The Journal of General Psychology, 2004, *131*(4), 411–425

Backward-Compatibility Effects With Irrelevant Stimulus–Response Overlap: The Case of the SNARC Effect

BERNIE CAESSENS
Department of Experimental Psychology
Ghent University, Belgium

BERNHARD HOMMEL
Department of Experimental and Theoretical Psychology
University of Leiden, The Netherlands
Max Planck Institute for Psychological Research
Munich, Germany

BERT REYNVOET
KOEN VAN DER GOTEN
Department of Experimental Psychology
Ghent University, Belgium

ABSTRACT. In 3 dual-task experiments, the relationship between primary-task response (R1) and secondary-task response (R2) was varied. In general, R1-left responses were faster when followed by the word *one*, and right responses were faster when followed by the word *two*. This backward-compatibility (BWC) effect indicated (a) that activation of R2 was not delayed until R1 selection was completed, and (b) that activation of the vocal responses was accompanied by the automatic activation of magnitude codes, known to be associated with spatial left–right codes (spatial-numerical association of response codes [the SNARC effect]). These findings supported the hypotheses (a) that BWC effects persist even with irrelevant R1–R2 overlap, (b) that the SNARC effect is based on associations between magnitude and spatial representations underlying response processing, and (c) that the production and perception of magnitudes relies on common codes.

Key words: backward compatibility, dual-task, response selection, SNARC effect

HOMMEL (1998) OBSERVED that, if two stimulus–reaction (S–R) tasks overlap in time, the primary task (S1–R1) is affected by compatibility between the secondary-task response (R2) and either the primary-task stimulus (S1) or the primary-task response (R1). That finding suggests that S2–R2 translation occurs in parallel to S1–R1 translation. Obviously, the observation of backward compatibility (BWC) runs counter to the widespread assumption of a structural bottleneck in S–R translation (Pashler, 1994; Welford, 1952). However, until now, BWC effects have been shown only with compatibility between the relevant features of R2 and S1 or R1. In the present study, we used the spatial-numerical association of response codes (SNARC effect; Dehaene, Bossini, & Giraux, 1993) as a means to investigate the possible limitations of automatic S–R translation under dual-task conditions. As we shall explain, the SNARC effect provides an opportunity to test for BWC effects under conditions in which irrelevant features of R2 are compatible or incompatible with R1. In addition, the design of the present study should allow us to extend the SNARC effect and to test whether the left–right spatial codes are used for the purpose of response selection, as has been assumed in the literature (Bächtold, Baumüller, & Brugger, 1998; Dehaene et al.).

Automaticity of the S–R Translation

If people perform more than one task at a time, then task performance often decreases rather dramatically (for overviews, see Meyer & Kieras, 1997; Pashler, 1994). To account for those forms of multiple-task decrements, several kinds of models have been proposed, ranging from capacity models to contention-scheduling models (for a comprehensive overview, see Meyer & Kieras). However, the most widely accepted account is still the response-selection bottleneck model, which was originally suggested by Welford (1952; see Pashler for an overview). Welford's model is based on the assumption that several stages in the transition from stimulus to response can be accessed from multiple tasks in parallel, but that S–R translation, or response selection, constitutes a structural bottleneck in allowing the selection of only one response (i.e., the response of only one task) at a time.

As mentioned heretofore, the idea of serial, capacity-limited S–R translation has been challenged by Hommel's (1998) finding that primary-task performance is affected by compatibility between R1 and R2 or between S1 and R2. For instance, Hommel presented colored letters (*H* or *S*) to his participants. In Experiment 1, the task was to respond manually with a left or right key press to the color of the letter and to respond vocally to the identity of the letter by saying either *left* or *right*. In contrast to what could be expected from a serial, capacity-limited

---

The research reported in this paper was supported by a grant to Bert Reynvoet from the Fund for Scientific Research–Flanders and a grant to Bernie Caessens from the Special Research Fund of Ghent University (011D6598), and by funding to Koen van der Goten from the Max Planck Institute, Munich.

The authors are indebted to Jan Lammertyn, Gino De Vooght, André Vandierendonck, and Els Stuyven for interesting discussions concerning an earlier version of this paper, and to Antoine Tavernier and Nicola Korrherr for their technical assistance.

Address correspondence to Bernie Caessens, Department of Experimental Psychology, Ghent University, Henri Dunantlaan 2, B-9000 Ghent, Belgium; bernie.caessens@ugent.be (e-mail).

theory of S–R translation, Hommel observed a significant performance benefit for R2–R1 compatible trials. That is, the participants were on average 75 ms faster pressing the right key, if the vocal response to the letter was also right, compared with when it was left. In another experiment (Experiment 3), Hommel changed the overlap between R2 and R1 into an overlap between R2 and S1 by having the participant respond to the letter identity with *red* or *green*, the colors of the letters. Again, he found a reliable compatibility benefit, this time defined from the R2–S1 overlap. It is interesting to note that in the latter experiment, the stimulus onset asynchrony (SOA) between the color and identity features was varied. The results showed that although the effect disappeared at larger onset differences, significant BWC effects were found at an SOA of 50 ms.

For R2 to affect R1 or S1, S2 must have been translated into R2 activation before R1 was selected, which suggests that S1–R1 and S2–R2 translation overlapped in time. One can draw similar conclusions from the studies of Lien and Proctor (2000), Logan and Delheimer (2001), Logan and Gordon (2001), and Logan and Schulkind (2000), who all demonstrated that R1 is affected by the compatibility between R1 and R2. Even stronger evidence for the automaticity of S–R translation has been provided by Hommel and Eglau (2002), who found that BWC effects are unimpaired by highly demanding memory-load conditions.

Although the results of the aforementioned studies all seem to point to the same conclusion, the degree to and the conditions under which S–R translation is automatic are not yet clear. For instance, Logan and Schulkind (2000) presented two digits on each trial. The task for the participants was either to indicate the magnitude of both digits, the parity of both digits, or, in a critical condition, the parity of one of the digits and the magnitude of the other. Logan and Schulkind observed BWC only if R1 and R2 belonged to the same task set (i.e., parity or magnitude) but not when task sets changed (i.e., parity and magnitude), which suggested that preparing for a task enables automatic S–R links to transform the cognitive system into a prepared-reflex machinery (Hommel, 2000). However, researchers have established that BWC effects can also arise from interactions between different tasks (Hommel, 1998; Hommel & Eglau, 2002), which raises the possibility that the observations of Logan and Schulkind are bound to particularities of their design, for example, their use of the same response categories in both tasks. More important for our purposes, it is a common characteristic of all previous BWC studies that the critical compatible or incompatible feature of R2 was relevant for the task, such as the words *red* or *green* in the tasks of Hommel and Hommel and Eglau. Therefore, the possibility remains that BWC effects are limited to the case in which relevant response features overlap. To examine that possibility, we attempted to see whether BWC effects could be demonstrated under conditions in which only an irrelevant feature of R2 overlapped with R1. By using the SNARC effect to induce between-task BWC, we were able to test for BWC effects under precisely those circumstances.

Spatial-Numerical Association of Response Codes

Models of human number representation propose that numbers are represented on an analog magnitude scale, which is commonly conceptualized as an oriented mental number line (Reynvoet & Brysbaert, 1999; Dehaene et al., 1993). Evidence for that assumption is found in a phenomenon called spatial-numerical association of response codes (SNARC), which has been observed in various tasks, such as parity judgment tasks (Dehaene et al.), phoneme monitoring tasks (Fias, Brysbaert, Geypens, & d'Ydewalle, 1996) and judgments of alphabetic order (Gevers, Reynvoet, & Fias, 2003). In those experiments, the researchers showed that participants reacted faster to the smaller elements of a given stimulus set (e.g., the numbers 1–5 in the set comprising the numbers 1–10) with the left-hand key than they did with the right-hand key, whereas the opposite was true for the larger elements—the SNARC effect. Researchers think that the effect originates from the left-to-right orientation of the mental number line (at least for Western cultures), which associates small numbers with the left side and large numbers with the right side. However, researchers have also shown that the SNARC effect does not necessarily rely on the absolute magnitude of numbers but rather on their relative position derived from a mental representation. For instance, the numbers 4 and 5 facilitate right-side responses when the stimuli in a parity task range from 0 to 5, but they facilitate left-side responses when the stimulus range is from 4 to 9 (Dehaene et al., Experiment 3). Similarly, Bächtold et al. (1998) found a reversal of the direction of the SNARC effect when participants imagined numbers on a clock rather than on a left–right oriented ruler. In other words, the SNARC effect seems to arise because numbers are imagined on a number line, which, by virtue of its spatial nature, activates spatial left–right representations that are used in response processing.

That indirect activation of left and right spatial response codes directly from magnitude activation should allow us to test for the limits of Hommel's (1998) BWC effect. That is, in all our experiments we had the participants perform two temporally overlapping tasks—a primary task that always had to be executed first (S1–R1) and a secondary task that had to be executed as fast as possible after the first response (S2–R2). It is important to note that the stimuli for the two tasks appeared in close temporal succession, so that S2 could be translated into R2 before R1 was carried out. R2 was compatible or incompatible with R1 in terms of SNARC, that is, a left or right R1 was paired with the R2 *one* or *two*, or vice versa. If the speed at which R1 was executed depended on its compatibility with R2, then that would imply that irrelevant spatial Task 2 response information was activated before R1 was executed. Such a finding would show that automatic translation is not restricted to task-relevant response features but, rather, that stimuli automatically activate all features of the associated response. With regard to SNARC, the backward-compatibility effects on R1 would suggest that saying one or two involves access to magnitude representations that in turn activate lateralized response codes. Such a finding would support the notion of ordered mental representations for magnitude and add further support to the notion that SNARC effects arise at the level of response processing.

EXPERIMENT 1

Experiment 1 followed the general design of Hommel's (1998) Experiment 1. That is, the participants performed two temporally overlapping tasks in each trial: a manual left–right response (R1) to the direction of a left- or right-pointing arrow (S1), and the vocal response *one* or *two* (R2) to the red or blue color of a frame (S2) that appeared briefly after the arrow (see Table 1). That design has several important features. First, magnitude was in no sense relevant for processing stimuli, so that any effect related to magnitude would be owing to automatic coding processes at the stage of the response. Second, numbers were not presented as stimuli, so that stimulus-induced magnitude coding is not likely. Third, the secondary responses (R2) referred to the numbers 1 and 2, which, according to a response-based interpretation of SNARC effects, are associated with left and right response codes, respectively. Fourth, if preparing a number-related response really were to activate a spatial response code in an automatic fashion, then the R2–R1 pairings one and left or two and right can be expected to be more compatible than the combinations of one and right or two and left. That allows for the following predictions: If, and only if, S2 is automatically translated into R2 and if processing numbers really activates spatial response codes, preparing the vocal response one should backward-prime the left-hand response (i.e., produce a faster R1 if a left-hand rather than a right-hand response is required) and preparing the vocal response two should backward-prime the right-hand response. In other words, R2–R1 compatibility in terms of SNARC should produce better performance in the primary task than R2–R1 incompatibility.

Method

Participants

Twenty adults (16 women, 4 men; age range: 19–29 years) were paid to participate for a session that lasted about 50 min. They all had normal or corrected-to-normal vision, and they were not familiar with the purpose of the experiment.

Materials, Procedure, and Design

For Task 1, the stimuli (S1) were arrows pointing to the left or right, to which the participants responded by pressing a response button with the left and right index finger, respectively. From a viewing distance of about 60 cm, the arrows measured about 0.3° wide and 0.4° high. For Task 2, the stimulus (S2) was a red or blue frame (about 2.9° wide and 1.3° high, with a line thickness of 0.14°) drawn around the location of S1. The participants responded with the word *eins* (*one* in

TABLE 1. Overview of Stimuli and Responses Used in Experiments 1, 2, and 3

Experiment	Task	Stimuli	Responses
1	1	left/right	left/right
	2	red/blue	one/two
2	1	1/2	single/double
	2	red/blue	left/right
3	1	*H/S*	left/right
	2	red/blue	one/two

German) or *zwei* (*two* in German). The S–R mapping of Task 2 was counterbalanced across participants.

The latencies and responses to Task 1 were recorded by means of a response box connected to the parallel port of a PC. The latencies to the Task 2 response were recorded by means of a microphone connected to the gameport. The vocal responses were recorded by the experimenter for later offline error analysis. We achieved millisecond accuracy by using the procedure described in Brysbaert, Bovens, d'Ydewalle, and Van Calster (1989).

A trial started with the presentation of a fixation cross at the center of the screen for 1,000 ms. After another blank interval of 250 ms, the stimulus of Task 1 was presented for 75 ms at the center of the screen. It was then replaced by the colored rectangle, which stayed on until the secondary response was given, or until the maximum trial duration of 3,500 ms was exceeded. The participants were instructed to perform the manual response before the vocal response.

After we had instructed the participants, three practice blocks of 16 trials (4 replications of every combination of arrow and number in random order) were presented. Then, 10 experimental blocks of the same size were administered. After every block, the participant had a break and then started the next block when he or she was ready.

Results

Premature responses (reaction time [RT] < 100 ms) and response omissions (RT > 1,500 ms) in one or the other task and task reversals (R2 before R1) accounted for less than 0.01% and were excluded from the analyses. The remaining RT data (from trials with two correct responses only) and error data from both tasks were analyzed as a function of compatibility (one/left and two/right) or incompatibility (one/right and two/left) between R2 and R1 (Table 2 shows the group means).

Two further analyses were run on the RTs from Task 1 (cf., Hommel, 1998). First, the RTs were analyzed as a function of compatibility and interresponse

TABLE 2. Mean Reaction Time (ms), Percentage of Errors, and Reaction Time Compatibility-Effect Sizes for Primary (Task 1) and Secondary (Task 2) Responses in Experiments 1, 2, and 3

	Compatible		Incompatible		
Experiment	RT	PE	RT	PE	ΔRT
		Task 1			
1	453	.00	465	.01	12
2	402	.04	410	.04	8
3	492	.02	505	.02	13
		Task 2			
1	897	.00	918	.02	21
2	665	.02	696	.04	31
3	886	.02	916	.05	30

Note. RT = reaction time; PE = percentage of errors; $\Delta RT = RT_{incompatible} - RT_{compatible}$.

interval (IRI) quintile. That is, for each participant and compatibility condition the RT means were calculated for the trials with the 20% shortest IRIs, for the trials with the 20% next-shortest IRIs, and so forth. Such an analysis shows whether the size of the compatibility effect varies with the IRI and, most important, whether it is restricted to trials with very short IRIs. If that is so, then BWC effects might be a side-effect of grouping responses to both tasks in a dual-task context. Such a finding would severely limit the interpretation of BWC effects, because researchers think that motor stages, much like perceptual stages, are not part of the hypothesized capacity-limited translation process.

Second, RTs were analyzed as a function of compatibility and RT quintile. That is, for each participant and compatibility condition, the RT means were calculated for the 20% fastest trials, the 20% next-fastest trials, and so forth. Such an analysis shows whether compatibility effects vary with relative response speed in the primary task. Logically, compatibility effects can be expected to increase with increasing manual RT, because that leaves more time for S2–R2 translation and resulting interactions between R1 and R2 (see Hommel, 1998). For all analyses, the significance criterion was set to $\alpha = .05$.

Task 1

The RTs were faster with R2–R1 compatibility than incompatibility, $F(1, 19) = 6.16$, $MSE = 220$, whereas the error rates yielded no effect, $F < 1$. There was no indication that the BWC effect in RTs was a result of response grouping. Mean IRI quintiles were 383, 441, 495, 568, and 919 ms with R2–R1 compatibility, and 392, 461, 514, 599, and 916 ms with incompatibility. The Quintile × Compatibility interaction was not significant, $F(4, 76) = 1.16$, $MSE = 642$, and there was no increase in compatibility effect with smaller IRIs. Moreover, even the shortest IRIs were too long to support a grouping explanation. Finally, the RT quintile analysis produced a significant Quintiles × Compatibility interaction, $F(4, 76) = 3.38$, $MSE = 1{,}307$, which indicated a stronger BWC effect as Task 1 takes more time to complete. Mean RT quintiles were 390, 418, 450, 497, and 706 ms for compatible trials and 394, 427, 460, 519, and 762 ms for incompatible trials, which showed an increase in the BWC effect from 4 to 56 ms.

Task 2

Compatibility between R2 and R1 produced a significant effect in RTs, $F(1, 19) = 6.38$, $MSE = 2{,}452$, but not in errors, $F < 1$.

Discussion

The results of Experiment 1 are clear in showing an effect of SNARC-based compatibility between R2 and R1 on the primary task. The presence of the effect has several important implications. First, with regard to BWC, the fact that performance in the primary task was affected by R2–R1 compatibility indicates that S2–R2 translation did not await selection of R1, as other researchers have observed in previous studies. Second, with regard to SNARC, it demonstrated that preparing a vocal number response, such as one or two, leads to the automatic activation of an associated spatial left or right code. That means that processing number information automatically leads to the coding of magnitude and that magnitude representations are associated with spatial codes. Third, the fact that in Experiment 1, only responses were related to numbers and no stimuli were shown, suggested that the spatial codes were used for response purposes, which supported a response-based locus of SNARC effects.

It is interesting to note that in Experiment 1, BWC effects were not based on the relationship between relevant response features (location for R1 and number for R2) but on the congruence between the relevant R1 feature and a task-irrelevant feature that was only indirectly associated with R2. That, in turn, suggested that activating a response would lead to the activation of all those codes that are associated with it. We will come back to that issue in the General Discussion.

EXPERIMENT 2

The results of Experiment 1 provided evidence that activating a response related to the numbers 1 or 2 leads to the activation of an associated left or right code, respectively, which can then prime other left and right responses. That seems to happen automatically, which suggests that there is a strong association between vocal number codes, magnitude codes, and spatial codes. Therefore, we should also be able to demonstrate the opposite effect, that is, that activating a left or right response leads to the priming of another response that is related to the numbers 1 or 2. That is what we attempted to do in Experiment 2, in which R1 required pressing a single key once or twice (a number-related response) and R2 consisted of a left–right key press (see Table 1). Obviously, if the codes of numbers, number magnitudes, and spatial response are associated, then preparing a left-hand response should backward-prime a single key press (i.e., the one response) and preparing a right-hand response should backward-prime a double key press (i.e., the two response).

Method

Sixteen adults (8 women, 8 men; age range: 18–34 years), who fulfilled the same criteria as those in Experiment 1, were paid to participate. The method was identical to that in Experiment 1, with the following exceptions. The responses were registered by means of a response box with small buttons on the left and right sides operated by the left and right index fingers, and a larger central button operated by both thumbs. R1 required pressing the central button once or twice in response to the visually presented numbers 1 and 2. Both thumbs were used to avoid lateralization, which could otherwise have interfered with the execution of R2. R2 required pressing the left or right button in response to the color of S2, the red or blue frame.

Results

Premature responses, response omissions, and reversals accounted for less than 0.01% of the trials. We used the same method as that outlined in the Results section of Experiment 1 to analyze the remaining data. See Table 2 for group means.

Task 1

Again, the RTs were faster with R2–R1 compatibility than incompatibility, $F(1, 15) = 7.901$, $MSE = 63.792$, and the error rates yielded no effect, $F < 1$. There was no indication of a role of response grouping in the IRI analysis. That is, the interaction of quintile and compatibility interaction was far from significant, $F(4, 60) = 1.54$, $MSE = 532$, and the IRIs ranged from 250 to 820 ms (250, 308, 378, 440, and 817 ms for compatible trials; 254, 325, 408, 483, and 820 ms for incompatible trials). In Experiment 2, the RT quintile did not modify the compatibility effect, so the Quintile × Compatibility interaction was not significant, $F < 1$. The mean RTs for the compatible trials were 341, 374, 407, 448, and 654 ms, whereas for incompatible trials they were 348, 380, 411, 456, and 666 ms. Although the BWC effect increased over time (from 6 to 12 ms), the increase failed to reach significance.

Task 2

Compatibility produced a significant effect in RTs, $F(1, 15) = 4.65$, $MSE = 1{,}334$, and error rates, $F(1, 15) = 22.34$, $MSE = 1.9145$, which indicated faster responses and fewer errors in the compatible condition than in the incompatible condition.

Discussion

Again, the results are clear in showing BWC effects indicative of SNARC-based interactions between R2 and R1. Obviously, preparing R2 overlapped with preparing R1, so that a left-hand R2 could prime one responses in Task 1 (i.e., single key presses) and a right-hand R2 prime two responses (i.e., double key presses). That is, the codes involved in preparing a single or double key press must be associated with, or even include, a spatial left or right code. In Experiment 1, we saw that the more time spent on Task 1, the stronger the BWC effect became. Evidently, the longer Task 1 takes, the more time there is for Task 2 to influence Task 1 processes. Although we found a similar trend in Experiment 2, the interaction was far from significant. It is possible that there was a lower limit to the BWC effect in that with the Task 2 delay (SOA), Task 1 had to take enough time for Task 2 stimuli to be translated into its corresponding response to allow for the BWC effects to occur. If we compare the quintile means from Experiment 1 with those from Experiment 2, then we see that the values were much lower in Experiment 2 and that from the 3rd quintile on, the BWC effects in both experiments were similar, which is exactly where the RT means are in the same range.

EXPERIMENT 3

Experiments 1 and 2 demonstrated effects of Task 2 response activation on Task 1 performance under conditions of SNARC-based compatibility relations between R2 and R1. In particular, we found that activating a number-related response primed the processing of spatial information in Experiment 1, and activating a spatial response primed the processing of number-related information in Experiment 2. However, one should note that in Experiments 1 and 2, the relationship between S1 and R1 was always compatible. On the one hand, that made Task 1 relatively easy so that performing it before Task 2, as instructed, was manageable for the participants. On the other hand, one could argue that it confounded the data in the sense that the presence of a spatial code in S1 (arrows) may have constituted an additional R2–S1 overlap. As a result, the question remains whether the effect on Task 1 is located on the stimulus or the response side because it has been shown repeatedly that actions can influence perception. For instance, Müsseler and Hommel (1997) have demonstrated that preparing a left–right key press can have specific effects on the identification of response-compatible stimuli, and Hommel (1998) found strong evidence for the priming of stimulus-related processes in Task 1 by response-related processes in Task 2. Given the dissimilar task stimuli in Experiments 1 and 2, the source of the effect on Task 1 seems undoubtedly related to Task 2 response processing (R2). However, under the above considerations, the target of the Task 2 influence might be located at the time of stimulus or response processing (S1 vs. R1). Therefore, although it seems clear that SNARC-based BWC effects are produced by response-related processes for Task 2, it is equally important to see whether they can and do affect response-related processes for Task 1.

To test for effects of pure R2–R1 interactions, we reduced the amount of spatial overlap between S1 and R2 by replacing the S1 arrow stimuli from Experiment 1 with the letters *H* and *S*. According to Dehaene et al. (1993, Experiment 4), letters of the alphabet do not exhibit the spatial associations that have been found for numbers in the SNARC effect. Under that assumption, replacing the arrows with letters would eliminate the R2–S1 overlap. However, in a recent study, Gevers et al. (2003) found reliable SNARC effects for letters of the alphabet, though the effect was reduced sharply under circumstances in which alphabetic order was irrelevant for the task. Because that was also the case for the present study, we expected the SNARC-based relationship between S1 and R2 to be considerably smaller in Experiment 3. Therefore, on the one hand, if R2 and S1 overlap was the main source of the observed BWC effect, then we expected that effect to be strongly reduced in Experiment 3 compared with Experiment 1. On the other hand, if comparable BWC effects occurred under those conditions, then that could demonstrate a direct impact of R2 activation on R1 and could make a strong case for localizing the SNARC-based BWC effect at R2–R1 overlap.

Method

Sixteen adults (8 women, 8 men; age range: 22–31 years) who fulfilled the same criteria as those in Experiment 1 were paid to participate. The method was the same as that in Experiment 1, except that Task 1 required a left–right key press to the letter *H* or *S*, which appeared in the center of the screen.

Results

Premature responses, response omissions, and reversals accounted for less than 0.01% of the trials. We used the same method as that outlined in the Results section of Experiment 1 to analyze the remaining data. See Table 2 for group means.

Task 1

The RTs were faster with R2–R1 compatibility than with incompatibility, $F(1, 15) = 9.31$, $MSE = 149$, whereas the error rates yielded no effect, $F < 1$. There was again no indication of a role of response grouping in the IRI analysis (297, 336, 383, 447, and 734 ms for compatible trials; 310, 353, 401, 465, and 700 ms for incompatible trials). However, as in Experiment 1, the compatibility effect increased with increasing RT in Task 1, $F(4, 60) = 5.54$, $MSE = 705$. Here, the mean quintiles were comparable with Experiment 1 and amounted to 401, 445, 493, 574, and 846 ms for compatible responses; and 402, 451, 507, 591, and 903 ms for incompatible responses.

Task 2

Compatibility yielded a significant effect in RTs, $F(1, 15) = 6.08$, $MSE = 1{,}193$, and in error rates, $F(1, 15) = 7.35$, $MSE = 1.7000$, which indicated faster responses and fewer errors in the compatible condition than in the incompatible condition.

Discussion

In contrast to Experiment 1, Experiment 3 did not include direct SNARC-based spatial compatibility between S1 and R2. Although some degree of overlap between R2 and S1 might still have existed, the amount of overlap should have been strongly reduced (Gevers et al., 2003). Nevertheless, the size of the BWC effect was virtually identical: 13 ms in Experiment 3 and 12 ms in Experiment 1. Because all other design features were exactly the same in both experiments, there is no reason to believe that R2–S1 interactions contributed to the effect in Experiments 1 and 3. In other words, the SNARC-based BWC effects in Experiments 1 and 3 are likely to have arisen exclusively from R2–R1 interactions.

GENERAL DISCUSSION

The three experiments of our study produced more or less identical results, namely, backward priming of primary-task responses through the presumably concurrent activation of SNARC-compatible secondary-task responses. Those findings have at least three important implications, two in regard to the main objectives of our study and a third in regard to the cognitive representation of actions.

First, the presence of BWC effects in all three experiments provided additional evidence for Hommel's (1998) claim of automatic, concurrent S–R translation in dual tasks. Backward priming has been demonstrated with spatial compatibility between R2 and R1 (Hommel; Lien & Proctor, 2000; Logan & Delheimer, 2001; Logan & Gordon, 2001; Logan & Schulkind, 2000), color-related compatibility between R2 and S1 (Hommel; Hommel & Eglau, 2002), and, in the present study, with SNARC-type compatibility between R2 and R1. The results in the aforementioned studies show that backward-compatibility effects under dual-task conditions are a fairly common phenomenon, suggesting that automatic S–R translation occurs under a wide variety of circumstances. What is more, the present findings represent an important extension of the previous observations in showing that even task-irrelevant response features can produce backward priming, such as the spatial codes that were obviously associated with the number-related R2 in Experiments 1 and 3. Also, from the present study, it seems that BWC effects appear only in a limited time window. On the one hand, research results have shown that BWC effects tend to disappear with longer SOA (Hommel), which is why we used an intermediate SOA of only 75 ms in the present study. On the other hand, our data seemed to suggest that some time is needed before BWC effects can be found. Together, we think that those characteristics of the BWC effect support the interpretation that BWC effects originate from parallel processing of response-related information under dual-task conditions. Some time is needed to go from Task 2 stimulus information to response information, and the longer Task 1 takes, the more time there is for that information to influence RT1. However, at some point, Task 1 responses will be executed, so that no additional influence from Task 2 activations is possible. Further research is needed to confirm that time course for the BWC effect.

Second, our findings strongly support the hypothesis of Dehaene et al. (1993) that magnitude information is automatically activated through number processing, and that magnitude codes are associated with spatial left–right codes. Although magnitude was of no relevance to the task, and even though only responses and not stimuli were related to numbers in Experiments 1 and 3, the presence of the observed BWC effects was based on the assumption that number-related processing activated spatial information. Such a finding also means that identical representations are used to code for magnitude on the basis of perception and action, which fits nicely with the results of Whalen, Gallistel, and Gelman (1999). They observed that the number of key presses for a given magnitude was subject to distance and size effects, just as for perceiving numerical stimuli. Also, our findings provide strong evidence for a response-based locus of SNARC effects. In Experiments 1 and 2, the performance in Task 1 could be affected only through SNARC-type compatibility with R2 but not S2, and in Experiment 3, only R1 could be affected by that kind of compatibility. Moreover, the BWC effect was the same size in Experiments 1 and 3, which indicated that SNARC-type compatibility between R2 and R1 was responsible. That is, SNARC effects are a result of number-related processing and the associated coding of magnitude leading to the activation of spatial codes that directly affect the selection of spatial responses. Converging support for a response-related account of SNARC effects is provided by a study of Fischer (2003). He found that when participants made left or right pointing responses to the parity status of a centrally presented number, SNARC compatibility determined movement times but not reaction times. That finding seems to suggest that the spatial codes activated in number processing are used in motor planning or even execution (see also Fischer, Castel, Dodd, & Pratt, 2003, for further evidence). Of course, that should not be taken to exclude any impact of the spatial codes on stimulus processing. However, whether stimulus processes can or cannot also be affected, it seems clear that SNARC effects are produced mainly by interactions between automatically activated number- or magnitude-associated spatial codes and spatially defined responses.

Finally, the observation of backward priming by task-irrelevant response features allows for some interesting conclusions as to how actions are cognitively represented and selected. In principle, S–R translation could be conceived of as triggering a condition-action rule, as suggested by, among others, Allport (1980), Anderson (1982), or Fagot and Pashler (1992). As such, registering some prespecified stimulus feature or its meaning would directly activate a particular motor program and the response is carried out. However, if that were so, why should activating the motor program for uttering one, for example, prime a left-hand key press? Obviously, then, planning an action is comprised of more, and certainly more cognitive work than merely triggering a motor program. As proposed by Hommel's (1996, 1997) action–concept model, actions may be represented cognitively by integrated networks of codes of the effects they produce. Accordingly, planning the utterance one involves the activation of codes of that action's effect. Of course, the effect of saying one is hearing "one," which means that planning the utterance is mediated by selecting a verbal code that also represents the number 1. Yet, one assumes that verbal number codes automatically activate magnitude representations as do visual numbers (Dehaene et al., 1993), which suggests that planning to say one leads to the activation of magnitude and spatial codes in the same way as the presentation of the digit 1 on a screen.

In summary, the processing of number-related information for judgments (as in the studies of Dehaene et al., 1993, and Fias et al., 1996) or action planning (as in the present study) leads to the automatic coding of magnitude, which again primes associated spatial responses. However, more research is needed to determine where those associations come from and how they are acquired.

REFERENCES

Allport, D. A. (1980). Patterns and actions: Cognitive mechanisms are content specific. In G. Claxton (Ed.), *Cognitive Psychology* (pp. 26–63). London: Routledge.

Anderson, J. R. (1982). Acquisition of cognitive skill. *Psychological Review, 89,* 369–406.

Bächtold, D., Baumüller, M., & Brugger, P. (1998). Stimulus–response compatibility in representational space. *Neuropsychologia, 36,* 731–735.

Brysbaert, M., Bovens, N., d'Ydewalle, G., & Van Calster, A. (1989). Turbo Pascal timing routines for the IBM microcomputer family. *Behavior Research Methods, Instruments and Computers, 21,* 73–81.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General, 122,* 371–396.

Fagot, C., & Pashler, H. (1992). Making two responses to a single object: Implications for the central attentional bottleneck. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 1058–1079.

Fias, W., Brysbaert, M., Geypens, F., & d'Ydewalle, G. (1996). The importance of magnitude information in numerical processing: Evidence from the SNARC effect. *Mathematical Cognition, 2,* 95–110.

Fischer, M. (2003). Spatial representations in number processing: Evidence from a pointing task. *Visual Cognition, 10,* 493–508.

Fischer, M. H., Castel, A. D., Dodd, M. D., & Pratt, J. (2003). Perceiving numbers causes spatial shifts of attention. *Nature Neuroscience, 6,* 555–556.

Gevers, W., Reynvoet, B., & Fias, W. (2003). The mental representations of ordinal sequences are spatially organised. *Cognition, 87,* B87–B95.

Hommel, B. (1996). The cognitive representation of action: Automatic integration of perceived action effects. *Psychological Research, 59,* 176–186.

Hommel, B. (1997). Toward an action–concept model of stimulus–response compatibility. In B. Hommel & W. Prinz (Eds.), *Theoretical issues in stimulus–response compatibility* (pp. 333–360). Amsterdam: North-Holland.

Hommel, B. (1998). Automatic stimulus–response translation in dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 1368–1384.

Hommel, B. (2000). The prepared reflex: Automaticity and control in stimulus–response translation. In S. Monsell & J. Driver (Eds.), *Control of cognitive processes: XVIII. Attention and performance* (pp. 247–273). Cambridge, MA: MIT Press.

Hommel, B., & Eglau, B. (2002). Control of stimulus–response translation in dual-task performance. *Psychological Research, 66,* 260–273.

Lien, M.-C., & Proctor, R. W. (2000). Multiple spatial correspondence effects on dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 1260–1280.

Logan, G. D., & Delheimer, J. A. (2001). Parallel memory retrieval in dual-task situations: II. Episodic memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27,* 668–685.

Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review, 108,* 393–434.

Logan, G. D., & Schulkind, M. D. (2000). Parallel memory retrieval in dual-task situations: I. Semantic memory. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 1072–1090.

Meyer, D. E., & Kieras, D. E. (1997). A computational theory of executive cognitive processes and multiple-task performance: I. Basic mechanisms. *Psychological Review, 104,* 3–65.

Müsseler, J., & Hommel, B. (1997). Blindness to response-compatible stimuli. *Journal of Experimental Psychology: Human Perception and Performance, 23,* 861–872.

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin, 116,* 220–244.

Reynvoet, B., & Brysbaert, M. (1999). Single-digit and two-digit Arabic numerals address the same semantic number line. *Cognition, 72,* 191–201.

Welford, A. T. (1952). The “psychological refractory period” and the timing of high-speed performance: A review and a theory. *British Journal of Psychology, 43,* 2–19.

Whalen, J., Gallistel, C. R., & Gelman, R. (1999). Nonverbal counting in humans: The psychophysics of number representation. *Psychological Science, 10*(2), 130–137.

Manuscript submitted April 2003
Revision accepted for publication July 2003