC effect was larger in the inducer task than in the diagnostic task. In the inducer task, the Simon effect was 108 ms in mostly congruent blocks and 8 ms in mostly incongruent blocks, $t(45) = 11.46$, $p < .001$. In the diagnostic task, the Simon effect was 69 ms in mostly congruent blocks and 49 ms in mostly incongruent blocks, $t(45) = 3.17$, $p < .01$.

Error percentages

We entered the percentages of errors into a three-factorial ANOVA with proportion, task, and congruency as within-subject variables. The results were similar to the RT findings. There were significant main effects for proportion, $F(1, 45) = 7.75$, $MSE = 29.15$, $p < .01$, $\eta_p^2 = .15$, task, $F(1, 45) = 10.77$, $MSE = 53.53$, $p < .01$, $\eta_p^2 = .19$, and congruency, $F(1, 45) = 39.48$, $MSE = 51.14$, $p < .001$, $\eta_p^2 = .47$. The main effect of proportion reflected more errors in mainly congruent blocks than in mainly incongruent blocks (6.4% vs. 4.8%). The main effect of task indicated more errors in the inducer task than in the diagnostic task (6.9% vs. 4.4%). The main effect of congruency reflected fewer errors with congruent than with incongruent trials (3.3% vs. 8.0%). The significant two-way interaction of Proportion × Congruency, $F(1, 45) = 35.77$, $MSE = 41.29$, $p < .001$, $\eta_p^2 = .44$, indicated a LWPC effect: Simon effects in errors were larger in mostly congruent blocks than in mostly incongruent blocks (differences = 8.7% vs. 0.7%). The two-way interactions of Task × Proportion and Task × Congruency were not significant, both $F(1, 45) < 1.0$. However, the three-way interaction of Proportion × Task × Congruency was significant, $F(1, 45) = 21.29$, $MSE = 23.37$, $p < .001$, $\eta_p^2 = .32$, indicating that the LWPC effect in error percentages was larger in the inducer task than in the diagnostic task. In the inducer task, the Simon effect was 11.6% in mostly congruent blocks and −1.1% in mostly incongruent blocks, $t(45) = 5.99$, $p < .001$. In the diagnostic task, the Simon effect was 5.8% in mostly congruent blocks and 2.4% in mostly incongruent blocks, $t(45) = 3.14$, $p < .01$.

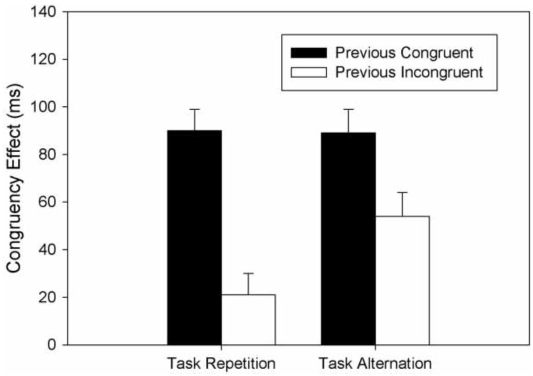

Figure 2. *Mean congruency effects (i.e., reaction times, RTs, from incongruent condition minus RTs from congruent conditions) observed in Experiment 1 as a function of task sequence (i.e., task repetition vs. task alternation) and stimulus–response (S–R) congruency in the previous trial. Error bars represent standard errors between participants.*

Sequential effects in RTs

We analysed sequential effects in RTs in a three-factorial ANOVA with task sequence (repetition vs. alternation), previous congruency (congruent vs. incongruent), and present congruency (congruent vs. incongruent) as within-subjects variables. Figure 2 shows the size of the congruency effect in the present trial as a function of task sequence and congruency in the previous trial. A significant main effect for task sequence, $F(1, 45) = 206.86$, $MSE = 1584.78$, $p < .001$, $\eta_p^2 = .82$, indicated shorter RTs for task repetitions than for task alternations (571 vs. 630 ms). A significant main effect for previous congruency, $F(1, 45) = 15.18$, $MSE = 427.66$, $p < .001$, $\eta_p^2 = .25$, reflected shorter RTs after congruent than after incongruent trials (596 vs. 605 ms). A significant main effect for present congruency, $F(1, 45) = 244.32$, $MSE = 1510.65$, $p < .001$, $\eta_p^2 = .84$, reflected shorter RTs with congruent than with incongruent trials (569 vs. 632 ms). A significant two-way interaction of Task Sequence × Present Congruency, $F(1, 45) = 15.94$, $MSE = 367.54$, $p < .001$, $\eta_p^2 = .26$, indicated a smaller repetition benefit with congruent trials (543 vs. 595 ms) than with incongruent trials (598 vs. 666 ms). Another way to interpret this interaction is that the Simon effect was smaller for task repetitions (difference = 55 ms) than for task alternations (difference = 71 ms). Moreover, a significant two-way interaction of Previous Congruency × Present Congruency, $F(1, 45) = 138.51$, $MSE = 453.80$, $p < .001$, $\eta_p^2 = .76$, reflected a Gratton effect: The congruency effect was larger after congruent trials (difference = 89 ms) than after incongruent trials (difference = 37 ms ms). The two-way interaction of Task Sequence × Previous Congruency was not significant, $F(1, 45) < 1$. Finally, a significant three-way interaction, $F(1, 45) = 12.66$, $MSE = 525.04$, $p < .001$, $\eta_p^2 = .22$, demonstrated that sequential modulations of congruency effects (i.e., Gratton effects) were larger for task repetitions than for task alternations (cf. Figure 2). However, separate two-way ANOVAs demonstrated significant Gratton effects (i.e., two-way interactions of Previous Congruency × Present Congruency) for task repetitions, $F(1, 45) = 115.40$, $MSE = 478.23$, $p < .001$, $\eta_p^2 = .72$, and for task alternations, $F(1, 45) = 28.59$, $MSE = 500.61$, $p < .001$, $\eta_p^2 = .39$.

Sequential effects in error percentages

We also analysed sequential effects in percentages of errors in a three-factorial ANOVA with task sequence (repetition vs. alternation), previous congruency (congruent vs. incongruent), and present congruency (congruent vs. incongruent) as within-subjects variables. A significant main effect for task sequence, $F(1, 45) = 89.52$, $MSE = 24.79$, $p < .001$, $\eta_p^2 = .67$, indicated fewer errors for task repetitions than for task alternations (2.0 vs. 6.9%). A significant main effect for previous congruency, $F(1, 45) = 14.63$, $MSE = 9.57$, $p < .001$, $\eta_p^2 = .25$, reflected more errors after congruent than after incongruent trials (5.0 vs. 3.8%). A significant main effect for present congruency, $F(1, 45) = 52.69$, $MSE = 22.47$, $p < .001$, $\eta_p^2 = .54$, reflected fewer errors with congruent than with incongruent trials (2.6 vs. 6.2%). A significant two-way interaction of Task Sequence × Previous Congruency, $F(1, 45) = 5.38$, $MSE = 12.09$, $p < .05$, $\eta_p^2 = .11$, indicated a larger repetition benefit after congruent trials (2.2 vs. 7.9%) than after incongruent trials (1.8 vs. 5.8%). A significant two-way interaction of Task Sequence ×

Present Congruency, $F(1, 45) = 24.23$, $MSE = 17.94$, $p < .001$, $\eta_p^2 = .35$, indicated a smaller repetition benefit with congruent trials (1.3 vs. 4.0%) than with incongruent trials (2.7 vs. 9.8%). Another way to interpret this interaction is that the Simon effect was smaller for task repetitions (difference = 1.4%) than for task alternations (difference = 5.8%). Moreover, a significant two-way interaction of Previous Congruency × Present Congruency, $F(1, 45) = 32.67$, $MSE = 8.97$, $p < .001$, $\eta_p^2 = .42$, reflected a Gratton effect: The congruency effect was larger after congruent trials (2.3 vs. 7.7%) than after incongruent trials (2.9 vs. 4.7%). The three-way interaction was not significant, $F(1, 45) = 1.24$, $MSE = 9.31$, $p = .27$, $\eta_p^2 = .03$, in contrast to the RT results.

Discussion

Experiment 1 investigated whether variations in the proportion of congruent trials in a Simon task (the inducer task) would modulate not only the Simon effect in the inducer task, but also the Simon effect in an unbiased (diagnostic) task. There was a strong LWPC effect for the inducer task, and there was a reduced—but significant—LWPC effect for the diagnostic task. In other words, the effects of manipulating the congruency proportion for one Simon task transferred to an unbiased task that was performed in parallel. In addition, sequential modulations occurred for task repetitions and—in a reduced manner—for task switches. Hence, both the LWPC effect and the Gratton effect generalized across tasks even though the two tasks involved different stimuli and responses. Yet, both tasks shared the relevant stimulus dimension (colour). Experiment 2 investigated the role of a shared stimulus dimension for the transfer of LWPC and Gratton effects.

EXPERIMENT 2

Experiment 1 demonstrated transfer of the LWPC effect and transfer of sequential modulations. Notebaert and Verguts (2008) suggested that transfer of sequential modulations across tasks is more likely if the tasks shared the same relevant dimension, which was the case in Experiment 1. Hence, in Experiment 2, we explored the relevance of a shared stimulus dimension for both the transfer of sequential modulations and the transfer of the LWPC effect by combining a horizontal and a vertical Simon task with different relevant stimulus dimensions. Participants now responded to a green or red stimulus in the horizontal Simon task, and to a square or diamond in the vertical Simon task (or vice versa). We expected sequential modulations for task repetitions only, and we expected LWPC effects within but not across tasks.

Method

Participants

Forty-eight student volunteers (38 female, 10 male; 39 right-handers, 9 left-handers) with a mean age of 23 years (range 20–30 years) participated for course credit. Half of the participants (19 female, 5 male) were assigned to Condition 1 where we manipulated the proportion of congruent trials in the horizontal Simon task; the other half of the participants (19 female, 5 male) were assigned to Condition 2 where we manipulated the proportion of congruent trials in the vertical Simon task.

Apparatus and stimuli

The apparatus was identical to that used for Experiment 1. Instead of four different colour stimuli, we used two colour stimuli (i.e., a red and a green circle) and two shape stimuli (i.e., a grey square and a grey diamond) in Experiment 2. For half of the participants, the colour stimuli were used in the horizontal Simon task, and the shape stimuli were used in the vertical Simon task; for the other half of the participants, the reverse was true.

Procedure

The procedure was similar to that in Experiment 1, except that the stimuli in the horizontal and the vertical Simon task varied on different perceptual dimensions (i.e., colour and shape).

Design

The experiment had a 2 (proportion) × 2 (task) × 2 (congruency) within-subjects design. The variable *proportion* coded the proportion of congruent trials in the inducer task (80% or 20%) in a block of trials. The variable *task* coded the type of task (inducer task vs. diagnostic task) in a trial. Finally, *congruency* coded the relationship between stimulus and response location (congruent vs. incongruent) in a trial.

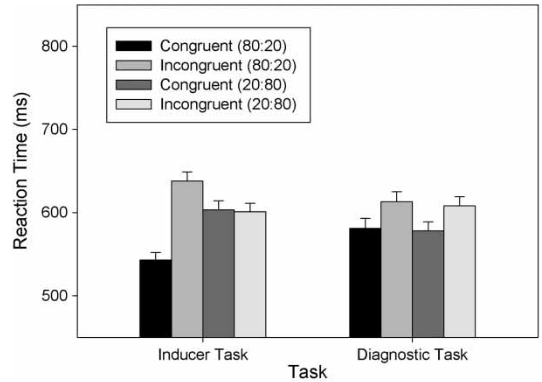

Figure 3. *Mean reaction times (RTs) observed in Experiment 2 as a function of task (inducer task vs. diagnostic task), stimulus–response (S–R) congruency (congruent or incongruent), and the proportion of congruent trials in the inducer task (80% or 20%). The ratio of congruent to incongruent trials in the diagnostic task was always 50:50. Error bars represent standard errors between participants.*

Results

The response deadline of 1000 ms excluded less than 2.0% of the trials in both tasks. Figure 3 shows mean RTs in both tasks (inducer task, diagnostic task) as a function of the proportion of congruent trials in the inducer task.

RT data

We entered RTs of correct responses into a three-factorial ANOVA with proportion, task, and congruency as within-subject variables. The analysis revealed a significant main effect for congruency, $F(1,\ 47) = 164.77$, $MSE = 1921.17$, $p < .001$, $\eta_p^2 = .79$, whereas the main effects for proportion and task were not significant, both $F(1,\ 47) < 1.0$. The main effect of congruency reflected shorter RTs with congruent than with incongruent trials (576 vs. 616 ms). Each two-way interaction was significant. The significant interaction of Task × Proportion, $F(1,\ 47) = 9.49$, $MSE = 556.59$, $p < .01$, $\eta_p^2 = .17$, reflected the finding that RTs were shorter in mostly congruent than in mostly incongruent blocks for the inducer task (591 vs. 602 ms), but not for the diagnostic task (597 vs. 593 ms). The significant interaction of Task × Congruency, $F(1,\ 47) = 4.95$, $MSE = 1356.54$, $p < .05$, $\eta_p^2 = .10$, reflected larger congruency effects for the inducer task (572 vs. 620 ms) than for the diagnostic task (579 vs. 611 ms). Most importantly, the two-way interaction of Proportion × Congruency, $F(1,\ 47) = 121.17$, $MSE = 473.40$, $p < .001$, $\eta_p^2 = .72$, indicated a LWPC effect: Simon effects were larger in mostly congruent blocks (difference = 64 ms) than in mostly incongruent blocks (difference = 15 ms). In addition, the three-way interaction of Proportion × Task × Congruency was also significant, $F(1, 47) = 109.32$, $MSE = 467.17$, $p < .001$, $\eta_p^2 = .70$, suggesting that the LWPC effect was larger in the inducer task than in the diagnostic task. In the inducer task, the Simon effect was 96 ms in mostly congruent blocks and 1 ms in mostly incongruent blocks, and this difference was significant, $t(47) = 14.44$, $p < .001$. For the diagnostic task, the Simon effect was 33 ms in mostly congruent blocks and 30 ms in mostly incongruent blocks. This difference was not significant, $t(47) = 0.47$, $p < .64$.

Error percentages

We entered the percentages of errors into a three-factorial ANOVA with proportion, task, and congruency as within-subject variables. The critical results were similar to the RT findings. There were significant main effects for proportion, $F(1,\ 47) = 6.74$, $MSE = 30.63$, $p < .05$, $\eta_p^2 = .13$, and congruency, $F(1,\ 47) = 25.59$, $MSE = 60.02$, $p < .001$, $\eta_p^2 = .35$, and a marginally significant main effect for task, $F(1,\ 47) = 3.86$, $MSE = 66.76$, $p = .06$, $\eta_p^2 = .08$. The main effect of proportion reflected more errors in mainly congruent blocks than in mainly incongruent blocks (7.2%

vs. 5.7%). The main effect of congruency reflected fewer errors with congruent than with incongruent trials (4.4% vs. 8.4%). The marginal main effect of task indicated more errors in the inducer task than in the diagnostic task (7.2% vs. 5.6%) A significant two-way interaction of Task × Proportion, $F(1, 47) = 5.37$, $MSE = 24.26$, $p < .05$, $\eta_p^2 = .10$, showed that the increase of errors in mostly congruent blocks was larger for the inducer task (8.6% vs. 5.9%) than for the diagnostic task (5.8% vs. 5.5%). The significant interaction of Task × Congruency, $F(1, 47) = 10.30$, $MSE = 39.05$, $p < .01$, $\eta_p^2 = .18$, reflected a larger Simon effect in error percentages in the inducer task (difference = 6.1%) than in the diagnostic task (difference = 2.0%). The significant two-way interaction of Proportion × Congruency, $F(1, 47) = 42.53$, $MSE = 36.87$, $p < .001$, $\eta_p^2 = .48$, indicated a LWPC effect: Simon effects in errors were larger in mostly congruent blocks (difference = 8.0%) than in mostly incongruent blocks (difference = −0.1%). In addition, the three-way interaction of Proportion × Task × Congruency was also significant, $F(1, 47) = 49.69$, $MSE = 30.41$, $p < .001$, $\eta_p^2 = .51$, indicating that the LWPC effect in error percentages was larger in the inducer task than in the diagnostic task. In the inducer task, the Simon effect was 14.1% in mostly congruent blocks and −2.0% in mostly incongruent blocks. This difference was significant, $t(47) = 7.80$, $p < .001$. For the diagnostic task, the Simon effect was 2.0% in mostly congruent blocks and 1.9% in mostly incongruent blocks. This difference was not significant, $t(47) = 0.13$, $p = .90$.

Sequential effects in RTs

We analysed sequential effects in RTs in a three-factorial ANOVA with task sequence, previous congruency, and present congruency as within-subjects variables. Figure 4 shows the size of the congruency effect in the present trial as a function of task sequence and congruency in the previous trial. A significant main effect for task sequence, $F(1, 47) = 354.34$, $MSE = 861.42$, $p < .001$, $\eta_p^2 = .88$, indicated shorter RTs for task repetitions than for task alternations (561 vs. 618 ms). A significant main effect for previous congruency, $F(1, 47) = 20.99$,

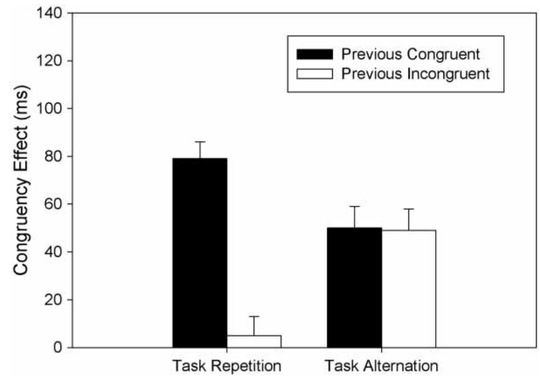

Figure 4. *Mean congruency effects (i.e., reaction times, RTs, from incongruent condition minus RTs from congruent conditions) observed in Experiment 2 as a function of task sequence (i.e., task repetition vs. task alternation) and stimulus–response (S–R) congruency in the previous trial. Error bars represent standard errors between participants.*

$MSE = 462.50$, $p < .001$, $\eta_p^2 = .31$, reflected shorter RTs after congruent than after incongruent trials (585 vs. 595 ms). A significant main effect for present congruency, $F(1, 47) = 106.54$, $MSE = 1889.31$, $p < .001$, $\eta_p^2 = .69$, reflected shorter RTs with congruent than with incongruent trials (567 vs. 613 ms). A significant two-way interaction of Task Sequence × Previous Congruency, $F(1, 47) = 5.73$, $MSE = 328.41$, $p < .05$, $\eta_p^2 = .11$, indicated a larger repetition benefit after congruent trials (difference = 61 ms) than after incongruent trials (difference = 52). A significant two-way interaction of Task Sequence × Present Congruency, $F(1, 47) = 5.05$, $MSE = 273.87$, $p < .05$, $\eta_p^2 = .10$, indicated a smaller repetition benefit with congruent trials (540 vs. 593 ms) than with incongruent trials (582 vs. 643 ms). Another way to interpret this interaction is that the Simon effect was smaller for task repetitions (difference = 42 ms) than for task alternations (difference = 50 ms). Moreover, a significant two-way interaction of Previous Congruency × Present Congruency, $F(1, 47) = 66.12$, $MSE = 505.54$, $p < .001$, $\eta_p^2 = .59$, reflected a Gratton effect: The congruency effect was larger after congruent trials (difference = 65 ms) than after incongruent trials (difference = 27 ms). Finally, a significant three-way interaction, $F(1, 47) = 49.83$, $MSE = 638.35$,

$p < .001$, $\eta_p^2 = .52$, demonstrated that sequential modulations of congruency effects (i.e., Gratton effects) were larger for task repetitions than for task alternations (cf. Figure 4). In fact, separate two-way ANOVAs revealed a significant Gratton effect for task repetitions, $F(1, 47) = 83.52$, $MSE = 780.97$, $p < .001$, $\eta_p^2 = .64$, but not for task alternations, $F(1, 47) < 1$.

Sequential effects in error percentages

We analysed sequential effects in percentages of errors in a three-factorial ANOVA with task sequence, previous congruency, and present congruency as within-subjects variables. A significant main effect for task sequence, $F(1, 47) = 45.20$, $MSE = 23.05$, $p < .001$, $\eta_p^2 = .49$, indicated fewer errors for task repetitions than for task alternations (3.3 vs. 6.6%). The main effect for previous congruency was not significant, $F(1, 47) = 2.90$, $MSE = 15.07$, $p = .10$, $\eta_p^2 = .06$. A significant main effect for present congruency, $F(1, 47) = 22.17$, $MSE = 37.12$, $p < .001$, $\eta_p^2 = .32$, reflected fewer errors with congruent than with incongruent trials (3.4 vs. 6.4%). The two-way interaction of Task Sequence × Previous Congruency was not significant, $F < 1$. A significant two-way interaction of Task Sequence × Present Congruency, $F(1, 47) = 10.68$, $MSE = 13.18$, $p < .01$, $\eta_p^2 = .19$, indicated a smaller repetition benefit with congruent trials (2.4 vs. 4.5%) than with incongruent trials (4.1 vs. 8.6%). Another way to interpret this interaction is that the Simon effect was smaller for task repetitions (difference = 1.5%) than for task alternations (difference = 4.1%). Moreover, a significant two-way interaction of Previous Congruency × Present Congruency, $F(1, 47) = 36.37$, $MSE = 12.07$, $p < .001$, $\eta_p^2 = .44$, reflected a Gratton effect: The congruency effect was larger after congruent trials (2.7 vs. 7.8%) than after incongruent trials (4.2 vs. 5.0%). The three-way interaction was also significant, $F(1, 47) = 17.94$, $MSE = 9.00$, $p < .001$, $\eta_p^2 = .28$, demonstrating that the Gratton effect in error percentages was larger for task repetitions than for task alternations. Separate two-factorial ANOVAs revealed a significant Gratton effect (i.e., two-way interaction of Previous Congruency × Present Congruency) for task repetitions, $F(1, 47) = 57.88$, $MSE = 9.79$, $p < .001$, $\eta_p^2 = .55$, but not for task alternations, $F(1, 47) = 3.0$, $MSE = 11.29$, $p = .10$, $\eta_p^2 = .06$.

Discussion

Experiment 2 tested whether transfer of LWPC and Gratton effects would no longer occur when the relevant stimulus dimensions were different in the two tasks involved (i.e., colour and shape). Results confirmed our expectations. In fact, the LWPC effect was restricted to the inducer task, and sequential modulations of congruency effects (i.e., the Gratton effect) occurred for task repetitions only. Together, Experiments 1 and 2 suggest that sharing the relevant stimulus dimension is a necessary condition for transfer to occur in both the Gratton effect and the LWPC effect.

EXPERIMENT 3

Experiment 1 showed that LWPC effects can transfer from one task to another, when both tasks involve different stimulus and response sets, and this finding is consistent with the application of generalized attentional control settings. However, sequential modulations also transferred across tasks in Experiment 1, producing an alternative explanation for the transfer of LWPC effects. The main purpose of Experiment 3 was to test whether transfer of LWPC effects could occur without transfer of sequential effects when the two tasks were made more distinct as in Experiment 1. Therefore, in Experiment 3, we mixed trials of a Simon task with trials of a Stroop task. In the two-choice Simon task, participants pressed a left key with the left hand to one stimulus and a right key with the right hand to another stimulus, and the imperative stimuli appeared at a left or a right location. In the two-choice Stroop task, participants vocally named the colour of a colour word. The two tasks involved different sets of relevant stimuli (e.g., red and green squares in the Simon task, blue and yellow words in the Stroop task) that varied on the same stimulus dimension (i.e., colour). However, the tasks involved different response modalities, different response sets, and different sources of conflict. Again, we varied the proportion of congruent items in the inducer task (between participants) and kept the proportion of congruent items constant in the diagnostic task.

We expected a LWPC effect for the inducer task (e.g., Bugg et al., 2008; Logan & Zbrodoff, 1979; Lowe & Mitterer, 1982). The question of interest was whether there would also be a LWPC effect in the diagnostic task and whether this transfer of the LWPC effect could occur without the simultaneous transfer of sequential modulations of congruency effects.

Method

Participants

Forty-eight student volunteers (42 female, 6 male; 44 right-handers, 4 left-handers) with a mean age of 24 years (range 19–45 years) participated for course credit. Half of the participants (21 female, 3 male) were assigned to Condition 1 where we manipulated the proportion of congruent trials in the Stroop task; the other half of the participants (21 female, 3 male) were assigned to Condition 2 where we manipulated the proportion of congruent trials in the Simon task.

Apparatus and stimuli

Participants sat in a dimly lit room in front of a colour TFT-monitor, with an unconstrained viewing distance of approximately 50 cm. A computer program written in E-Prime (e.g., Schneider, Eschman, & Zuccolotto, 2002) controlled stimulus presentation and collected responses. In the Simon task, participants performed keypress responses with their index fingers on the two peripheral keys of a response box connected to the serial port of the PC. In the Stroop task, two microphones registered different features of the participants' vocal responses. Through one microphone, also connected to the response box, we measured the vocal reaction time (RT) to the nearest millisecond. Through the other microphone, plugged into the line-in switch of the PC, we recorded the participants' vocal response to allow for the offline analysis of response accuracy in the Stroop task.

A plus sign, presented at screen centre, served as a fixation. The visual stimulus for the Simon task was a coloured square (size: 2.5 cm × 2.5 cm) that appeared 6.5 cm to the left or right of the fixation point. The visual stimulus for the Stroop task was a coloured colour-word (blue, green, red, or yellow) that appeared at screen centre in lowercase letters of the Arial font. The font size of 36 corresponded to approximately 1 cm in height and 0.7 cm in width. We used different sets of two colours for the two tasks. For half of the participants, the colours blue and yellow appeared in the Simon task, whereas the colours green and red appeared in the Stroop task; the opposite was true for the other half of participants. For the Stroop task, the two colours were orthogonally combined with the two corresponding colour words. Hence, there were four individual stimuli in each task.

Procedure

At the beginning of the experiment, the instructions appeared on the screen, and participants could read them at leisure. The instructions informed the participants about the two tasks and the S–R mappings in the two tasks. For the Simon task, instructions told participants to press a left or right key as quickly as possible to the colour of a square presented to the left or right of fixation. For both pairs of colours (i.e., blue–yellow; green–red), we counterbalanced the mapping of colour to response key (left or right) across participants. For the Stroop task, instructions told participants to vocally name as quickly as possible the colour of a word presented at fixation.

Each trial started with a 1000-ms blank screen followed by a fixation cross presented in the centre of the screen for 500 ms. In Simon-task trials the fixation cross remained on screen, and the coloured square appeared to the left or right of fixation. Participants responded with a left or right key press with the respective index finger. Upon the response the screen turned blank for 1000 ms before the next trial started. In Stroop trials, the fixation cross was replaced by a colour word. Participants named the word's colour into a microphone. Upon response onset the screen turned blank for 1000 ms, during which the response was recorded.

There were three short practice blocks at the beginning of the experiment. In the first block, participants practised the Simon task for 16 trials. In the second block, participants practised the Stroop task for 16 trials. In the third block, participants practised both tasks in random order for 16 trials. The experimental phase contained six blocks with 80 trials each. Blocks 1–3 and Blocks 4–6 differed with respect to the proportion of congruent trials in the inducer task, whereas the ratio between congruent and incongruent trials was always 50:50 in the diagnostic task. Half of the participants performed in Condition 1 with the Stroop task as the inducer task and the Simon task as the diagnostic task. The other half of the participants performed in Condition 2 with the Simon task as the inducer task and the Stroop task as the diagnostic task. For one half of the participants in each condition, the inducer task involved 80% congruent and 20% incongruent trials in Blocks 1–3, but 20% congruent and 80% incongruent trials in Blocks 4–6. The opposite applied to the other half of the participants in each condition. Participants could take short breaks between blocks. The whole experiment took 30–40 minutes.

Design

The experiment had a 2 (proportion) × 2 (task) × 2 (congruency) mixed design. The variable *proportion* coded the proportion of congruent trials in the inducer task (80% or 20%) in a block of trials. The variable *task* coded the type of task (inducer task vs. diagnostic task) in a trial. Finally, *congruency* coded the relationship (congruent vs. incongruent) between the irrelevant stimulus feature (i.e., colour in Stroop task; location in Simon task) and the response in a trial.

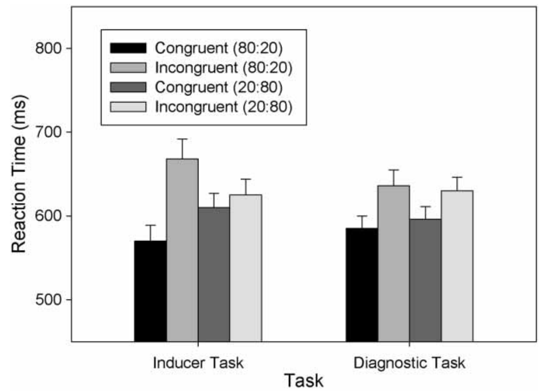

Figure 5. *Mean reaction times (RTs) observed in Experiment 3 as a function of task (inducer task vs. diagnostic task), stimulus–response (S–R) congruency (congruent or incongruent), and the proportion of congruent trials in the inducer task (80% or 20%). The ratio of congruent to incongruent trials in the diagnostic task was always 50:50. Error bars represent standard errors between participants.*

Results

We removed all trials where RTs were longer than 1500 ms. We used a larger cut-off point here because vocal RTs are typically longer than manual RTs. The criterion eliminated less than 3.0% of trials in both tasks, which is similar to Experiments 1 and 2. Moreover, we excluded the results from two participants in Condition 2 from the analysis. The first participant had committed 48% errors in the Stroop task (i.e., this participants always read the word instead of naming the word's colour), whereas the other participant had committed 32% errors in the Simon task (compared to a mean of 5%, $SD = 6$, of the whole sample). Figure 5 shows mean RTs in both tasks (inducer task, diagnostic task) as a function of the proportion of congruent trials in the inducer task.

RT data

We entered RTs of correct responses into a three-factorial ANOVA with proportion, task, and congruency as within-subject variables. The analysis revealed a significant main effect for congruency, $F(1, 45) = 136.62$, $MSE = 1612.41$, $p < .001$, $\eta_p^2 = .75$, whereas the main effects were not significant for proportion or task, both $F(1, 45) < 1.0$. The main effect of congruency reflected shorter RTs with congruent than with incongruent trials (590 vs. 639 ms). The only significant two-way interaction of Proportion × Congruency, $F(1, 45) = 61.83$, $MSE = 921.40$, $p < .001$, $\eta_p^2 = .58$, indicated a LWPC effect: Congruency effects were larger in mostly congruent blocks (difference = 74 ms) than in mostly incongruent blocks (difference = 24 ms). The two-way interactions of Proportion × Task and Task × Congruency were not significant, both $Fs(1, 45) < 1.5$, both $ps > .20$. However, the three-way interaction of Proportion × Task × Congruency was significant, $F(1, 45) = 33.88$, $MSE = 762.17$, $p < .001$, $\eta_p^2 = .43$, suggesting that the LWPC effect was larger in the inducer task than in the diagnostic task. In the inducer task, the congruency effect was 98 ms in mostly congruent blocks and 15 ms in mostly incongruent blocks, and this difference was significant, $t(45) = 8.79$, $p < .001$. In the diagnostic task, the congruency effect was 50 ms in mostly congruent blocks and 33 ms in mostly incongruent blocks. This difference was also significant, $t(45) = 2.16$, $p < .05$.

Error percentages

We entered the percentages of errors into a three-factorial ANOVA with proportion, task, and congruency as within-subject variables. There were significant main effects for proportion, $F(1, 45) = 9.70$, $MSE = 14.58$, $p < .01$, $\eta_p^2 = .17$, and congruency, $F(1, 45) = 15.43$, $MSE = 33.62$, $p < .001$, $\eta_p^2 = .26$, and a marginally significant main effect for task, $F(1, 45) = 3.99$, $MSE = 32.96$, $p = .05$, $\eta_p^2 = .08$. The main effect of proportion reflected more errors in mostly congruent blocks than in mostly incongruent blocks (4.2% vs. 2.9%). The main effect of congruency reflected fewer errors with congruent than with incongruent trials (2.4% vs. 4.7%). The marginal main effect of task indicated more errors in the inducer task than in the diagnostic task (4.1% vs. 2.9%). A marginally significant interaction of Task × Proportion, $F(1, 45) = 3.66$, $MSE = 17.43$, $p = .06$, $\eta_p^2 = .08$, reflected the finding that the error increase in mostly congruent blocks was larger for the inducer task (5.2% vs. 3.1%) than for the diagnostic task (3.2% vs. 2.8%). The two-way interaction of Task × Congruency was not significant, $F(1, 45) < 1.0$. Importantly, however, there was a significant two-way interaction of Proportion × Congruency, $F(1, 45) = 25.40$, $MSE = 22.63$, $p < .001$, $\eta_p^2 = .36$, reflecting a LWPC effect: Congruency effects in errors were larger in mostly congruent blocks (difference = 4.9%) than in mostly incongruent blocks (difference = −0.1%). In addition, the three-way interaction of Proportion × Task × Congruency was also significant, $F(1, 45) = 35.12$, $MSE = 20.52$, $p < .001$, $\eta_p^2 = .44$, indicating that the LWPC effect in error percentages was larger in the inducer task than in the diagnostic task. In the inducer task, the congruency effect was 8.1% in mostly congruent blocks and −2.5% in mostly incongruent blocks. This difference was significant, $t(45) = 6.03$, $p < .001$. For the diagnostic task, the congruency effect was 2.2% in mostly congruent blocks and 1.7% in mostly incongruent blocks. This difference was not significant, $t(45) = 0.73$, $p = .47$.

Sequential effects in RTs

We analysed sequential effects in RTs in a three-factorial ANOVA with task sequence, previous congruency, and present congruency as within-subjects variables. Figure 6 shows the size of the congruency effect in the present trial as a function of task sequence and congruency in the previous trial. A significant main effect for task sequence, $F(1, 45) = 268.13$, $MSE = 2962.11$, $p < .001$, $\eta_p^2 = .86$, indicated shorter RTs for task repetitions than for task alternations (563 vs. 656 ms). A marginally significant main effect for previous congruency, $F(1, 45) = 3.39$, $MSE = 487.23$, $p = .07$, $\eta_p^2 = .07$, reflected shorter RTs after congruent than after incongruent trials (608 vs. 612 ms). A significant main effect for present congruency, $F(1, 45) = 145.87$, $MSE = 1549.09$, $p < .001$, $\eta_p^2 = .76$, reflected shorter RTs with congruent than with incongruent trials (585 vs. 635 ms). The two-way interactions of Task Sequence × Previous Congruency and of Task Sequence × Present Congruency were not significant, both

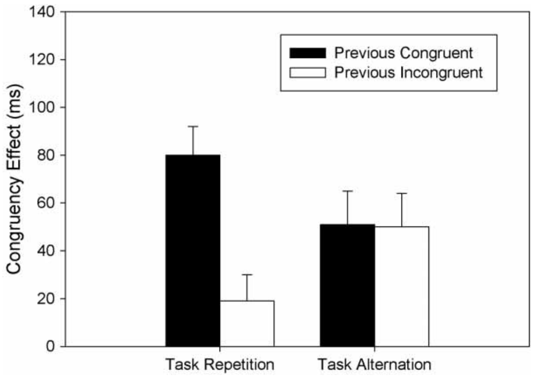

Figure 6. *Mean congruency effects (i.e., reaction times, RTs, from incongruent condition minus RTs from congruent conditions) observed in Experiment 3 as a function of task sequence (i.e., task repetition vs. task alternation) and stimulus–response (S–R) congruency in the previous trial. Error bars represent standard errors between participants.*

$F < 1.1$. However, a significant two-way interaction of Previous Congruency × Present Congruency, $F(1, 45) = 12.50$, $MSE = 1640.30$, $p < .001$, $\eta_p^2 = .22$, reflected a Gratton effect: The congruency effect was larger after congruent trials (difference = 65 ms) than after incongruent trials (difference = 34 ms). Finally, a significant three-way interaction, $F(1, 45) = 21.26$, $MSE = 943.92$, $p < .001$, $\eta_p^2 = .32$, demonstrated that sequential modulations of congruency effects (i.e., Gratton effects) were larger for task repetitions than for task alternations (cf. Figure 6). In fact, separate two-way ANOVAs revealed a significant Gratton effect for task repetitions, $F(1, 45) = 20.53$, $MSE = 1976.88$, $p < .001$, $\eta_p^2 = .31$, but not for task alternations, $F(1, 45) < 1$.

Sequential effects in error percentages

We analysed sequential effects in percentages of errors in a three-factorial ANOVA with task sequence, previous congruency, and present congruency as within-subjects variables. A significant main effect for task sequence, $F(1, 45) = 68.87$, $MSE = 3.95$, $p < .001$, $\eta_p^2 = .61$, indicated fewer errors for task repetitions than for task alternations (1.7 vs. 3.4%). A significant main effect for previous congruency, $F(1, 45) = 12.58$, $MSE = 3.21$, $p < .01$, $\eta_p^2 = .22$, reflected more errors after congruent trials than after incongruent trials (2.9 vs. 2.2%). A significant main effect for present congruency, $F(1, 45) = 14.90$, $MSE = 13.73$, $p < .001$, $\eta_p^2 = .25$, reflected fewer errors with congruent than with incongruent trials (1.8 vs. 3.3%). The two-way interactions of Task Sequence × Previous Congruency, $F(1, 45) = 2.48$, $MSE = 3.96$, $p = .12$, $\eta_p^2 = .05$, and of Task Sequence × Present Congruency, $F < 1$, were not significant. However, a significant two-way interaction of Previous Congruency × Present Congruency, $F(1, 45) = 29.53$, $MSE = 4.33$, $p < .001$, $\eta_p^2 = 0.40$, reflected a Gratton effect: The congruency effect was larger after congruent trials (1.5 vs. 4.2%) than after incongruent trials (2.0 vs. 2.4%). The three-way interaction was also significant, $F(1, 45) = 13.01$, $MSE = 4.73$, $p < .01$, $\eta_p^2 = .22$, and showed that the Gratton effect in error percentages was larger for task repetitions than for task alternations. Separate two-factorial ANOVAs revealed a significant Gratton effect (i.e., two-way interaction of Previous Congruency × Present Congruency) for task repetitions, $F(1, 45) = 38.31$, $MSE = 4.79$, $p < .001$, $\eta_p^2 = .46$, but not for task alternations, $F(1, 45) = 1.40$, $MSE = 4.27$, $p = .24$, $\eta_p^2 = .03$.

Discussion

There was a strong LWPC effect for the frequency-biased inducer task, and the LWPC effect transferred to the unbiased diagnostic task. Moreover, sequential modulations of congruency effects (Gratton effects) occurred only within tasks but not between tasks, replicating previous studies (e.g., Funes et al., 2010a, 2010ba). Hence, Experiment 3 replicated the dissociation between LWPC effects and Gratton effects and additionally showed that the transfer of LWPC effects can occur between tasks that did not share stimuli, responses, or the source of conflict.

GENERAL DISCUSSION

Summarized across three experiments, we made four important observations. First, we consistently observed strong LWPC effects for frequency-biased dimensions or tasks that were mixed with frequency-unbiased dimensions or tasks. Second, we observed transfer of the LWPC effect from a frequency-biased inducer task to an unbiased task under specific conditions. The fact that this transfer occurred is theoretically significant because it is incompatible with the S–R (contingency) learning account (Schmidt & Besner, 2008) of the LWPC effect (see below). Third, we observed transfer of the LWPC effect without sequential modulations of congruency effects between tasks (in Experiment 3). This is an important dissociation suggesting different mechanisms behind the LWPC effect and the sequential modulation of congruency effects—in line with the proposal by Funes et al. (2010b). Fourth, transfer was restricted to conditions where the two tasks shared the relevant stimulus dimension (but not stimuli) and did not occur when the two tasks had different relevant stimulus dimensions, suggesting that control operates on the processing of the relevant information, confirming a similar notion by Notebaert and Verguts (2008).

The present set of experiments conceptually replicated and extended previous findings of Funes et al. (2010b) and Bugg and Chanani (2011). Funes et al. (2010b) had shown that manipulating the frequency of Simon-like response conflict, while maintaining the frequency of Stroop-like stimulus conflict, modulated not only the size of the Simon effect, but also the size of the Stroop effect. Hence, the LWPC effect transferred from one source of conflict (location congruency) to another source of conflict (shape congruency). In contrast, sequential modulations of congruency effects did not transfer. From this pattern, Funes et al. concluded that the LWPC effect and the Gratton effect arise from different mechanisms. In particular, they proposed that adaptation to conflict frequency (i.e., the LWPC effect) relates to a top-down control mechanism that operates by enhancing the processing of the relevant target information. In contrast, according to their analysis, the Gratton effect relates to more specific priming processes.

The results of our experiments extend previous findings in several ways. First, we showed that the LWPC effect does also transfer between two tasks that involve different stimulus sets, different response sets, and different sources of conflict. This finding was especially striking in Experiment 3 where the two tasks only shared the relevant stimulus dimension (i.e., colour). Second, in contrast to previous studies (e.g., Blais & Bunge, 2010; Bugg et al., 2008), we showed that transfer of LWPC effect can occur between two tasks that each involve only two stimulus–response pairs. Third, our results demonstrate that sharing the relevant stimulus dimension seems to be a necessary condition for transfer of the LWPC effect between tasks, constraining accounts of LWPC effects.

Transfer of adaptation to conflict frequency

The transfer of LWPC effects is consistent with an account in terms of a top-down control mechanism that operates by enhancing the processing of the relevant target information (e.g., Funes et al., 2010b). At the same time, transfer effects are at odds with three other accounts of the LWPC effect. The *S–R (contingency) learning* account fails to explain the transfer of LWPC effects. According to this account, participants learn to predict a response from different correlations between irrelevant stimuli and responses (e.g., Schmidt, 2013; Schmidt & Besner, 2008). Obviously, contingency learning cannot produce a difference between conditions that occur with equal frequencies (cf. Bugg & Crump, 2012). A related account explains the LWPC effect in terms of item-specific control processes (Blais & Bunge, 2010; Bugg et al., 2008). This account claims that, during the course of an experiment, participants form associations between particular stimuli and an attentional control setting for processing each stimulus (e.g., Bugg & Crump, 2012; Bugg et al., 2008). Similar to the contingency-learning account, the item-specific control account fails to explain the transfer of LWPC effects to frequency-unbiased items because all items from this set occur with equal frequency.

Finally, transient adaptations to the congruency level of the immediately preceding trial could also add up to produce more sustained effects of congruency proportion (*sequential* hypothesis). However, the fact that transfer of the LWPC effect can occur without sequential modulations of congruency effects across tasks contradicts an account of LWPC effects in terms of sequential modulations.

Our findings concerning the shared stimulus dimension are consistent with recent findings on the transfer of adaptation to the frequency of other S–R relationships. For example, Proctor, Yamaguchi, Dutt, and Gonzalez (2013) mixed compatible and incompatible trials of a task where stimulus location was the relevant feature with (congruent and incongruent) trials of a Simon task where stimulus colour was the relevant feature. In addition, Proctor et al. varied the proportion of compatible trials in the location-relevant task. The proportion of compatible trials had a strong effect on the spatial-compatibility (or mapping) effect in the location-relevant task, but not on the Simon effect in the location-irrelevant task. From our point of view, this transfer probably did not occur because the two tasks involved different relevant dimensions: location in the inducer task and colour in the diagnostic Simon task.

Two studies, which used traditional Stroop stimuli both as frequency-biased inducer stimuli and as unbiased diagnostic stimuli, failed to observe transfer of the LWPC effect when each set contained only two stimuli and responses (Blais & Bunge, 2010; Bugg et al., 2008). According to Bugg and Chanani (2011), transfer suggesting global control did not occur in these studies because the two-item stimulus sets provide ideal conditions for stimulus-specific learning (of stimulus–response associations, or stimulus–attention associations; Bugg & Crump, 2012). Consistent with this hypothesis, transfer of LWPC effects occurred when the number of stimuli in the inducer set was increased to four (Bugg & Chanani, 2011). At first sight, the fact that both Funes et al. (2010b) and we (Experiment 1, Experiment 3) consistently observed transfer of LWPC effects with only two inducer stimuli appears at odds with the previous findings and the proposal of Bugg and Chanani (2011). There is, however, an important difference between the Stroop task used in previous studies, which seems to require at least four inducer stimuli for producing transfer of LWPC effects, and the Simon task used in our experiments, which seems to require only two inducer stimuli for transfer. The difference is that the Stroop task involves highly overlearned S–R mappings, whereas the Simon task involves arbitrary S–R mappings that need to be stored in working memory (WM). As a result, a Stroop task with two stimuli might impose lower demands on WM capacity than a Simon task with two stimuli, leaving more capacity for learning and maintaining irrelevant S–R contingencies.

Control-based accounts of the LWPC effect

In addition to demonstrating transfer of LWPC effects (without concurrent transfer of Gratton effects), we also established boundary conditions for the transfer. In particular, our findings demonstrate that sharing the relevant stimulus dimension is a critical condition for transfer of the LWPC effect between two tasks. These findings are suggestive as to the attentional mechanisms that underlie adaptation to the frequency of conflict (i.e., the LWPC effect). In fact, these findings suggest that adaptation to the frequency of conflict in the inducer task mainly involves changes of the attentional weights for the relevant stimulus dimension and not changes of the attentional weights for the irrelevant stimulus dimension, consistent with a proposal made by Funes et al. (2010a, 2010b).

An account in terms of attention to the relevant stimulus dimension is, however, inconsistent with the majority of attentional accounts of LWPC effects (e.g., Lindsay & Jacoby, 1994; Logan, 1980; Logan & Zbrodoff, 1979; Lowe & Mitterer, 1982). These accounts assume that participants typically process relevant and irrelevant stimulus features in parallel, and LWPC effects mainly result from modulations of attention to the irrelevant stimulus dimension. And, in fact, there is empirical evidence supporting this notion. Using the process-dissociation procedure, Lindsay and Jacoby (1994) demonstrated that varying the proportion of congruent items in a Stroop task affected the contribution of word-reading processes to performance, but not the contribution of colour-naming processes. Moreover, these authors also found that varying the proportion of congruent items did not affect colour-naming responses to neutral items that were mixed with congruent and incongruent stimuli. These findings are consistent with accounts of LWPC effects in terms of attention to the nominally irrelevant stimulus dimension.

A flexible control account of LWPC effects in terms of attention to the irrelevant stimulus dimension could explain the present pattern of findings. First, the transfer of LWPC effects between tasks that involve different irrelevant dimensions (e.g., spatial vs. verbal in Experiment 3) or different sources of conflict (Funes et al., 2010b) would require a general form of attentional control setting for irrelevant stimulus features (i.e., "attend to all features of stimuli"), instead of or in addition to specific attentional control settings for the irrelevant feature dimension of the inducer stimuli. Second, the effect of a shared relevant dimension on transfer of LWPC effects between tasks would imply that the general attentional control setting is only established when all stimuli share the relevant stimulus dimension. Third, the finding that the LWPC effect was consistently larger for the biased than for the unbiased task suggests that the generalized attentional control setting requires some time to develop during the course of the experiment. Yet, an account in terms of attention to the relevant stimulus dimension seems more parsimonious.

As pointed out by Logan and Zbrodoff (1982), rather than dividing attention between correlated stimulus dimensions, participants might deliberately respond to the irrelevant stimulus dimension when it is highly predictive of the correct response. In particular, in a typical Stroop task, participants might produce the compatible response to word shape with mostly congruent stimuli, but the incompatible response to word shape with mostly incongruent stimuli, respectively. This notion is consistent with the reversal of congruency effects that is often observed with mostly incongruent conditions (e.g., Logan, 1980; Logan & Zbrodoff, 1979). Moreover, this notion is also consistent with the fact that LWPC effects typically occur with two-stimulus sets, but not with four-stimulus sets (e.g., Logan, Zbrodoff, & Williamson, 1984). The explanation would be that each stimulus has a unique incompatible response with two-stimulus sets, but not with four-stimulus sets. This attention-switching, or task-recoding, account could explain our findings if the recoded task rules are general enough as to be applicable to both the inducer and the diagnostic task. Moreover, the account is viable for our experiments because each stimulus had a unique incompatible (or incongruent) response in each of our experiments. However, the fact that transfer of LWPC effect depends on a shared relevant stimulus dimension does not easily follow from an account of LWPC effects in terms of task recoding.

An interesting question concerning cognitive adaptation to conflict frequency relates to the role of *awareness* for the frequency manipulation. Unfortunately, we did not probe our participants' awareness for the LWPC manipulation, but some studies addressed this issue with regard to context-specific proportion-congruent (CSPC) effects. CSPC effects arise when sets of mostly congruent stimuli and sets of mostly incongruent stimuli are presented within in the same block of trials, but in different "contexts" (e.g., locations). A first group of studies used subliminal stimulus presentation for investigating the role of awareness in CSPS effects, but obtained mixed results. Some studies suggest that CSPC effects require awareness (Heinemann, Kunde, & Kiesel, 2009) but others do not (Reuss, Desender, Kiesel, & Kunde, 2014; Schouppe, de Ferrere, Van Opstal, Braem, & Notebaert, 2014). In another study, Crump, Gong, and Milliken (2006) asked participants whether they were aware of the precise proportion manipulation following the experiment. Results indicated that participants were not able to explicitly describe the proportion manipulation, suggesting that the obtained CSPC effect did not depend on awareness. Moreover, in a follow-up study, Crump, Vaquero, and Milliken (2008) showed that informing participants about the CSPC manipulation in advance was not sufficient to produce robust CSPC effects. It thus seems possible to implement context-specific adaptation to conflict frequency without awareness. Hence, it would not be surprising to see transfer without awareness, but because we did not garner awareness, we cannot investigate this.

Independent support for a flexible control account was presented by Abrahamse, Duthoo, Notebaert, and Risko (2013). They demonstrated that participants who started with a mostly incongruent list did not readjust (i.e., the congruency effect did not increase) when a new mostly congruent list followed, whereas participants who started with a mostly congruent list did readjust (i.e., the congruency effect decreased) when a mostly incongruent list followed. This effect was explained by assuming that participants who started with a mostly incongruent list blocked the (unreliable) irrelevant dimension and hence did not notice that the congruency proportion changed. It is, however, also possible that, in mostly incongruent blocks, participants increased attention to the relevant dimension rather than decreasing attention to the irrelevant dimension.

Transfer of adaptation to recent conflict

Although the present study was mainly concerned with sustained adaptation to conflict frequency (i.e., the LWPC effect), our experiments also investigated transient adaptation to conflict (i.e., the Gratton effect) in three experiments. Therefore, our experiments also produced new empirical data on the transfer characteristics of sequential modulations of congruency effects. We only observed transfer of sequential modulations from one task to another in Experiment 1, whereas Experiments 2 and 3 suggested that sequential modulation was task-specific or conflict-specific. The existing evidence concerning the transfer of sequential modulations of congruency effects is heterogeneous, and various theoretical accounts have been proposed. According to the adaptation-by-binding model, put forward by Verguts and Notebaert (2008, 2009), detection of conflict leads to the strengthening of the association between the response and the task-relevant stimulus dimension. Therefore, this model predicts that transfer of sequential modulation is more likely when the two tasks share the relevant stimulus dimension than when the two tasks differ in terms of the relevant stimulus dimension. This prediction was confirmed in our Experiments 1 and 2, combining a horizontal and a vertical Simon task that either shared the relevant stimulus dimension or did not. Braem, Verguts, and Notebaert (2011) reported corroborating evidence for this associative account, showing that such transfer only occurred when responses were executed with the same effector. Still, other studies failed to find a transfer of sequential effects even when the two tasks shared both the relevant dimension and response modality (Funes et al., 2010a, 2010b), thereby suggesting that such attentional modulation is very specific to the type of conflict encountered on the previous trial (e.g., Egner, Delano, & Hirsch, 2007). Funes et al. (2010a, 2010b) indeed showed that sequential effects can be effectively eliminated when switching from stimulus conflict to response conflict on consecutive trials.

In an attempt to reconcile the heterogeneous findings, Hazeltine, Lightman, Schwarb, and Schumacher (2011) proposed that rather than different sources of information (e.g., the relevant dimension or type of conflict), the salience of the boundary between the two tasks will determine whether sequential modulation transfers or not. In a series of four experiments varying response and stimulus modalities, they indeed found that (transfer of) sequential modulation crucially depended on participants' subjective representations of the task boundaries. In this view, participants in Experiment 1 might have classified both vertically and horizontally presented stimuli as belonging to the same task set, enabling a transfer of the control settings. Most importantly for the current results, though, the pattern of transfer for these sequential effects was qualitatively different from the pattern of transfer for the proportion-congruent effects. Therefore, our findings corroborate previous research suggesting the existence of two separate control systems for overcoming recent versus frequent conflict (Funes et al., 2010b).

CONCLUSION

In summary, two experiments produced further empirical evidence that LWPC effects can transfer across tasks, indicating that adaptation to conflict frequency involves a cognitive control process that does not strictly distinguish between sources of conflict or experimental tasks. Moreover, our experiments also provide further evidence for the independence of the LWPC effect from sequential modulations of congruency effects, suggesting different mechanisms for sustained adaptation to conflict frequency and transient adaptation to most recent conflict. In our view, the observation that sustained adaptation to conflict frequency is less task-specific than transient adaptation to recent conflict is not surprising because modulating conflict in a task-specific way is much more difficult if a large number of trials have to be considered than if only a single event has to be considered.

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