Influence of bias on visuospatial and verbal compatibility effects in mixed-mapping environments

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Abstract The advantage for the compatible mapping of physical locations or arrows to keypresses is reduced when trials with compatible and incompatible mappings are mixed, whereas the advantage is increased for location words. We evaluated explanations of these mixing effects by varying the proportions of compatible and incompatible trials for groups performing with each stimulus mode. The mappings were compatible on 75%, 50%, and 25% of the trials, respectively, for compatibly biased, unbiased, and incompatibly biased conditions. For locations and arrows, compatible bias increased the SRC effect, and incompatible bias reduced the effect; for location words, the incompatible bias was stronger than the compatible one. Reaction time distributions showed that, with locations and arrows, initial activation toward either the compatible (unbiased condition) or the predominant (biased conditions) response was transient. With words, activation of the corresponding response increased across the distribution, regardless of bias condition. The influence of bias on the SRC effects was relatively independent of the mixing and sequential effects, and was different for words than for nonwords. These results are consistent with the view that visuospatial stimuli produce transient activation of the corresponding or predominant response, whereas location words produce phonological activation, required for word identification, that persists.

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Spatial stimulus–response compatibility (SRC) effects occur for any stimuli with spatial content that are mapped to spatial responses (see Proctor & Vu, 2006, for a review). In two-choice reaction tasks, a compatible mapping of a left stimulus to a left response and a right stimulus to a right response yields faster responding than does the incompatible mapping when the stimuli are left and right physical locations (e.g., Shaffer, 1965), left- and right-pointing arrows (e.g., de Jong, 1995), or the words LEFT and RIGHT (e.g., Vu & Proctor, 2004). When compatible and incompatible mappings are mixed within trial blocks, however, the SRC effects for physical-location and arrow-direction stimuli are eliminated, whereas that for location words is increased in size (Vu & Proctor, 2004). The aim of the present study was to evaluate alternative explanations for these influences of mixing on task performance and to determine the way in which processing of visuospatial and verbal stimuli under mixed-mapping conditions differs. This was accomplished by manipulating the relative frequencies of compatible and incompatible trials to introduce a bias toward one or the other mapping (e.g., de Jong, 1995).

Explanations of SRC effects

The SRC effects for stimuli signifying location are a consequence of the stimulus and response sets having overlap, or similarity, at the conceptual level—and in the case of physical locations, at the physical level as well

(Kornblum & Lee, 1995). Not only do the three stimulus modes show SRC effects when mapped to keypress responses, but the reaction time (RT) distribution functions are similar as well. When the RTs for compatible and incompatible trials of each participant are rank ordered, divided into quantile bins, and averaged across participants, the SRC effect increases across the RT distribution for all three stimulus modes, with the largest SRC effect occurring for the longest RTs (Vu & Proctor, 2004, Exp. 1).

All stimulus modes also produce SRC effects when the stimulus location information is irrelevant to the task, although the effects are smaller than those obtained when the location information is relevant (e.g., Vu & Proctor, 2004). The term *Simon effect*, named after J. R. Simon (1990), is used to identify the effect obtained with irrelevant physical location and often for the effects obtained with irrelevant arrow directions and location words. Due in large part to the occurrence of the Simon effect, most accounts of SRC effects rely on two response activation routes (e.g., Kornblum & Lee, 1995; Zorzi & Umiltà, 1995): (a) a direct route, through which the corresponding response is activated automatically via long-term stimulus–response associations, and (b) an indirect route, through which intentional translation of the stimulus to the task-defined response is achieved through short-term associations implemented for the task or the application of task rules. Both of these routes are often presumed to contribute to the advantage of the compatible mapping over the incompatible one (e.g., Kornblum & Lee, 1995).

Influences of mixed compatible and incompatible mappings

Although robust SRC effects are obtained for all three stimulus modes when compatible and incompatible mappings are deployed in distinct trial blocks, differences emerge when the mappings are mixed and vary randomly from trial to trial. With mixed mappings, the mapping for the trial must be signaled in some way. Shaffer (1965) used the horizontal or vertical orientation of a separate, centered line to signal the mapping, but most other studies have used the color of the imperative stimulus (e.g., Heister & Schroeder-Heister, 1994). Similar results are obtained with both methods of signaling the mapping. Relative to blocks of a single mapping, RTs are lengthened overall when mappings are mixed, regardless of whether the location information is conveyed by physical locations, arrows, or words, as would be expected from the global mixing cost evident in most studies of task switching (see Kiesel et al., 2010, for a review). For physical locations and arrows, RTs are increased more for the compatible mapping than for the incompatible mapping, resulting in

elimination of the usual benefit in performance for the compatible mapping (de Jong, 1995; Heister & Schroeder-Heister, 1994; Shaffer, 1965; Vu & Proctor, 2004, 2008; Yamaguchi & Proctor, 2006). In contrast, for location words, mixing of compatible and incompatible mappings slows responses more for the incompatible mapping, resulting in a larger SRC effect than when the mappings are blocked (Vu & Proctor, 2004).

Several factors could underlie the elimination of the SRC effects for physical locations and arrows that occurs when compatible and incompatible mappings are mixed (Los, 1996). Many authors have favored a *suppression hypothesis*, according to which the tendency to make the compatible response is suppressed with mixed mappings. Evidence consistent with this hypothesis is that the SRC effect is reinstated when the mapping is cued in advance (de Jong, 1995; Shaffer, 1965). Based on these and other results, de Jong concluded that “... the reduction of SRC effects reflects an active initial suppression of the compatible mapping rule. This suppression appears to be necessary in order to prevent the compatible rule from producing detrimental interference when the incompatible rule is called for instead” (p. 187). Although de Jong stated the suppression hypothesis in terms of mapping rules, other authors have assumed that the suppression is of the direct response activation route (Proctor & Vu, 2006; Van Duren & Sanders, 1988). Stoffels (1996) conducted experiments with four-choice spatial tasks in which two physical-location stimuli were mapped compatibly to responses and two were not, and he concluded that suppression of the direct route was a significant factor contributing to elimination of the SRC effect (see also Ehrenstein & Proctor, 1998). The suppression hypothesis can explain the influence of mixing for physical-location and arrow stimuli, but it cannot account for the increase in the SRC effect in mixed-mapping environments obtained with location words. There is no reason to think that less suppression is required when mappings of location words are mixed than when they are not. Thus, another factor, such as priming of the corresponding response by phonological activation of a word in the process of identifying its meaning (e.g., Frost, 1998; Yeh & Eriksen, 1984), is needed to explain the increased SRC effect for words.

A second account, the *transient-activation hypothesis* (de Jong, 1995), is based on an assumption that a stimulus automatically activates its corresponding response by way of the direct route, but this activation dissipates quickly (see, e.g., Hommel, 1994). In agreement with this assumption, the Simon effect for physical location decreases across the RT distribution (de Jong, Liang, & Lauber, 1994). However, such a decrease does not occur for Simon effects produced by arrows or location words (Proctor, Miles, &

Baroni, 2011). Assuming transient activation, the overall delay in responding with mixed mappings in SRC tasks might be sufficient to allow activation to diminish by the time response selection occurs (see, e.g., Risko & Besner, 2008, Exp. 1). With mixed compatible and incompatible S–R mappings, Vu and Proctor (2004) found RT distribution patterns consistent with the transient-activation hypothesis. SRC effects of about 30 ms were evident for arrows and physical locations at short RT bins; the effects peaked for RTs around 450 ms, and then decreased and tended to reverse at longer RT bins. In contrast, for location words, the SRC effect under mixed-mapping conditions was 70 ms at the shortest RT bin and increased monotonically across bins, to more than 150 ms at the last two of ten bins.

A third account attributes elimination of the SRC effect under mixed-mapping conditions to different patterns of trial-to-trial adaptation of processing in mixed blocks than in pure blocks with constant mapping, which we call the *sequential-modulation hypothesis*. Sequential effects are well documented within the Simon effect literature (see, e.g., Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002), with the Simon effect being evident mainly when the relation between stimulus location and response on the prior trial was corresponding. Whether the sequential effects are due to suppression of the direct route following noncorresponding trials (e.g., Iani, Rubichi, Gherri, & Nicoletti, 2009) or retrieval of prior episodes (e.g., the stimulus and response from the prior trial; Chen & Melara, 2009) is a matter of ongoing debate. As applied to SRC effects with mixed mappings, the RT on the current trial is dependent on the relation of the mapping for that trial to the mapping for the prior trial: The RT is shorter when the mapping repeats than when it switches (Shaffer, 1965; Vu & Proctor, 2008). Indeed, in the condition of de Jong's (1995) Experiment 1 with the shortest interval between the onsets of the mapping signal and the imperative stimulus (an arrow), the SRC effect was evident on mapping-repetition trials but not on mapping-switch trials. Because in pure-mapping conditions there are no mapping-switch trials, the sequential effect involving repetition or switch of mappings introduced when mappings are mixed could be responsible for the reduced size of the SRC effect.

A final possible explanation is the *bias hypothesis*, which assumes that it is more difficult to activate the incompatible mapping when it is in an unprepared state than when it is in a prepared state (de Jong, 1995). Accordingly, under mixed-mapping conditions (for physical location or arrow stimuli), the incompatible mapping is prepared instead of the compatible mapping, and this preparation bias counters the benefit of the compatible mapping. The bias hypothesis could also account for the increased SRC effect under mixed-mapping conditions for

words, by assuming that the compatible mapping is the one that is kept in the prepared state. One possible reason for such preparation is that phonological processing associated with identifying words may be “the default procedure of the cognitive system” (Frost, 1998, p. 72).

De Jong (1995) evaluated the bias hypothesis for arrows in his Experiment 2 by manipulating the percentages of compatible and incompatible trials within a trial block (50% each in an unbiased block, and 67% for one vs. 33% for the other in compatibly and incompatibly biased blocks). The onset of the mapping signal, a high- or low-frequency tone, preceded that of the left or right arrow by 10 ms on half of the trials, and 800 ms on the other half. For the 10-ms cue (which approximates a no-precue condition), the SRC effects were 29, 23, and 6 ms, respectively, for the high (67%), intermediate (50%), and low (33%) mapping probabilities. De Jong interpreted this result pattern, in which the compatible mapping showed an advantage over the incompatible mapping when the mappings were prepared (high probability), but not when they were unprepared (low probability), as support for the suppression hypothesis rather than the bias hypothesis. However, if the SRC effect is calculated within each of the trial blocks, rather than across those with compatible and incompatible biases, as de Jong did, it can be seen that the influence of mapping bias on the SRC effect was symmetric: The SRC effect was 70 ms in the compatibly biased condition, 23 ms in the unbiased condition, and –30 ms in the incompatibly biased condition. This symmetry implies that bias toward the compatible mapping did not result in release of suppression of that mapping, because such release should have produced a larger shift in the SRC effect (as compared to the unbiased condition) for the compatibly biased condition than for the incompatibly biased condition.

De Jong's (1995) results were limited to arrow stimuli and are somewhat ambiguous with regard to how bias alters response selection when mappings are mixed. In addition, the experiment included other manipulations that might have had interactive effects with the bias manipulation on RT: Within each block, stimulus discriminability (low vs. high) and (as mentioned) the interval between the onsets of the mapping signal and arrow (10 and 800 ms) varied randomly, which could have caused participants to adopt strategies to try to prepare for the cued mapping. Although 10 ms is a short lag between onsets, the functional time available likely was longer, because an auditory stimulus (the mapping signal) is usually processed faster than a visual stimulus (the arrow; Sanders, 1998). That de Jong obtained a 23-ms SRC effect when the compatible and incompatible mappings were equally likely is consistent with this possibility, since the typical finding is that the SRC effect is eliminated, at least in

studies using physical-location stimuli. Also, de Jong did not examine whether the bias effects were a result of the differential contributions of sequential effects in the various bias conditions, although a sequential-effects analysis reported for his Experiment 1 (in which the two mappings were equally likely) showed different result patterns following mapping repetitions than following mapping switches. Finally, RT distribution analyses, which should show evidence of transient activation if it is occurring, were not reported. Therefore, we conducted a thorough investigation of the influence of mapping bias on the SRC effect for arrow directions, physical locations, and location words under conditions in which mapping bias alone was varied.

Present study

In the present study, we varied the proportions of compatible and incompatible trials so that one or the other mapping predominated, being appropriate 75% of the time. We also included an unbiased control condition in which the two mappings occurred equally often. These three bias conditions were conducted separately for each of the three stimulus modes—physical locations, arrow directions, and location words. Both stimulus mode and mapping bias were manipulated between subjects. The bias manipulation should result in the predominant mapping showing a benefit relative to the unbiased control condition. Both the bias and suppression hypotheses of the elimination of the SRC effect predict a larger influence of the compatible bias than of the incompatible bias on the SRC effect, because participants are presumed to have not prepared or to have suppressed the compatible mapping in the unbiased condition. If the transient activation for physical locations and arrows and the increasing activation for location words are consequences of automatic processes, the distribution functions obtained for the compatibly and incompatibly biased conditions should be similar to those of the unbiased conditions. However, if the activation is under cognitive control, the shapes of the distribution functions should vary as a function of the relevance of the corresponding response. Finally, because more of the preceding trials are compatible than incompatible in the compatibly biased condition, and vice versa for the incompatibly biased condition, the sequential-modulation hypothesis predicts increases and decreases, respectively, in overall SRC effects relative to the unbiased condition. If the influence of mixing on the SRC effects is solely a consequence of altered sequential dependencies, then analyses that take into account the sequential effects should show no remaining contribution of mixing to the SRC effects.

Method

Participants

A group of 144 undergraduate students from Purdue University participated for experimental credit toward an introductory psychology course requirement. Stimulus mode and bias condition were varied between subjects, with 16 participants randomly assigned to each condition. All participants were naïve to the study and reported having normal or corrected-to-normal vision.

Apparatus and stimuli

The stimuli were presented on personal computers with 14-in. VGA color monitors. Micro Experimental Laboratory (MEL, Version 2.01) was used to program the experiment. Participants were seated directly in front of the monitor, at a distance of approximately 55 cm. The stimuli were red or white (MEL color codes 4 and 15, respectively) circles (5 mm, or 0.52° , diameter), presented in left or right locations [60 mm (6.23°) from center], location words [lowercase “left” or “right” (approximately 12×5 mm and 15×5 mm; visual angles of $1.56^\circ \times 0.52^\circ$ and $1.24^\circ \times 0.52^\circ$, respectively), presented at the center of the screen], or filled arrows [2.54 cm (2.64°) long, with the width of the arrowhead being 2.86 cm (2.98°) and the width of the tail being 1.27 cm (1.32°), presented in the center of the computer screen]. Responses were made by pressing the “z” and “/” keys, the leftmost and rightmost keys on the bottom row of the computer keyboard, with the index fingers of the corresponding hands.

Procedure

Each participant was tested individually in a session consisting of 400 trials. Participants were told that on each trial a red or white stimulus would appear on the screen, and they were to respond to the white (red) stimulus with a compatible mapping and the red (white) stimulus with an incompatible mapping. For the compatible mapping, they were to press the left key to the left stimulus and the right key to the right stimulus. For the incompatible mapping, they were to respond with the right key to the left stimulus and the left key to the right stimulus. For the unbiased condition, half of the trials were compatible and half incompatible; for the compatibly biased condition, 75% of trials were compatible and 25% incompatible; for the incompatibly biased condition, 25% were compatible and 75% incompatible. For all conditions, the order in which the compatible and incompatible trials occurred was randomized. The participants were told about the proportions of compatible and incompatible trials they would

receive prior to starting the experiment. Both speed and accuracy of responding were emphasized.

RTs were measured from stimulus onset to the depression of a response key. The stimulus remained present until a response was made, after which there was a 1-s intertrial interval during which the screen was blank. A 400-Hz error tone was presented for 500-ms after an incorrect response, and it was followed by the 1-s intertrial interval.

Results

Trials for which the RT was less than 200 ms or greater than 2,000 ms were not included in the analyses (less than 1% of all trials). The first 20 trials were considered practice and were also not included in the analyses. For the main analyses, mean correct RTs and percentage errors (PEs) were submitted to 3 (stimulus mode: physical locations, arrows, or words) $\times$ 2 (mapping: compatible or incompatible) $\times$ 3 (mapping bias: unbiased, compatible bias, and incompatible bias) ANOVAs (see Table 1 for means). Condition and stimulus mode were between-subjects factors, and mapping was a within-subjects factor.

Reaction time

Main analysis The main effects of mapping and stimulus mode were significant, $F(1, 135) = 106.98$, $MSE = 1,410$, $p < .001$, $\eta_p^2 = .44$, and $F(2, 135) = 24.76$, $MSE = 23,979$, $p < .001$, $\eta_p^2 = .27$, respectively. These reflect an overall SRC effect of 45 ms and longer RTs for location words ($M = 742$ ms) than for arrows ($M = 614$ ms) and physical locations ($M = 599$ ms). The interaction between mapping and stimulus mode was also significant, $F(2, 135) = 82.56$, $MSE = 1,410$, $p < .001$, $\eta_p^2 = .55$. There was no significant

SRC effect for physical locations (-5 ms), $F(1, 45) < 1.0$, whereas arrows showed a small SRC effect of 17 ms, $F(1, 45) = 6.89$, $MSE = 1,024$, $p = .012$, $\eta_p^2 = .13$, and location words showed a large SRC effect of 125 ms, $F(1, 45) = 151.43$, $MSE = 2,482$, $p < .001$, $\eta_p^2 = .77$.

Mapping bias had no main effect and did not interact with stimulus mode, $F_s < 1.0$. However, it did interact with mapping, $F(2, 135) = 167.42$, $MSE = 1,410$, $p < .001$, $\eta_p^2 = .71$: The SRC effect was 138 ms for the compatibly biased condition, 58 ms for the unbiased condition, and -59 ms for the incompatibly biased condition. Thus, the mapping bias manipulation was effective.

The three-way interaction of mapping $\times$ mapping bias $\times$ stimulus mode approximated the .05 level, $F(4, 135) = 2.42$, $MSE = 1,410$, $p = .051$, $\eta_p^2 = .07$. In accord with a priori expectations, we conducted two contrasts to clarify the interaction, one that compared physical locations to arrows, and another that compared those two conditions to location words. The first contrast showed no three-way interaction of mapping and bias with arrow versus location stimulus modes, $F < 1.0$: The increase in the SRC effect for the compatibly biased condition (relative to the unbiased condition) and the decrease in the SRC effect for the incompatibly biased condition were of similar magnitudes for physical locations (SRC effects of 91, -4 , and -103 ms, respectively) and arrows (SRC effects of 117, 12, and -78 ms, respectively). The second contrast showed a three-way interaction, $F(2, 138) = 4.72$, $MSE = 2,846$, $p = .010$, $\eta_p^2 = .06$, indicating that the mapping $\times$ bias interaction for location words differed from the pattern shown by arrows and physical locations. Pairwise comparisons of the SRC effect for words, with the Bonferroni correction for multiple comparisons, showed that the SRC effect in the compatibly biased condition (208 ms) did not differ from that in the unbiased condition (164 ms, $p > .25$), but the SRC effect in

Table 1 Mean RT and PE (in parentheses) for each stimulus mode as a function of bias condition and mapping

Stimulus Mode and Bias Condition	Mapping		SRC Effect
	Compatible	Incompatible	
Physical Locations			
Compatibly biased	547 (2.25%)	638 (2.90%)	91 (0.65%)
Unbiased	615 (2.85%)	611 (1.46%)	−4 (−1.39%)
Incompatibly biased	643 (5.48%)	541 (1.62%)	−102 (−3.86%)
Arrow Directions			
Compatibly biased	548 (2.66%)	665 (4.17%)	117 (1.51%)
Unbiased	611 (4.32%)	623 (3.32%)	12 (−1.00%)
Incompatibly biased	656 (4.79%)	578 (1.78%)	−78 (−3.01%)
Location Words			
Compatibly biased	606 (1.56%)	814 (5.70%)	208 (4.14%)
Unbiased	681 (3.06%)	845 (5.20%)	164 (2.14%)
Incompatibly Biased	751 (4.88%)	755 (4.61%)	4 (0.27%)

the incompatibly biased condition (4 ms) was smaller than both ($p < .001$).

RT distribution analysis We ranked RTs for compatible and incompatible trials and divided them into five RT bins, and the SRC effect was calculated for each bin. The plots of the SRC effect for the bins as a function of mean RTs are shown in Fig. 1. The distribution functions for the unbiased conditions replicate those reported by Vu and Proctor (2004). For physical locations and arrows, there was a positive SRC effect of 30–40 ms at the early bins that disappeared and turned negative as RT increased. In contrast, the location words showed the smallest SRC effect at the shortest RT bins, with the effect increasing

across the distribution. With regard to the bias manipulation, the functions for physical locations and arrows showed similar, relatively symmetric patterns, consistent with the comparable effects obtained for the compatibly and incompatibly biased conditions in the main analysis. Relative to the unbiased condition, the SRC effect was altered in the direction of the mapping bias, with the bias effects being largest at the RT bins in the first half of the distributions. For words, however, the mapping bias exerted a similar effect across the entire distribution; thus, the asymmetry in the mapping bias effect was evident throughout the distributions, and not just for the fast responses.

An ANOVA performed on the SRC effect (difference in RTs between incompatible and compatible mappings) showed a main effect of bin, $F(4, 540) = 15.88$, $MSE = 2,067$, $p < .001$, $\eta_p^2 = .11$, but this was determined mainly by the location words, as indicated by the bin $\times$ mode interaction, $F(8, 540) = 33.60$, $MSE = 2,067$, $p < .001$, $\eta_p^2 = .33$. Separate ANOVAs for physical locations and arrows both showed small effects of bin: respectively, $F(4, 180) = 9.51$, $MSE = 1,175$, $p < .001$, and $F(4, 180) = 2.51$, $MSE = 1,849$, $p = .043$, $\eta_p^2 = .05$ with sphericity assumed, and $p = .10$ with the Huynh–Feldt correction. The SRC effects were more positive at the fast-response end of the distribution than at the slow end. For location words, the distribution effect was stronger, $F(4, 180) = 49.08$, $MSE = 3,176$, $p < .001$, $\eta_p^2 = .52$. The SRC effect was 67 ms at the first bin and increased to 211 ms at the last bin.

Bin also interacted with mapping bias, $F(8, 540) = 2.93$, $MSE = 2,067$, $p = .029$, $\eta_p^2 = .04$, and the three-way interaction of those variables with mode was significant, $F(16, 540) = 1.91$, $MSE = 2,067$, $p = .017$, $\eta_p^2 = .05$, with sphericity assumed, but not with the Huynh–Feldt correction, $p = .071$. The separate ANOVAs for each stimulus mode showed that the bin $\times$ bias interaction was significant for physical locations, $F(4, 180) = 9.16$, $MSE = 2,994$, $p < .001$, $\eta_p^2 = .29$, but not for arrows, $F(4, 180) = 1.58$, $p = .202$, or words, $F < 1.0$.

Sequential-effects analysis The RT data were analyzed as a function of mapping, mapping repetition, and stimulus-position repetition for each bias condition and mode. To avoid duplication, below we report only effects involving mapping repetition or stimulus repetition.

There were main effects of mapping repetition, $F(1, 135) = 485.43$, $MSE = 6,923$, $p < .001$, $\eta_p^2 = .78$, and stimulus repetition, $F(1, 135) = 251.89$, $MSE = 5,500$, $p < .001$, $\eta_p^2 = .65$: RTs were shorter when the mapping repeated ($M = 606$ ms) than when it switched ($M = 714$ ms), and when the stimulus position repeated ($M = 625$ ms) than when it switched ($M = 695$ ms). Mapping repetition and stimulus repetition interacted, $F(1, 135) = 54.79$, $MSE = 3,774$,

Fig. 1 Mean stimulus–response compatibility (SRC) effects as a function of reaction time bin and bias condition for (a) physical locations, (b) arrow directions, and (c) location words

$p < .001$, $\eta_p^2 = .29$, with RTs being shortest when both the mapping and the stimulus repeated ($M = 558$ ms), longest when both switched ($M = 735$ ms), and intermediate when only the mapping or the stimulus repeated ($M_s = 654$ and 693 ms, respectively); all of the pairwise comparisons were significant, $p < .001$, using t tests with the Bonferroni adjustment. Thus, although the maximum benefit occurred when both mapping and stimulus repeated (177 ms), each type of repetition alone produced a benefit relative to when neither type of repetition was present, with the benefit being larger for mapping repetition (81 ms) than for stimulus repetition (42 ms).

Mapping repetition and stimulus repetition entered into a three-way interaction with stimulus mode, $F(2, 135) = 4.08$, $MSE = 3,774$, $p < .02$, $\eta_p^2 = .06$. The three stimulus modes showed the same qualitative pattern (see Fig. 2). Although there was a tendency for the benefit of complete repetitions relative to complete switches to be largest for location words (194 ms), intermediate for arrow directions (178 ms), and smallest for physical locations (160 ms), this difference was not significant, $F(2, 135) = 1.36$, $MSE = 9,961$, $p = .26$, $\eta_p^2 = .02$. Instead, the comparison of mapping repetition alone to stimulus repetition alone produced a significant interaction with stimulus mode, $F(2, 135) = 8.30$, $MSE = 2,462$, $p < .001$, $\eta_p^2 = .11$: The benefit for mapping repetition relative to stimulus repetition had significant values of 45 ms for physical locations and 55 ms for arrows, but only a nonsignificant 16 ms for words.

Several terms involving mapping were significant. There was a two-way interaction of mapping with mapping repetition, $F(1, 135) = 5.01$, $MSE = 3,248$, $p < .03$, $\eta_p^2 = .04$, as well as a three-way interaction of those variables with stimulus repetition, $F(1, 135) = 56.45$, $MSE = 2,080$, $p < .001$, $\eta_p^2 = .30$. The SRC effect was larger when mapping repeated ($MD = 54$ ms) than when it switched ($MD = 40$ ms). The SRC effect showed the same pattern as the two-way interaction of mapping repetition with stimulus repetition (see Fig. 3), with the SRC effect being larger when the mapping and stimulus both repeated ($MD = 72$ ms)

Fig. 2 Mean RTs as a function of mapping repetition and stimulus repetition for physical locations, arrows, and words

Fig. 3 Mean RTs as a function of mapping repetition and stimulus repetition for compatibly mapped and incompatibly mapped trials

or both switched ($MD = 64$ ms) than when only the mapping ($MD = 39$ ms) or only the stimulus ($MD = 16$ ms) repeated.

Mapping and mapping repetition also entered into three-way interactions with stimulus mode, $F(2, 135) = 7.94$, $MSE = 3,248$, $p < .001$, $\eta_p^2 = .11$, and bias condition, $F(1, 135) = 48.84$, $MSE = 3,248$, $p < .001$, $\eta_p^2 = .42$. The larger SRC effect when mapping repeated than when it switched was evident when the stimulus mode was physical locations or arrows, but not location words, for which the SRC effect was larger when the mapping switched (see Fig. 4a). Also, the larger SRC effect on mapping repetition trials was evident in the unbiased and compatibly biased conditions, with the incompatibly biased condition showing the opposite pattern (see Fig. 4b). These effects were modified by a four-way interaction of mapping repetition with the variables of mapping, bias condition, and stimulus mode, $F(4, 135) = 2.90$, $MSE = 3,248$, $p < .025$, $\eta_p^2 = .08$. As is shown in Fig. 5, the pattern of the SRC effect being larger when the mapping repeated in the compatibly biased and unbiased conditions, but larger when it switched in the incompatibly biased condition, was evident for locations and arrows, but not words. For words, there was little difference in the SRC effect on repetition and switch trials in the compatibly biased and unbiased conditions, whereas in the incompatibly biased condition, the SRC effect was much larger when the mapping switched than when it repeated.

By itself, stimulus repetition interacted with stimulus mode, $F(2, 135) = 5.22$, $MSE = 5,500$, $p < .01$, $\eta_p^2 = .07$, with the stimulus repetition benefit being larger for words ($MD = 88$ ms) than for physical locations ($MD = 57$ ms) and arrows ($MD = 61$ ms). These effects were modified by a three-way interaction with mapping, $F(2, 135) = 11.94$, $MSE = 2,435$, $p < .001$, $\eta_p^2 = .15$. The larger benefit for stimulus repetition with the word stimuli was due to the incompatible mapping benefiting the most from stimulus repetition (see Fig. 6).

To determine whether the influence of bias on the overall SRC effects was solely a result of altering the sequential

a Mapping x Mapping Repetition x Stimulus Mode **b Mapping x Mapping Repetition x Bias Condition** **Fig. 4** Mean stimulus–response compatibility (SRC) effects as a function of mapping repetition or switch for (a) each stimulus mode and (b) each bias condition

composition of trials, we performed an analysis of the RT data that controlled for the fact that sequential effects are

Mapping x Mapping Repetition x Bias Condition x Stimulus Mode **Fig. 5** Mean stimulus–response compatibility (SRC) effects as a function of mapping repetition or switch and stimulus mode for each bias condition**Mapping x Stimulus Repetition x Stimulus Mode** **Fig. 6** Mean stimulus repetition benefits as a function of mapping and stimulus repetition for each stimulus mode

weighted differentially across conditions when the proportions of compatible and incompatible trials are manipulated (see Risko, Blais, Stolz, & Besner, 2008). The pattern of significant effects was the same in this ANOVA as in the original ANOVA reported in the main analysis. The nonsignificant three-way interaction of mapping $\times$ bias $\times$ mode moved farther away from the .05 α level ($p = .13$) than in the ANOVA of unadjusted data ($p = .07$), but the difference in patterns for physical locations and arrows as compared to words remained evident in the mean data. The physical-location and arrow-direction stimuli showed symmetric biasing effects in the direction of the predominant mapping (physical locations, 37, 2, and -50 ms; arrows, 57, 12, and -28 ms, for the compatibly biased, unbiased, and incompatibly biased conditions, respectively). In contrast, the location words showed an asymmetry, with the SRC effect being of similar magnitude in the compatibly biased condition (169 ms) and the unbiased condition (164 ms), with both being larger than the SRC effect in the incompatibly biased condition (62 ms), p s $< .001$ with the Bonferroni correction.

Percentage error

The only variable that showed a main effect was that of stimulus mode, $F(2, 135) = 5.09$, $MSE = 9.39$, $p = .007$, $\eta_p^2 = .07$, with errors being most frequent with location words ($M = 4.17\%$), intermediate with arrows ($M = 3.51\%$), and least frequent with physical locations ($M = 2.76\%$). In addition, stimulus mode interacted with compatibility, $F(2, 135) = 29.96$, $MSE = 2.81$, $p < .001$, $\eta_p^2 = .31$: The SRC effects were negative for physical locations (-1.52%), $F(1, 45) = 27.34$, $MSE = 2.05$, $p < .001$, $\eta_p^2 = .38$, and arrows (-0.84%), $F(1, 45) = 6.08$, $MSE = 2.75$, $p = .018$, $\eta_p^2 = .12$, but positive for words (2.00%), $F(1, 45) = 26.64$, $MSE = 3.62$, $p < .001$, $\eta_p^2 = .37$. The compatibility $\times$ bias interaction was also significant, $F(2, 135) = 42.85$, $MSE = 2.81$, $p < .001$.

.001, $\eta_p^2 = .39$, with overall SRC effects of 2.14% in the compatibly biased condition, 0.07% in the unbiased condition, and –2.38% in the incompatibly biased condition. There was no three-way interaction of the variables, $F(4, 135) < 1.0$.

Discussion

SRC effects with equal numbers of compatible and incompatible trials

The results for the unbiased conditions, in which the compatible and incompatible mappings occurred equally often, replicated those obtained previously (Vu & Proctor, 2004). When the two mappings were equally likely, only the location words showed a strong SRC effect of 164 ms, with the arrows and physical-location stimuli showing nonsignificant effects of 12 and –4 ms, respectively. These data confirm that if the reduced SRC effect when mappings are mixed reflects either suppression of the tendency to make the corresponding response or preparation to respond incompatibly, the mechanism initiating the suppression or state of preparation operates only when the stimuli are physical locations or arrow directions. Although the meaning of a location word could in principle be determined without activating a phonological representation, most models of word processing assume that phonology plays a significant role in access to meaning (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Harm & Seidenberg, 2004). The lack of suppression therefore might be due to the word's phonological identity being activated and priming the corresponding response (e.g., Yeh & Eriksen, 1984), regardless of whether the mapping for the trial is compatible or incompatible.

The RT distribution functions for the unbiased conditions were also different for the arrows and physical locations than for the location words. The SRC effects for the arrows and physical locations tended to peak relatively early in the distribution and then decreased, shifting to somewhat negative after about the first 40% of the distribution, whereas the SRC effect for the location words increased across the RT distribution. These results confirm that mixing has different effects on the processing of visuospatial and verbal stimuli.

The distribution functions obtained with arrows and physical locations are consistent with activation being transient. Comparison of the distribution functions for pure and mixed mappings in Vu and Proctor's (2004) Experiment 1 (see their Fig. 2) showed that for the fastest responses, the SRC effects were of similar magnitude (approximately 30 ms) for the pure and mixed blocks. However, whereas the SRC effect increased from that point throughout the remainder of the distribution for the pure-mapping blocks, it showed a function like those for the

unbiased conditions of the present study for the mixed-mapping blocks. Thus, the distribution functions suggest that the elimination of the SRC effect in mixed-mapping conditions is not due to global suppression of the direct route, but to dissipation of the activation produced via this route once it occurs, through either an unintentional decay process (e.g., Hommel, 1994) or an intentional suppression process (e.g., Ridderinkhof, 2002).

In contrast to the distribution functions for arrows and physical locations, the monotonically increasing SRC effect function for location words with mixed mappings is not consistent with the activation being transient. For words, Vu and Proctor's (2004) experiment showed that the SRC effect for the fastest responses was larger when the mappings were mixed (70 ms) than when they were in pure blocks (close to 0 ms), although for both mixed and pure blocks the SRC effect then increased across the distribution, as it did for the unbiased condition of the present study. The initially large effect in mixed-mapping conditions, coupled with the increase across the distribution, is in agreement with the hypothesis that the location word is named as part of the identification process, and thus primes the corresponding response.

With regard to sequential effects, for the unbiased condition, there was a clear benefit of mapping repetition (or a cost of mapping switch), with the repetition benefit being larger for the compatible mapping than for the incompatible mapping for all three stimulus modes. For arrows and locations, the SRC effect was positive numerically on mapping-repetition trials, and negative numerically on mapping-switch trials. This pattern, which is similar to that reported by de Jong (1995) for arrows when the mapping was cued 100 ms in advance, implies that when the proportions of compatible and incompatible mappings are altered, the change in composition of the switch and repeat trials for the two mappings should influence the overall SRC effect. The difference in the SRC effects on repetition and switch trials was smallest for the location words, with positive SRC effects being obtained with both trial types, suggesting that whether the mapping repeats or switches is less crucial for words, consistent with the words being named, regardless of mapping.

SRC effects when compatible or incompatible trials predominate

Bias toward one mapping or the other had the anticipated influence on performance: When the compatible mapping predominated, the SRC effect was larger than in the unbiased condition for both RTs and PEs, whereas when the incompatible mapping predominated, the SRC effect was smaller than in the unbiased condition. For arrow-direction and physical-location stimuli, the compatible and incompatible biases had

approximately symmetric influences on the SRC effects. This symmetric influence of the two biases does not show any evidence of the compatible mapping being suppressed or unprepared in the “unbiased” condition. If release of suppression or change to preparing for the compatible mapping were to have occurred in the compatibly biased condition, the SRC effect would have changed more for that condition than for the incompatibly biased condition.

That the compatible mapping did not benefit more than the incompatible mapping from an increase in relative frequency is somewhat surprising, given that the compatible mapping has been shown to benefit more than the incompatible mapping from being precued with certainty for both arrow and physical-location stimuli (de Jong, 1995; Shaffer, 1965). Evidently, there must be essentially complete certainty that a compatible response will be correct for any such suppression to be released or preparation bias to be overcome. Evidence that the compatible mapping benefits from complete certainty that the corresponding response will be correct has been provided in studies in which two spatial-choice tasks are performed concurrently with the left and right hands. In such situations, the compatible mapping shows a unique benefit when it applies to both tasks, rather than just to one, eliminating all uncertainty that the corresponding response will be correct (Proctor & Vu, 2009).

For location words, the increase in the SRC effect when compatible trials predominated was considerably less than the decrease that occurred when incompatible trials predominated. In fact, when the influence of sequential effects was removed, the SRC effect in the compatibly biased condition was the same size as that in the unbiased condition. This lack of influence of increased expectancy for the compatible mapping on the SRC effect for location words suggests that, even when the two mappings are equally frequent, participants have an implicit bias toward the compatible mapping. This bias, again, is probably caused by activation of the corresponding response through use of phonology to identify the word (e.g., Frost, 1998; Yeh & Eriksen, 1984). Although the SRC effect for words did not increase with the compatible bias, the compatible trials showed a decrease in RT as compared to the unbiased condition. However, the incompatible trials showed a similar benefit, which resulted in the overall RT being 40 ms less than in the unbiased condition, although this difference was not significant ($p > .75$ with the Bonferroni adjustment). If the overall reduction of RTs in the compatibly biased condition turns out to be reliable, the implication would be that the explicit compatible bias exerts its influence mainly on the identification of location words, which affects both trial types, rather than on response selection, which would benefit only the compatible trials. In models of word recognition (e.g., Coltheart et

al., 2001; Harm & Seidenberg, 2004), this could be accomplished by increasing the weighting of the phonological process in word identification when compatible trials predominate.

The bias manipulation also produced distinct RT distribution patterns for the visuospatial and verbal stimuli. For physical locations and arrows, a bias toward the compatible mapping elevated the SRC effect across the whole function, with the largest effects still being evident in the first half of the distribution functions. Bias toward the incompatible mapping produced functions that were the mirror reverse of those for the condition with bias toward the compatible mapping: The largest negative SRC effect, favoring the incompatible mapping, occurred in the first half of the distribution. Thus, the biasing condition led to a tendency for fast responses, in particular, to be biased toward the predominant mapping. These data suggest that the mapping bias led to response activation that favored the predominant mapping (e.g., through the stimulus–response associations defined for the task), even if that mapping was incompatible. This activation, too, seemed to be relatively transient.

For location words, in contrast, the functions for the two bias conditions were close to parallel to that for the unbiased condition throughout the entire RT distribution, with the SRC effect being least at the early bins, and then increasing across the distributions for all three bias conditions. With incompatible bias, this increase resulted in the SRC effect changing from negative (i.e., toward the incompatible response) early in the RT distribution to positive later in the distribution. The parallel, increasing functions for location words suggest that there is no change in the activation pattern associated with the words as time progresses, consistent with the view that the word’s phonology plays a role in identification regardless of bias, and that the influence of an incompatible bias would come at response selection. The relative lack of influence of the bias manipulations on the properties of the distribution functions for all three stimulus modes suggests that expectancy for a particular mapping influences the relative amount of activation toward the response alternatives but does not have much effect on the time course of that activation.

For all stimulus modes, the mapping repetition benefit evident in the unbiased condition was modulated by the bias manipulation. The larger benefit for the compatible mapping in the unbiased condition was also evident in the compatibly biased condition. However, in the incompatibly biased condition, this pattern shifted to favor repetition of the incompatible mapping, indicating that the larger benefit for the compatible mapping in the other two bias conditions was not solely an automatic consequence of having two compatibly mapped trials occur in a row. A strategic interpretation of this finding would suggest that participants do not prepare as much for the next trial to be compatibly

mapped if the previous one was compatible when they know that it is unlikely that the next trial will also use the compatible mapping. Although the SRC effects are influenced by the numbers of repetition and switch trials, the mixing and bias effects are not solely a consequence of them, counter to the sequential-modulation hypothesis for the influence of mixing on the SRC effects.

Summary and conclusion

The results for physical-location and arrow-direction stimuli conform to the following account: Direct activation of the corresponding response occurs in mixed-mapping conditions when compatible and incompatible mappings are equally likely. However, this activation is transient. Bias in the relative frequencies of compatible and incompatible trials has its influence mainly on differential preparation for the two mappings, which again exerts its influence on performance in the activation that occurs shortly after stimulus onset. The mirror-image distribution functions suggest that the stimulus–response associations defined for the dominant mapping determine whether the compatible or the incompatible response is activated, but then this activation dissipates. For location words, the SRC effect is enhanced when mappings are mixed, rather than being eliminated (see also Vu & Proctor, 2004). This enhancement is due to an increase in initial activation that grows across time, rather than being transient. Introducing a compatible bias has much less influence on the SRC effect for words than does introducing an incompatible bias, which implies that there is already an implicit bias toward the corresponding response when compatible and incompatible trials occur equally often. This bias is likely a result of the phonological codes that play a role in word identification, priming the corresponding response. In addition, words also showed a larger repetition benefit for the incompatible mapping than for the compatible mapping, and a larger benefit for stimulus repetition with the incompatible mapping, all suggesting that naming of the word through the identification process occurs with both mappings.

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