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Repetition and the SNARC Effect With One- and Two-Digit Numbers

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The SNARC (Spatial Numerical Association of Response Codes) effect is the finding that small numbers elicit faster left than right responses and large numbers elicit faster right than left responses. This effect suggests that numbers activate left-right magnitude-laterality codes and that these codes interact with the selection of left-right responses. In the present research, subjects made parity decisions for one-digit numbers (in Experiment 1) and two-digit numbers (in Experiment 2), and we examined the effect of stimulus repetition on the SNARC effect. With single-digit stimuli, responses were faster and the SNARC effect was eliminated when stimuli were identical on successive trials. With two-digit stimuli, responses were faster when the ones digit was repeated, but the SNARC effect was found regardless of whether the digit was repeated or not. We argue that magnitude-laterality codes are activated in the process of accessing number information in memory and that this process can be short circuited if the visual stimulus matches that on the previous trial. Thus, no SNARC effect is found in Experiment 1 when identical stimuli are presented on successive trials. However, this result is not found in Experiment 2 because successive stimuli do not match even if the ones digit is repeated.

Keywords: SNARC effect, repetition effect

In the present research, we examined the activation of left-right spatial information in the processing of one- and two-digit numbers. Dehaene, Bossini, and Giraux (1993) observed that small numbers yielded faster left than right responses and larger numbers yielded faster right than left responses in a parity judgment task. They labeled this phenomenon the Spatial Numerical Association of Response Codes (SNARC) effect. Dehaene and his colleagues explained the SNARC effect by assuming that digit magnitude was represented in an analog fashion along a mental number line, with small numbers on the left and large numbers on the right. Although some researchers have disputed the notion that an analog representation underlies this effect (e.g., Santens & Gevers, 2008), it seems clear that numerical stimuli can activate what might be termed left-right "magnitude-laterality codes" in which "left" is associated with small digits and "right" with large digits. A critical question is the circumstances under which such representations are generated and how they influence response processes. In the present research, we assessed whether the SNARC effect would be observed when stimuli are repeated from trial to trial, both with one-digit and two-digit numbers. Repeating stimuli has been theorized to short circuit some of the processing needed to produce a response (e.g., Pashler & Baylis, 1991), and no SNARC effect would be expected if the skipped stages are necessary for that effect.

Previous research suggests that there are two components to the SNARC effect. On one hand, Fischer, Castel, Dodd, and Pratt (2003) found that merely presenting numbers could direct attention to spatial locations in a manner consistent with the SNARC effect. In their task, a digit was presented at fixation, and, after a delay, a detection target was presented randomly to either the left or the right. In keeping with a positional, left-to-right association with magnitude, responses to targets on the left were faster when preceded by a small digit and responses to targets on the right were faster when preceded by a larger digit. Related results were obtained by Nicholls, Loftus, and Gevers (2008) using an unspeeded perceptual discrimination task. These results suggest that left-right laterality codes are activated upon presentation of digits and can serve to direct attention under some circumstances.

Other research implies that the activation of such laterality codes can have effects on response selection as well. Keus and Schwarz (2005) presented digits in a parity judgment task to either the left or the right visual field. In keeping with previous research, they observed a Simon effect (Simon & Wolf, 1963; Simon, 1969) in which stimuli in the left visual field produced faster left-hand responses and stimuli in the right visual field produce faster right-hand responses. However, this pattern also interacted with the SNARC effect: The SNARC effect was larger when the side of the stimulus presentation was incongruent with the required response. Because the Simon effect is often attributed to the process of response selection (e.g., Lu & Proctor, 1995; Mapelli, Rusconi, & Umlita, 2003), Keus and Schwarz used additive-factors logic to infer that the SNARC effect must also be related to response-selection processes.

A similar conclusion was reached by Müller and Schwarz (2007). They used a parity-judgment task as either the first or the second task in a psychological refractory period (PRP) paradigm. Results from this paradigm are often interpreted in term of a processing bottleneck in the stage of response selection (e.g., Pashler, 1994). In such an account, when one stimulus follows the other at short SOAs, the response selection for the second task must wait until the response selection for the first task is com-

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pleted. When the parity task was the first task in the experiments of Müller and Schwarz, the relationship between stimulus magnitude and response hand in the first task also affected the time to respond to the second task. According to the logic of a bottleneck model, this suggests that the SNARC effect was localized at or prior to the response selection stage. In addition, when the parity task was the second task, the SNARC effect was additive with the effect of SOA; this, in turn, suggests the SNARC effect was localized at or after response selection. Together, these conclusions imply that the SNARC effect occurred as a result of interference in the process of selecting a response.

Based on this prior research, we propose the following outline of how the SNARC effect may arise in speeded parity judgments. We suggest that in making such a judgment, there are stages of visual encoding, memory access, parity retrieval, and response selection. These stages are depicted in the top panel of Figure 1. In stimulus encoding, a visual representation of the stimulus is constructed. This representation is then used to access the store of information in memory concerning the number, including, for example, a verbal label for the stimulus. In order to classify the stimulus as odd or even, parity information must then be retrieved for the digit. After classifying the stimulus as odd or even, subjects would use the task stimulus-response mapping to select and then execute a manual response. In this analysis, there are two components to the SNARC effect. During memory access, magnitude information is activated along with associated laterality information. Thus, a code for "left" or "right" is activated automatically when number information is accessed in memory. Second, this laterality code can interact with the selection of the left- or right-hand response. For example, the stimulus "8" would automatically generate a laterality code of "right," which would interfere with the selection of a left-hand response but facilitate the selection of a right-hand response. This interaction is depicted in the figure.

The account depicted in Figure 1 is broadly consistent with Gevers, Verguts, Reynvoet, Cassens, and Fias's (2006) dual-route model of the SNARC effect. Their model does not include stages of visual encoding and memory access but rather begins with a presumed "mental number" line consisting of a set of "number units." In a parity judgment task, these units in turn activate magnitude units and parity units in parallel. Both sets of units then provide input to response activation units. The SNARC effect is predicted because the "small" magnitude unit tends to activate a left-hand response and the "large" unit tends to activate a right-hand response. This may either facilitate or interfere with the activation of the correct response based on the parity units. The activation of the number units serves the role of our memory access stage in Figure 1 in that it provides access to information about the stimulus magnitude and parity. Similarly, the magnitude units are equivalent to our concept of magnitude-laterality codes because they activate left- or right-hand responses in the response-selection layer. Finally, the activation of the parity units in the Gevers et al. model is equivalent to the parity-retrieval stage of processing hypothesized in Figure 1. In both our description of the processing and in the Gevers et al. model, there is parallel input to the process of response selection from both magnitude information and parity information, and the interaction of these two sources of information produces the SNARC effect.

In order to further explore our account, we examined the SNARC effect with repeated responses. Responses to repeated stimuli are generally faster than responses to different stimuli (Bertelson, 1965; Rabbitt, 1968; Smith, 1968). Pashler and Baylis (1991), among others, proposed a "shortcut" hypothesis to explain this advantage of repeating stimuli: On each trial, a "transient link"

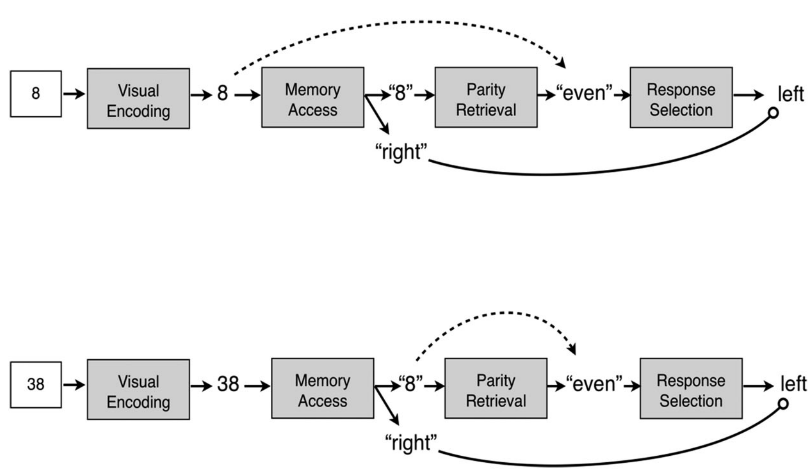

Figure 1. Possible processing pathways producing a SNARC effect in Experiment 1 (top) and Experiment 2 (bottom). After visual encoding, memory access produces a variety of information about the stimulus, including a verbal label ("8" in this example) and an associated laterality ("right"). Subsequently, the parity of the stimulus must be retrieved ("even") and a response selected based on the current stimulus-response mapping. However, the laterality code activated during memory access may interfere with the selection of the correct response, as illustrated here by the inhibitory connection between "right" and the response, "left." The dotted lines represent processing shortcuts. In Experiment 1, parity information from the previous trial can be used if the visual encoding of the current stimulus matches that from the previous trial, allowing memory access and parity retrieval to be skipped. In Experiment 2, parity retrieval can be skipped when the verbal label for the ones digit matches that on the previous trial.

is created that allows some stage or stages of processing to be skipped. Our interpretation of the transient-link mechanism is that representations generated on the previous trial are maintained in working memory. Then, if a representation of the current stimulus matches the corresponding representation from the previous trial, a subsequent representation from the previous trial can be used on the current trial without performing the intervening processing. Dehaene (1996) found evidence for Pashler and Baylis' (1991) shortcut hypothesis in the context of a magnitude comparison task. In one experiment, they presented the numbers 1, 4, 6, or 9 as either digits or words and requested subjects to decide whether the stimulus was less than or greater than five. Consistent with previous work, Dehaene found a distance effect, in which magnitude judgment times decreased as the difference in magnitude between the presented number and the comparison number increased. However, there was no evidence of distance effects for repeated stimuli. Dehaene argued that repetition effects resulted from a shortcut in which the magnitude comparison stage was skipped with repeated stimuli.

In contrast to the results of Dehaene (1996), Schwarz and Ischebeck (2000) found additive effects of repetition and numerical distance in a very similar experiment. Subjects performed magnitude comparison as before, but the stimuli consisted of the numbers 2, 3, 4, 6, 7, and 8, again presented as either digits or words. The additive effects of repetition and distance in their data suggest that magnitude comparison was not skipped. It is not clear why Schwarz and Ischebeck obtained different results in their study. However, one possibility is that the somewhat more restricted range of the stimuli (2–8 rather than 1–9) and greater stimulus uncertainty (6 stimuli rather than 4) made magnitude comparison more difficult and less likely to be short circuited. Based on their results, Schwarz and Ischebeck argued that the locus of the repetition effect was prior to magnitude comparison, during the initial encoding of the stimulus.

In the present research, we used the repetition effect as a tool for understanding the nature of the SNARC effect. In Experiment 1, subjects made parity judgments of single-digit numbers, and in Experiment 2, subjects made parity judgments of two-digit numbers. In both cases, we assessed whether the SNARC effect would be additive with the repetition effect or whether it would diminish or disappear when the stimuli were repeated. If the SNARC effect is eliminated with repeated stimuli, it would suggest that a stage of processing involved in the SNARC effect was skipped.

Experiment 1

In Experiment 1, we examined the effects of stimulus and response repetition on the SNARC effect with single-digit numbers. In order to disentangle effects of repeating the stimuli from that of repeating the responses, we considered the results from three conditions: In the same-stimulus condition, the current stimulus was identical to the stimulus presented on the preceding trial. In the same-response condition, stimuli presented on successive trials were different. However, the stimuli were either both odd or both even and required the same response. In the different-response condition, the required responses on successive trials were different. Under many circumstances, such a manipulation demonstrates that the effect of repeating the response is small relative to the effect of repeating the stimulus (e.g., Pashler & Baylis, 1991). The critical result concerned the magnitude of the SNARC effect in each of these repetition conditions.

In addition to the interaction of the SNARC effect and repetition, we also considered two other effects that have been found in parity judgment. Hines (1990) found that responses were faster when both digits were even than when they were both odd. A similar advantage for even digits was observed when subjects decided whether presented digits in a number pair were both even or both odd. We refer to this effect as the parity effect. Hines interpreted this difference as an effect of linguistic markedness. Often, adjectives come in pairs consisting of an unmarked form and a derived, marked form, and "odd"-"even" may comprise such a pair, with "even" being the unmarked form. Presumably, the parity effect occurs because the simpler, unmarked representation of "even" is retrieved more readily. The second effect is a hand-response effect in which right-hand responses are faster for "even" responses and left-hand responses are faster for "odd" responses. Nuerk, Iverson, and Willmes (2004) also argued that this effect is related to markedness. In particular, they hypothesized that the labels "left" and "right" comprised a marked and unmarked pair like "odd" and "even" and that responses are faster when the markedness for the parity of the stimulus matches that for the response. Interactions of both of these effects with the repetition effect should provide additional constraints on the nature of processing.

Method

Subjects. Twenty undergraduates from the University of Alberta participated in the experiment in partial fulfillment of a course requirement. All subjects reported themselves to be right-handed, and this was verified by noting the hand used to sign the consent form.

Apparatus and stimuli. The stimuli used for the experiment were the digits 1–9, excluding the digit 5. Stimuli were presented on a 37-cm LCD computer monitor with a resolution of 1024 × 768 and a refresh rate of 75 Hz. Stimuli were presented centrally in bold 30-point Arial font. At a typical viewing distance of 60 cm, the stimuli subtended approximately 2.5° of visual angle vertically. Responses were collected on a USB computer keyboard.

Procedure. On each trial, a randomly chosen stimulus was presented on the screen until the subject made a response. Subjects indicated whether each digit was odd or even by pressing either the "a" key on the computer keyboard with their left index finger or the "l" key with their right index finger. Subjects were instructed to respond as quickly and accurately as possible. There was a blank interval of 500 ms before the next trial.

Each subject took part in two stimulus-response mapping conditions. In one condition, subjects made "even" responses with their left index finger and "odd" responses with their right index finger. The mapping was reversed in the other condition. The order of the two conditions was balanced across subjects. Each condition consisted of a block of 20 practice trials followed by two blocks of 250 experimental trials. There was a short rest after each experimental block, lasting until the subject indicated that he or she was ready to proceed by pressing the space bar.

Except for the first trial in a block, the stimulus on each trial was identical to that of the previous trial (same-stimulus condition), a different stimulus that required the same response as that on the previous trial (same-response condition), or a stimulus that required a different response from the previous trial (different-response condition). Because the stimuli were selected randomly from among eight possibilities, the a priori probability of these three conditions was .125, .375, and .5. The actual distribution of presented trials is indicated in Table 2.

Analysis. Data from one subject whose error rate exceeded 10% was excluded from the analysis. Further, due to a programming error, stimuli in one of the experimental blocks with the odd-left/even-right stimulus-response mapping were not selected randomly. This block was omitted from the analysis. The average error rate for the remaining trials was 5.1% across all subjects. Only correct trials preceded by correct trials were included in the response-time analysis. As a result, 10.0% of the trials were excluded from the analysis. For each subject, we calculated the median response time for each repetition relation, stimulus, and stimulus-response mapping. This created a dataset that was balanced with respect to repetition condition (same stimulus, same response, and difference response) even though the number of trials in these conditions varied.

In order to assess the evidence for different interpretations of results, nested linear models were compared using likelihood ratios. The likelihood ratio indicates how likely the data are given the best fit of one model relative to how likely the data are given the best fit of the other model. The likelihood given the best fit of a model is related to the inverse of the variance that is not explained by that model (cf. Dixon & O'Reilly, 1999). Thus, the ratio of two likelihoods provides an intuitive index of how much better one model fits the data than the other.

Following the suggestion of Glover and Dixon (2004), the likelihood ratio was adjusted for the differing degrees of freedom in the two models based on the Akaike Information Criterion or AIC (Akaike, 1973); we will refer to this statistic as λ_{adj}. The adjusted likelihood ratio thus incorporates both relative precision of the model fits (in terms of relative likelihood) and parsimony (in terms of the relative degrees of freedom). Selecting a model based on the adjusted likelihood ratio is equivalent to comparing models in terms of AIC values, a common approach to model comparison. Moreover, this approach provides an intuitive index of the evidence for different interpretations of the results without the well-known problems with null-hypothesis significance testing. However, by way of comparison, a statistically significant result in some prototypical hypothesis testing situations would correspond to an adjusted likelihood ratio of about 3. (Our calculations of adjusted likelihood ratios was based on the AIC values returned for the model fits; however, Glover and Dixon describe how they can be easily derived from traditional analysis of variance tables.)

In our analyses, the SNARC effect was measured as the linear component of the interaction between magnitude and response hand. Evidence for the SNARC effect is sometimes assessed by calculating, for each subject, the slope of the line relating the difference between left- and right-hand responses to stimulus magnitude, and then using this statistic as a dependent variable (e.g., Fias, 2001). However, this approach is statistically interchangeable with the examination of the linear trend in the context of a linear model, as was done here. We also used contrasts to assess two other effects: The parity effect was calculated as the difference between "odd" responses and "even" responses, and the hand-response effect was the difference between the effect of hand (i.e., left vs. right) for even and odd stimuli.

Linear mixed-effects analysis was used to fit the models using the program lmer in the R package lme4 (Bates, Maechler, & Dai, 2008; R Development Core Team, 2008). In mixed-effects analysis, the structure of the random effects must be specified explicitly. Exploratory analyses indicated that good fits were obtained if each subject was assumed to have an independent and random mean response time, repetition effect, SNARC effect, and hand-response effect. All of the models compared used this random-effects structure and varied only in the fixed effects. We used mixed-effects analysis because we believe it provides a more modern and robust approach to analyzing repeated measures designs. However, the present results would be similar if repeated-measures analysis of variance were used. As indicated previously, the analyses were performed using the subject medians in each condition, and the number of trials that contributed to each median differed for the repeated-stimulus, repeated-response, and different-response conditions. Because medians based on smaller samples are less stable, this approach leads to a nonspherical distribution of variance. To assess whether this aspect of our analysis might distort the evidence for different patterns of results, we conducted a series of Monte Carlo simulations with an exact analog of the present design and analysis. The results of these simulations indicated that there was no tendency for our approach to produce artifactual evidence for differences across repetition conditions.

Accuracy data was analyzed similarly but using generalized linear mixed-effects analysis using a binomial link function (Faraway, 2006; Dixon, 2008), an approach tantamount to logistic regression. However, because of the small number of errors, trials were collapsed over small digits (1–4) and large digits (6–9).

Results

As shown in Table 1, there was an advantage for the same-stimulus condition but little difference between the same-response and different-response conditions. Figure 2 shows the SNARC effect, graphed as the difference between left- and right-hand responses as a function of digit magnitude. The general increase in this difference reflects the advantage for right-hand responses for large numbers and the advantage of left-hand responses for small numbers. However, it is also apparent from Figure 2 that the interaction between response hand and magnitude was not purely a linear function of magnitude. In particular, a hand-response effect was observed in which "even" responses were relatively fast with the right hand, and "odd" responses were relatively fast with the left hand, leading to the saw-tooth pattern evident in the figure. The critical result in Figure 3 shows a comparison of the magnitudes for the SNARC effect across repetition-relation conditions. As can be seen, there was a SNARC effect in the different-response and the same-response conditions but virtually no such effect in the same-stimulus condition. Figure 4 shows a comparison of the hand-response effect across the repetition-relation conditions. Unlike the SNARC effect, there was little tendency for the effect to decrease with repeated stimuli. Finally, Figure 5 shows the magnitude of the parity effect across repetition conditions. There was no difference between odd and even responses in the same-stimulus condition. However, when successive stimuli differed, the direction of the effect varied with the response: Repeated responses showed an advantage for even digits, while different response showed a smaller advantage for odd digits.

Table 1
Response Time (and Standard Error) in ms in Experiment 1[a]

Stimulus	Same stimulus Left hand	Same stimulus Right hand	Same response Left hand	Same response Right hand	Different response Left hand	Different response Right hand
1	402 (12)	420 (12)	472 (11)	523 (11)	476 (11)	518 (11)
2	423 (11)	422 (11)	517 (11)	493 (11)	523 (11)	522 (11)
3	431 (11)	443 (11)	520 (11)	519 (11)	504 (11)	527 (11)
4	440 (11)	423 (11)	494 (11)	489 (11)	521 (11)	518 (11)
6	437 (11)	420 (11)	526 (11)	475 (11)	541 (11)	533 (11)
7	406 (12)	405 (11)	503 (11)	495 (11)	515 (11)	494 (11)
8	417 (11)	396 (11)	506 (11)	460 (11)	530 (11)	495 (11)
9	428 (12)	442 (12)	576 (11)	534 (11)	552 (11)	527 (11)
	422 (6)		506 (4)		519 (5)	

[a] Standard errors are derived from the standard errors of the parameter estimates in a fit of a full model, exclusive of the standard error of intercept.

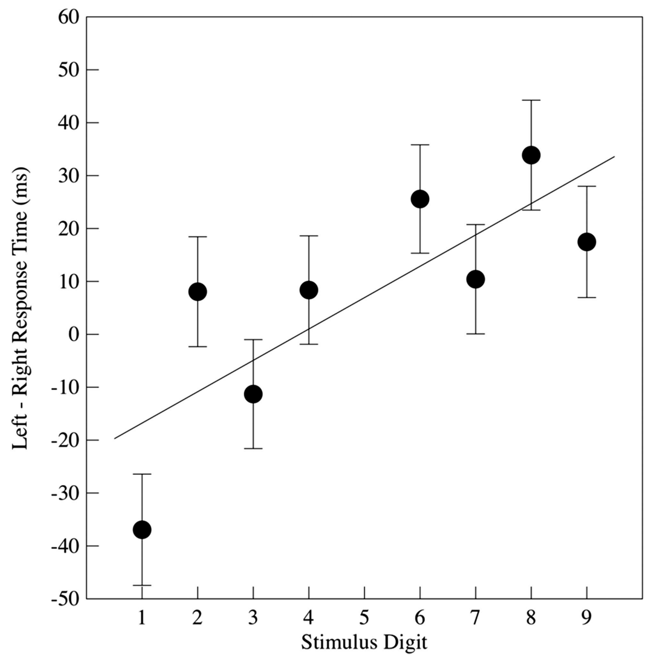

Figure 2. The SNARC effect expressed as the difference between left- and right-hand responses as a function of stimulus magnitude in Experiment 1. Error bars represent standard errors of the corresponding parameter estimates in a full model.

To assess the evidence for this pattern of results, we began with a base model that included stimulus and hand as fixed effects, as well as the random subject effects. Increasingly more complex models were assessed by adding additional fixed effects and then comparing the new model to the simpler one using the adjusted likelihood ratio; the magnitude of the likelihood ratio provides an index of the evidence for those additional fixed effects. We first considered evidence for a repetition effect. The repetition effect was captured by two orthogonal contrasts: The first contrast indexed the stimulus repetition effect by comparing same-stimulus trials to the average of same-response and different-response trials (i.e., those trials on which the stimulus differed from the previous trial). The second contrast indexed the response repetition effect by comparing same-response trials (with nonrepeated stimuli) to different-response trials. Adding the contrast for the stimulus repetition effect produced a much better model ($\lambda_{adj} > 1{,}000$). However, adding the effect for response repetition lead to only a slight improvement ($\lambda_{adj} = 1.26$).

Second, we considered evidence for the SNARC effect. As described previously, the SNARC effect was measured as the slope of the line relating the left-right hand to stimulus magnitude as depicted in Figure 2. This slope is equivalent to the interaction of response hand with the linear trend across stimulus magnitude. Adding the contrast for the overall SNARC effect led to a substantially better model ($\lambda_{adj} = 702.74$). However, the model was improved further if the contrast was limited to different-stimulus trials by replacing the contrast coefficients for same-stimulus trials with zero ($\lambda_{adj} = 33.27$). In other words, the superior fit of this model provides evidence for an interaction in which the SNARC effect occurs in the same-response and different-response conditions but not in the same-stimulus condition. We also assessed whether there was any evidence for more general variation in the magnitude of the SNARC effect across repetition conditions. This was done by including separate SNARC contrasts for each repetition condition (i.e., repeated stimulus, repeated response, and different response). The new model was worse than the model that simply limited the SNARC to the different-stimulus conditions ($\lambda_{adj} = 0.20$). Together, these comparisons provide good evidence that there was a SNARC effect on different-stimulus trials but none on same-stimulus trials.

Third, we considered evidence for the hand-response effect. A contrast for this effect consisted of the difference between the hand effect (i.e., the difference between left- and right-hand responses) for even stimuli and odd stimuli. Adding this contrast led to an

Table 2
Proportion Correct (and Standard Error) and N in Experiment 1[a]

Stimulus	Same stimulus Left hand	Same stimulus Right hand	Same response Left hand	Same response Right hand	Different response Left hand	Different response Right hand
Small	.989 (.004) 542	.985 (.005) 517	.945 (.007) 1691	.960 (.006) 1643	.947 (.007) 2189	.959 (.006) 2131
Large	.992 (.004) 538	.981 (.006) 546	.961 (.006) 1722	.930 (.009) 1654	.965 (.005) 2116	.943 (.008) 2171
	.987 (.002) 2143		.951 (.004) 6710		.954 (.005) 8607	

[a] Standard errors were derived from the standard errors of the parameter estimates in a fit of a full model, exclusive of the standard error of the intercept.

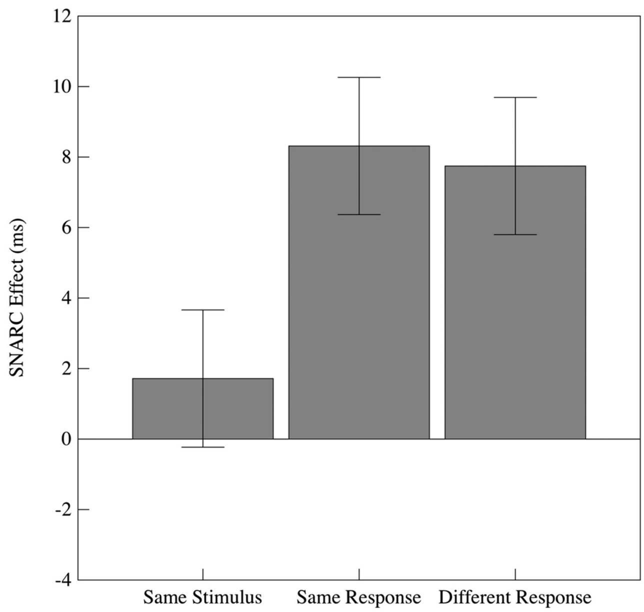

Figure 3. The SNARC effect as a function of repetition condition in Experiment 1. The SNARC effect was calculated as the slope of the function relating the difference between left- and right-hand responses to the stimulus magnitude. Error bars represent standard errors of the corresponding parameter estimates in a full model.

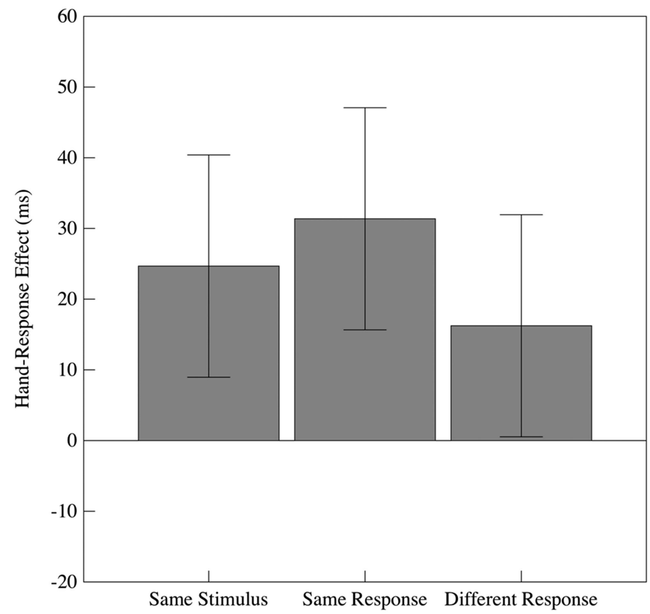

Figure 4. The hand-response effect as a function of repetition condition in Experiment 1. The hand-response effect was calculated as the difference between left- and right-hand responses for even stimuli less the difference between left- and right-hand responses for odd stimuli. Error bars represent standard errors of the corresponding parameter estimates in a full model.

improved model (λ_{adj} = 8.05). However, there was no evidence that this effect varied across repetition condition: When separate contrasts were added for the repeated-stimulus condition, repeated-response condition, and different-response condition, the new model was worse (λ_{adj} = 0.24).

Fourth, we assessed evidence for the interaction of parity and repetition condition. We included in our original base model a factor stimulus; thus, the overall parity effect was already included in our model. However, adding the interaction between parity and repetition condition improved the model substantially (λ_{adj} > 1000).

Finally, we asked whether there was any evidence for other components of the interaction between hand and stimulus (shown in Figure 2) besides the SNARC effect and the hand-response effect. A model that included all 7 degrees of freedom of this interaction was worse than a model that incorporated only the SNARC effect and the hand-response effect (λ_{adj} = 0.03). Thus, these two effects appeared to provide an adequate account of the interaction between hand and stimulus.

Table 2 shows the proportion correct for the three repetition conditions and eight stimuli. Accuracy generally mirrored the response time effects: Accuracy was higher for repeated stimuli, and the difference between left- and right-hand responses increased with stimulus magnitude (i.e., there was a SNARC effect for accuracy). Similar to the response times, the SNARC effect was not apparent for repeated stimuli.

Nested (generalized) linear models were compared to assess the evidence for this pattern of results. As before, we began with a base model that included fixed effects of response hand and stimulus magnitude. Adding an effect for repeated stimuli improved the model substantially (λ_{adj} > 1000), but there was little evidence that adding a simple effect of repeated responses with different stimuli improved the model (λ_{adj} = 0.50). Because we collapsed over small and large digits, the SNARC effect corresponded to a 2 × 2 interaction between response

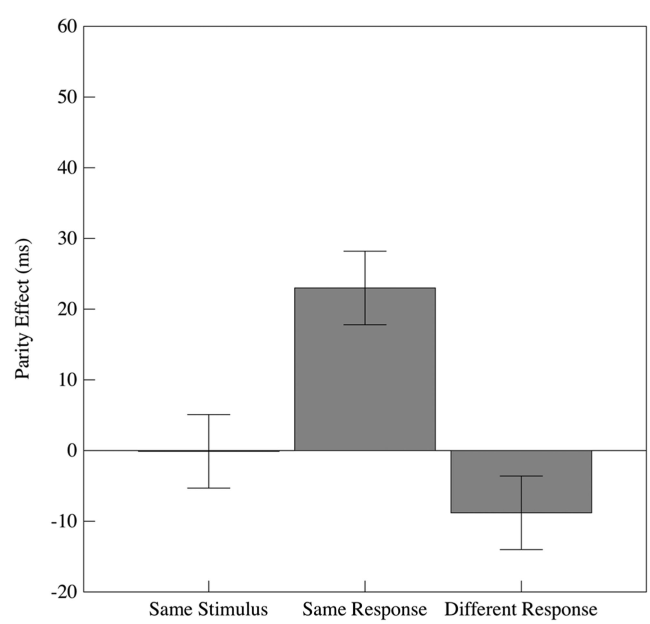

Figure 5. The parity effect as a function of repetition condition in Experiment 1. The parity effect was the difference between responses to "odd" stimuli and "even" stimuli. Error bars represent standard errors of the corresponding parameter estimates in a full model.

hand and large versus small; adding this interaction for the nonrepeating stimuli also improved the model substantially ($\lambda_{adj} > 40.60$). However, extending the SNARC effect to all repetition conditions did not improve the model appreciably ($\lambda_{adj} = 1.17$).

Discussion

The critical result from Experiment 1 was that when the present stimulus was identical to the previous stimulus, there was no evidence of a SNARC effect. Our interpretation of this result is that with repeated stimuli, a stage of processing necessary for the SNARC effect was short circuited. In particular, we hypothesize that when the same stimulus is presented on successive trials, the stages of memory access and parity retrieval is not needed to select a response. As depicted in the top panel of Figure 1, subjects may be able to detect a match between the visual encoding of the current stimulus and that from the previous trial. When this occurs, they can use the associated parity classification from the previous trial in order to select a response. In this analysis, because the memory access is short circuited, there is less of a tendency to activate the magnitude-laterality codes and little potential interference in the selection of a response.

Although the most natural interpretation of the shortcut hypothesis is that the stage of memory access is simply omitted with repeated stimuli, there are good reasons to doubt that this is the case. In particular, there are a variety of situations in which information concerning magnitude would seem to be activated even though there is no logical requirement for accessing digit information in memory. For example, in an experiment by Fias, Lauweryns, and Lammertyn (2001), a SNARC effect was observed when subjects were required to judge the orientation of a line that was superimposed on a number. Similarly, when subjects are asked to judge the physical size of digit stimuli, responses are faster when the numerical magnitude is compatible (e.g., Henik & Tzelgov, 1982). Such results imply that memorial information concerning the magnitude of the presented stimuli must have been accessed even though subjects could easily have accomplished the task without accessing such information. Effects of numerical magnitude are not always found. For example, Fias (2001) failed to find a SNARC effect in a phoneme monitoring task, and Fias et al. (2001) failed to find such an effect when subjects judged the color of a digit. Nevertheless, it seems clear that memory access occurs automatically under at least some circumstances. In the present context, we conjecture that memory access takes place even with repeated stimuli.

For these reasons, our interpretation of the shortcut hypothesis is that all of the potential processing pathways operate concurrently but with different time courses. The top panel of Figure 1 depicts three pathways: a parity pathway that involves retrieving parity information and using this information to select a response, a magnitude pathway that tends to activate either a left- or right-hand response based on the magnitude of the stimulus, and a shortcut pathway that entails using the representations from the preceding trial to select a response based on the parity of the preceding stimulus. With nonrepeated stimuli, both the magnitude pathway and the parity pathway would tend to activate a response. In this case, interference would occur if the two tendencies conflict, and facilitation would occur if they are consistent. This interaction leads to the observed SNARC effect with nonrepeated stimuli. With repeated stimuli, though, the shortcut pathway would also operate. Moreover, because the shortcut omits several time-consuming operations, it would generally be able to activate a response before any potential interference from the magnitude pathway. In other words, with repeated stimuli, the shortcut pathway wins a race to activate a response, and no SNARC effect is observed. This general architecture is consistent with results showing that the SNARC effect is generally larger in slower tasks (Wood, Willmes, Nuerk, & Fischer, 2008).

The pattern of results for the hand-response effect suggests that the response selection stage is not short circuited with repeated stimuli. In this effect, left-hand responses were faster to even numbers and right-hand responses were faster to odd numbers. Nuerk, Iverson, and Willmes (2004) hypothesized that odd-even and left-right comprised marked/unmarked adjective pairs, with “even” and “right” being the unmarked forms. According to this analysis, the hand-response effect arises because responses are faster when the verbal labels for the stimulus (“odd” or “even”) match that for the response (“left” or “right”) in terms of markedness. It seems reasonable to suppose that this interaction between stimulus and response labels occurs in the process of selecting a response. For example, Proctor and Cho (2006) attributed correspondence effects of this general sort to an accrual mechanism in response selection. However, if the locus of the hand-response effect is in response selection, the failure to find an interaction with repetition implies that response selection must still take place with repeated stimuli. Thus, the results suggest that the stages of memory access and parity retrieval are skipped in the shortcut pathway, but not response selection. Rather, the parity representation of the previous stimulus is retained and this parity representation is used to select a response.

This analysis is consistent with the results for the parity effect shown in Figure 5. Although Hines (1990) argued that the parity effect was due to markedness, we prefer an alternative interpretation: When subjects consider the parity of two digits, both digits having the same parity would prime the retrieval of “even” while having two digits of different parity would prime “odd.” This would explain why, for example, Hines found a robust parity effect when judgments were made of pairs of digits and a minimal effect with single digits. Similarly, it provides an account for interaction with previous response shown in Figure 5. In the repeated-response condition, subjects make either an “even” response followed by another “even” response, or an “odd” response followed by another “odd” response. By hypothesis, this repeated parity would prime the retrieval of “even,” leading to the observed positive parity effect (calculated as odd minus even). In contrast, in the different-response condition, subjects encounter either odd followed by even or even followed by odd. In either case, the sequence would prime the retrieval of “odd,” leading to the observed negative parity effect (i.e., an advantage for “odd” digits). Regardless of the merits of this interpretation, though, the failure to find a parity effect of any form in the repeated-stimulus condition is consistent with the view that this stage is short circuited and does not contribute to most responses.

Experiment 2

In Experiment 2, we extended our analysis of the interaction of repetition and the SNARC effect by examining these effects with two-digit numbers. The tens digit in a two-digit number is irrelevant to a parity judgment, and in principle, subjects could perform the task just as they did with single-digit stimuli. In keeping with that expectation, Dehaene et al. (1993) found a SNARC effect for the ones digit when subjects were asked to judge the parity of two-digit numbers. However, a variety of other results indicate that the tens digit affects performance. For example, Dehaene et al. found as well that parity judgments were slower when the ones and tens digit differed in parity, even though the tens digit was technically irrelevant to the task. We refer to this as a parity-congruity effect. Indeed, asking subjects to respond to the parity of two-digit numbers is tantamount to asking them to respond to a target when it is flanked by an irrelevant distractor. In other words, it is a version of the well-studied flanker task (e.g., Eriksen & Eriksen, 1974). In the flanker task, just as in the parity task with two-digit numbers, the flanking stimuli interfere with responses to the central target when they are associated with the alternative response and facilitate responses when they are associated with the same response. Nuerk, Bauer, Krummenacher, Heller, and Willmes (2005) demonstrated a similar interference effect of flanking digits on magnitude comparison. Thus, it seems likely that the tens digit is processed when making parity judgments of the ones digit.

If subjects process the (irrelevant) tens digit when making parity judgments, it would alter our characterization of the process (as summarized in Figure 1). In particular, the visual encoding stage would produce a representation of both digits, not simply a representation of the (relevant) ones digit. As a consequence, the visual representation of the stimulus would typically differ from that generated on the previous trial, even if the ones digit were the same. In turn, this means that the visual representation could not be used as the basis of a shortcut as it was in Experiment 1. Instead, subjects would have to access memory using the entire two-digit stimulus, and only subsequently focus on the ones digit to find information about parity. As shown in the lower panel of Figure 1, we hypothesize that a shortcut would be available after memory access: Based on a match of the retrieved label of the ones digit, they may be able to short circuit the retrieval of parity information. This would presumably lead to a response time advantage for trials with a repeated ones digit. However, magnitude-laterality codes would already have been activated at this point, and the speedup in response time may not be sufficient to avoid interference during response selection. Thus, according to this analysis, an advantage may be found for repeating the ones digit, but a SNARC effect would still be predicted.

Method

Subjects. Twenty-eight undergraduates from the University of Alberta (who did not participate in Experiment 1) participated in Experiment 2. All subjects were paid an honorarium of $10. All subjects were right-handed; this was verified by noting the hand used to sign the consent form.

Procedure. The apparatus, methods, and instructions generally were identical to Experiment 1. However, the stimuli used for the experiment were the two-digit numbers, apart from those that contained the digit 5 and those in which the tens digit was identical to the ones digit. Each subject participated in two conditions that varied in terms of the stimulus-response mapping, and each condition consisted of 64 practice trials followed by two blocks of 256 test trials in which each digit appeared as the ones digit 32 times in a random order. The tens digit was selected randomly on each trial, with the constraint that the tens digit and the ones digit were not identical and that the resulting two-digit stimulus differed from that presented on the previous trial. Because the ones digit was selected randomly (as in Experiment 1), the probability of stimuli in the same-stimulus, same-response, and different-response conditions was 1/8, 3/8, and 1/2 as in Experiment 1. The actual distribution of trials across conditions is shown in Table 4.

Analysis. Three subjects had error rates greater than 10%, and their data were excluded from the analysis. The average error percentage for the remaining subjects was 4.0%. Only correct trials preceded by correct trials were included in the analysis, requiring 7.8% of the trials to be excluded. For each subject, the median response time for each ones digit, repetition condition, parity congruity, and response was calculated, leading to a balanced dataset as in Experiment 1.

The same model-comparison approach as in Experiment 1 was used. However, in Experiment 2, “same stimulus” refers to the repetition of the ones digit, rather than a repetition of the entire presented display. Exploratory analyses indicated that good fits were obtained with the same random effects structure as in Experiment 1: Each subject was assumed to have an independent and random mean response time, repetition effect, SNARC effect, and hand-response effect.

Accuracy data was analyzed similarly but using generalized linear mixed-effects analysis using a binomial link function (as in Experiment 1). However, because of the small number of errors, magnitude, hand, and their interaction was collapsed into a single variable of magnitude-hand compatibility, with left-hand responses to small digits being compatible, right-hand responses to small digits being incompatible, and the reverse for large digits.

Results

As shown in Table 3, responses were substantially faster when the ones digit was repeated than when they were different, but the advantage for repeating responses when the ones digits were different was smaller. Figure 6 shows the difference in response times between left and right hand as a function the magnitude of the ones digit. There was an overall increase in the difference with the magnitude of the ones digit, replicating the SNARC effect found in Experiment 1. However, there was little evidence of the hand-response effect that was found previously (i.e., the “saw-tooth” pattern from Figure 2). We have no simple explanation for why this effect did not occur with two-digit stimuli. However, Nuerk at al. (2004) suggested that this effect was associated with verbal labels for the digits, and it is possible that such labels are less strongly activated with two-digit numbers.

Figure 7 shows the magnitude of the SNARC effect across the three repetition-relation conditions. In contrast to the results of Experiment 1, the SNARC effect in the repeated-stimulus condition was just as large as that in the other two conditions. Figure 8 shows the parity-congruity effect as a function of the repetition relation. Overall, subjects responded faster if the tens and ones

Table 3
Response Time (and Standard Error) in ms in Experiment 2[a]

		Same stimulus		Same response		Different response	
Ones digit	Tens digit	Left hand	Right hand	Left hand	Right hand	Left hand	Right hand
1	Congruent	463 (18)	479 (19)	531 (18)	526 (18)	523 (18)	537 (18)
2	Congruent	499 (18)	585 (19)	521 (18)	524 (18)	554 (17)	551 (17)
3	Congruent	525 (18)	494 (18)	561 (18)	549 (18)	552 (17)	566 (17)
4	Congruent	447 (19)	480 (18)	521 (18)	516 (18)	562 (17)	540 (17)
6	Congruent	519 (18)	493 (18)	543 (18)	514 (18)	581 (17)	566 (17)
7	Congruent	533 (18)	471 (18)	531 (18)	533 (18)	565 (17)	538 (17)
8	Congruent	519 (18)	462 (18)	561 (18)	510 (18)	563 (17)	544 (17)
9	Congruent	570 (18)	507 (19)	582 (18)	549 (18)	591 (18)	557 (18)
1	Incongruent	570 (19)	493 (18)	542 (18)	558 (18)	543 (18)	555 (18)
2	Incongruent	519 (19)	519 (18)	546 (18)	520 (18)	566 (17)	591 (17)
3	Incongruent	512 (18)	527 (18)	593 (18)	588 (18)	573 (17)	559 (17)
4	Incongruent	485 (18)	472 (19)	539 (18)	518 (18)	586 (17)	560 (17)
6	Incongruent	540 (18)	498 (18)	557 (18)	521 (18)	585 (17)	579 (17)
7	Incongruent	562 (18)	466 (18)	589 (18)	543 (18)	559 (17)	539 (17)
8	Incongruent	515 (18)	493 (18)	587 (18)	521 (18)	610 (17)	555 (17)
9	Incongruent	529 (18)	503 (19)	600 (18)	565 (18)	600 (18)	566 (18)
		508 (6)		546 (4)		563 (4)	

[a] Standard errors derived from the standard errors of the parameter estimates in a fit of a full model, exclusive of the standard error of intercept.

digit shared the same parity, and there was no clear variation in this effect across repetition relation. Finally, Figure 9 shows the parity effect as a function of repetition condition. The pattern was similar to that in Experiment 1: There a positive parity effect for same-response trials a trend for a negative parity effect for different-response trials. As before, there was a minimal effect of parity in the same-stimulus condition.

In order to quantify the evidence for this interpretation, nested models were fit to the results as in Experiment 1. As before, our initial model contained main effects of the ones digit and hand, as well as the random subject effects. First, we considered evidence for the repetition effect. Adding the effect of stimulus repetition improved the model substantially ($\lambda_{adj} > 1000$), but adding an effect of response repetition (for nonrepeated stimuli) provided a somewhat smaller further improvement ($\lambda_{adj} = 49.16$).

Second, we considered evidence for the SNARC effect. Adding an overall SNARC effect provided a substantial improvement ($\lambda_{adj} > 1000$). However, unlike the results in Experiment 1, constraining the SNARC effect to different-stimulus trials led to a worse model, ($\lambda_{adj} = 0.004$), as did adding a SNARC contrast for each repetition condition ($\lambda_{adj} = 0.19$). In other words, there was good evidence for a SNARC effect when the ones digits was repeated, and evidence against the interaction between the SNARC effect and stimulus repetition observed in Experiment 1. We also assessed whether there was evidence for any other components of the hand × stimulus interaction depicted in Figure 5. A model that included all 7 degrees of freedom for this interaction was worse than one that included merely the SNARC effect ($\lambda_{adj} = 0.102$. Adding the remaining degrees of freedom for the hand × stimulus interaction failed to improve the model ($\lambda_{adj} = 0.02$).

Third, we considered evidence for the parity-congruity effect. Our model of best fit so far included fixed effects of hand and stimulus, an effect of repeated stimulus and an overall SNARC effect. Adding the parity-congruity effect led to a substantially superior model ($\lambda_{adj} > 1000$). Constraining this effect to the different-stimulus conditions did not improve the model ($\lambda_{adj} = 0.50$), and neither did adding separate parity-congruity contrasts for each of the repetition conditions ($\lambda_{adj} = 0.26$). In sum, there was evidence for a stimulus repetition effect, a SNARC effect, and a parity-congruity effect; however, the stimulus-repetition effect did not interact with either the SNARC or the parity-congruity effect.

Table 4
Proportion Correct (and Standard Error) and N in Experiment 2[a]

Hand-magnitude	Tens digit	Same stimulus		Same response		Different response	
Compatible	Congruent	.992 (.003)	695	.978 (.003)	2702	.979 (.003)	3661
Incompatible	Congruent	.981 (.005)	832	.958 (.005)	2739	.966 (.004)	3707
Compatible	Incongruent	.993 (.003)	753	.956 (.005)	2712	.966 (.004)	3655
Incompatible	Incongruent	.983 (.005)	764	.946 (.006)	2738	.958 (.005)	712
		.989 (.002)	3044	.961 (.003)	10891	.968 (.003)	14737

[a] Standard errors were derived from the standard errors of the parameter estimates in a fit of a full model, exclusive of the standard error of the intercept.

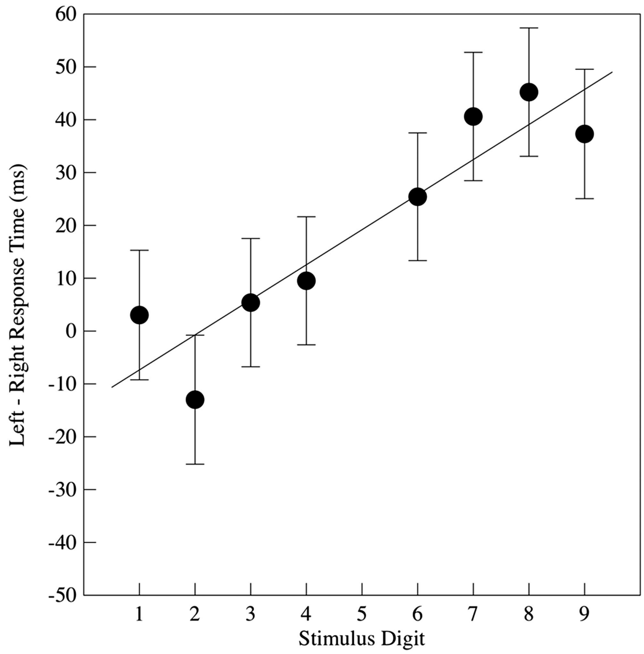

Figure 6. The SNARC effect expressed as the difference between left- and right-hand responses as a function of ones-digit magnitude in Experiment 2. Error bars represent standard errors of the corresponding parameter estimates in a full model.

Fourth, we considered evidence for the interaction of parity and repetition condition shown in Figure 9. Adding this interaction led to a substantially better model ($\lambda_{adj} > 1000$).

Finally, we also assessed the evidence that the pattern of interaction between the repetition and SNARC effects varied across experiments. To do so, we calculated the magnitude of the SNARC effect in each repetition condition for each subject in Experiments 1 and 2. We then compared two models of these data: In the first, the SNARC effect was assumed to be the same in all three repetition conditions in both experiments; in the second, the SNARC effect in Experiment 1 was assumed to be limited to the repeated response and nonrepeated-response conditions. The latter model was substantially better ($\lambda_{adj} = 63.88$). Further, constraining the SNARC effect to these repetition conditions in both experiments led to a substantially inferior model ($\lambda_{adj} < 0.0001$). Thus, the results provide strong evidence that the pattern of interactions differs across experiments.

Table 4 shows the proportion correct as a function of the compatibility between response hand and magnitude, parity congruity, and repetition relation. Generally, accuracy mirrored response time: Accuracy was higher for repeated stimuli, for responses that are compatible with the magnitude of the ones digit (i.e., the SNARC effect), and for stimuli in which the ones and tens digits matched in parity (i.e., the parity congruity effect). Nested linear models were fit to assess the evidence for this interpretation. A model that included the effect of repeated stimuli was substantially better than the null model ($\lambda_{adj} > 1000$), and adding the effect of repeating responses improved the model somewhat further ($\lambda_{adj} = 4.04$). Adding the SNARC effect improved the model ($\lambda_{adj} = 219.87$), and the model with an overall SNARC effect was better than one in which the effect was constrained to different-stimulus conditions ($\lambda_{adj} = 9.67$). Adding the effect of parity congruity improved the model ($\lambda_{adj} > 1000$), and there was weak evidence that the effect was limited to the different-stimulus conditions ($\lambda_{adj} = 2.92$).

Discussion

There were two critical aspects of the results of Experiment 2: First, repeating the ones digit led to a decrease in response time, even though the entire visual stimulus was not identical to that on the previous trial. Second, a SNARC effect was found in Experiment 2 for both repeated and nonrepeated stimuli, in contrast to the results of Experiment 1. We discuss our interpretation of these two results in turn.

We hypothesize that the repetition effect found in Experiment 2 was due to short circuited processing, just as in Experiment 1. However, the fact that the two-digit stimulus differed from that on the previous trial, even when the ones digit was the same, implies that the visual representation would not match the representation from the previous trial, and, as a consequence, the memory access stage could not be short circuited. Rather, subjects must analyze the visual representation, focus on the representation of the ones digit, and use this to access memory. Having done so, though, subjects would arrive at a representation that could form the basis of a shortcut. If the ones digit is the same as that on the previous trial, the verbal label for the digit retrieved during memory access would match that from the previous trial. At this point, subjects could use that representation to skip the retrieval of parity information and instead reuse the representation of

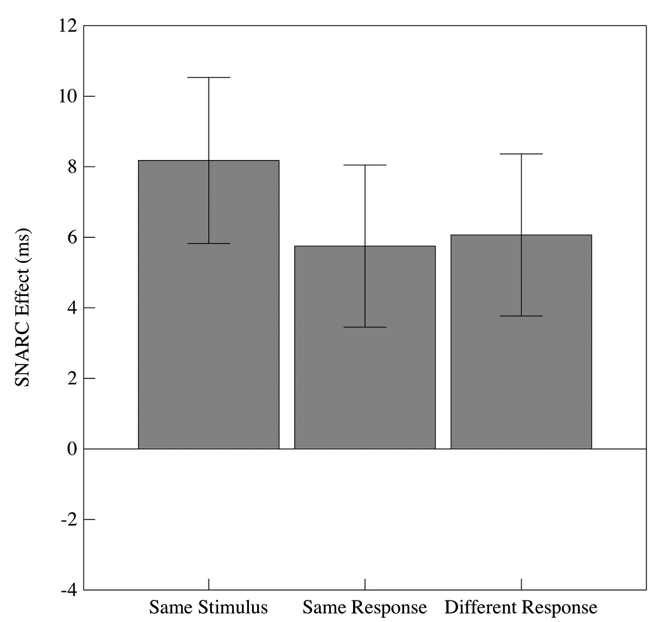

Figure 7. The SNARC effect as a function of repetition condition in Experiment 2. The SNARC effect was calculated as the slope of the function relating the difference between left- and right-hand responses to the ones-digit magnitude. Error bars represent standard errors of the corresponding parameter estimates in a full model.

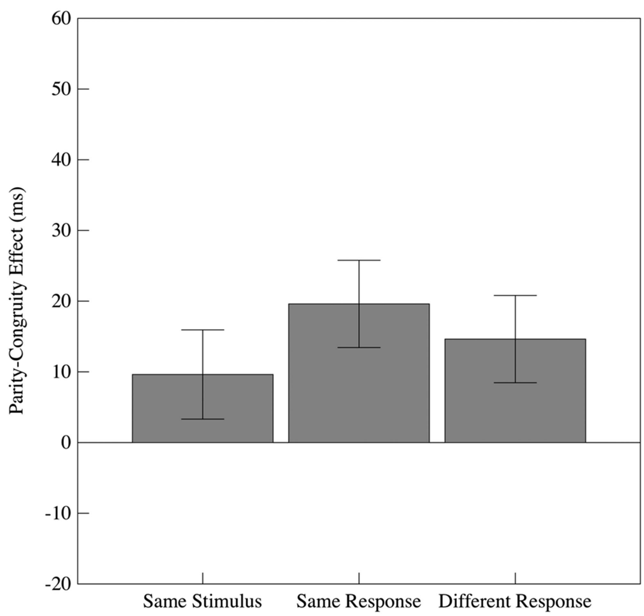

Figure 8. The parity-congruity effect as a function of repetition condition in Experiment 2. The parity congruity effect was the difference in response time for incongruent stimuli (i.e., odd tens digit and even ones digit or even tens digit and odd ones digit) and congruent stimuli (i.e., both digits were even or both were odd). Error bars represent standard errors of the corresponding parameter estimates in a full model.

parity from the previous trial. This scenario is depicted in the lower panel of Figure 1.

Although this short circuit is not as substantial as the one hypothesized to operate in Experiment 1, it may be sufficient to produce an attenuated decrease in response time. Indeed, the magnitude of the repetition effect was substantially smaller in Experiment 2 (47 ms, $SE = 9$ ms) than it was in Experiment 1 (85 ms, $SE = 8$ms). Moreover, because the shortcut occurs after a magnitude-laterality code for the stimulus is activated, the speedup in response time was apparently insufficient to forestall interference during response selection. We argue that, as a consequence, a SNARC effect was observed for both repeated and nonrepeated digits.

We also observed a parity congruity effect, consistent with previous research on parity judgments of two-digit numbers (e.g., Dehaene et al., 1993). This interaction between the ones and tens digit implies that subjects did not simply filter the tens digit at a peripheral level and that at least some processing of the tens digit was performed. We noted that the structure of the stimuli is similar to that used in the flanker task in which responses have to be made to one item in the presence of another item that was also associated with a response. A common account of the interference in the flanker task is that both the target and the distractors tend to activate responses in parallel and that incompatible responses inhibit one another (e.g., Eriksen & Schultz, 1979; Nuerk et al., 2005). Consistent with this analysis, our interpretation of the parity-congruity effect is that both of the stimulus digits tend to evoke a parity response and that selecting the correct response to the ones digit is more difficult when these two tendencies conflict.

Finally, the pattern of parity effects shown in Figure 9 is similar to that observed in Figure 5, as is our interpretation. In particular, we assume that repeating parity primes the retrieval of "even," while changing parity primes the retrieval of "odd." Moreover, the fact that parity appears to have little effect on response time in the same-stimulus condition suggests that parity retrieval is short circuited in this condition, just as we assumed in Experiment 1.

General Discussion

The results of the two experiments together provide important constraints on the nature of the SNARC effect. In Experiment 1, using one-digit numbers, a SNARC effect was only found with nonrepeated stimuli. However, in Experiment 2, using two-digit numbers, the SNARC effect was found both when the ones digit was repeated and when it was not, even though repeating the ones digit lead to savings in response time. We first discuss our analysis of the repetition effect; subsequently, we describe how that effect moderates the SNARC effect. Finally, we comment on the more general implications of these results for the representation of number.

A repetition effect was found in both experiments in which identical stimuli on successive trials led to faster response times. Our interpretation of this effect follows from that of Pashler and Baylis (1991) and Smith, Chase, and Smith (1973), and others who have suggested that repeated stimuli allow some aspects of processing to be curtailed. For example, Pashler and Baylis argued that a transient link was formed that allowed some stage to be short circuited; Smith et al. suggested that a representation of previous stimuli was maintained in short-term memory and tagged with the appropriate response. One characterization of such a shortcut mechanism is that an association is formed among processing

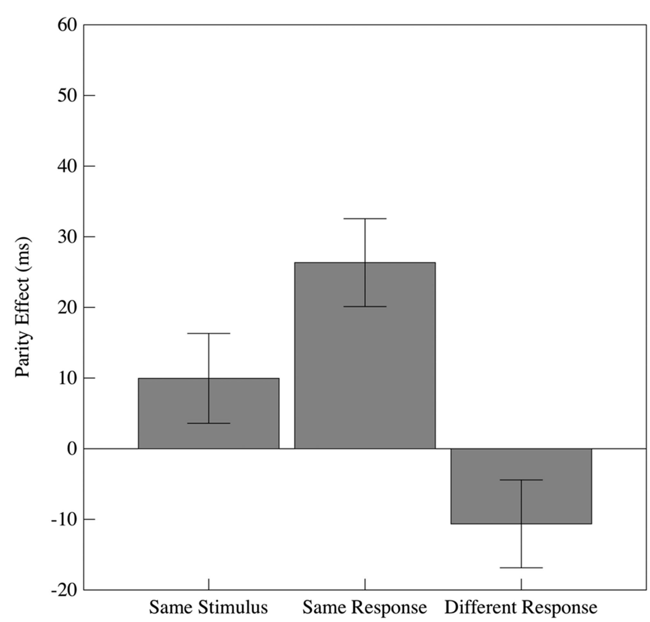

Figure 9. The parity effect as a function of repetition condition in Experiment 2. The parity effect was the difference between responses to "odd" stimuli and "even" stimuli. Error bars represent standard errors of the corresponding parameter estimates in a full model.

representations generated on a trial and maintained in working memory. Consequently, if processing on the following trial generates a representation that matches one from the preceding trial, the working memory association can be used to eliminate a subsequent stage of processing. Generally, this matching process will take less time than the processing it replaces, and a repetition effect will ensue.

Our analysis of the SNARC effect is that it must involve two components. As a rough characterization of the processing in parity judgments, we argue that subjects must encode the stimulus, access information associated with the digit in memory, retrieve information about parity, use stimulus-response mapping information in working memory to select a response, and then execute that response. The first component of the SNARC effect, we argue, is the spontaneous activation of magnitude-laterality codes during the process of memory access. In other words, small digits produce an activation of the concept “left” and large numbers produce an activation of “right.” The second component of the SNARC effect is the subsequent interaction of these codes with the response. In particular, the activated laterality code interferes with the process of selecting a left or right response if they are incompatible. Our interpretation of the present results is that the effect of magnitude-laterality codes on response selection is much less likely to occur when the memory access stage can be short circuited and a response selected on the basis of parity information from the previous trial. Although memory access may still proceed automatically in this case, the activation of the magnitude-laterality codes may be too late to affect the response appreciably. Thus, in Experiment 1, no SNARC effect is found with repeated stimuli. In contrast, in Experiment 2, the visual stimulus is not identical to that on the preceding trial, and consequently there is no basis for short circuiting the memory access stage. With a repeated ones digit, subjects may be able to short circuit the retrieval of parity information, and this would lead to a response time advantage. However, because this shortcut is smaller and occurs after the activation of magnitude-laterality codes, a SNARC effect is still observed.

This characterization of the parallel processing paths is consistent with the recent results of Cohen (2009). He presented subjects with digits and asked them to determine whether the presented number was 5. In this task, it would be possible to select a response based simply on visual encoding, and a processing pathway would be possible akin to the short-circuit pathway in the top panel of Figure 1. Consistent with this interpretation, response times were a function of the physical similarity between the presented number and “5” and are unrelated to their numerical distance between the stimulus and the standard. Cohen argued that his results undermine the view that numerical magnitude is automatically retrieved when a number is presented. However, it is also possible, as suggested by Figure 1, that magnitude information is retrieved in parallel but that the processing sequence is too brief to observe effects any effects. Thus, we argue that Cohen’s results provide additional support for the architecture of numerical processing we have outlined here.

We have made two critical assumptions about the processing of number in interpreting our results. First, we assumed that magnitude-laterality codes are activated in the course of accessing number information in memory. Second, we assumed that memory access will, under many circumstances, take place automatically, much as the reading of a word is automatic in the Stroop task (but see, e.g., Risko, Stolz, & Besner, 2005). According to these assumptions, a SNARC effect may or may not occur depending on the time course of the task-relevant processing. If memory access is not required to produce a task response, any effect of magnitude-laterality codes must race with that task-relevant processing in order to have an effect on response selection. In Experiment 1, for example, we argue that with repeated stimuli, response selection will generally occur before magnitude-laterality codes can exert any influence. In other situations, a SNARC effect may be found if the required judgment takes more time. In contrast, if memory access is required to produce a task response, magnitude-laterality codes will already have been activated before any further processing is required. As a consequence, even if the subsequent processing is relatively rapid, some effect on response selection may be found. This situation corresponds to the pattern of results found in Experiment 2.

A central assumption in our interpretation of the pattern of results is that the activation of the magnitude-laterality codes is distinct from the locus of the SNARC interference effect. In particular, we argue that the interference occurs during response selection and that this stage of processing is not skipped with repeated stimuli. The conclusion that the SNARC effect involves interference during response selection is suggested by a variety of results. For example, Müller and Schwarz (2007) found that the SNARC effect was additive with the effect of stimulus onset asynchrony in a psychological refractory period paradigm, a pattern that is often associated with effects on response selection (e.g., Pashler, 1994). Similarly, Keus and Schwarz (2005) found an interaction between the SNARC effect and the Simon effect, commonly attributed to the response selection processes (e.g., Lu & Proctor, 1995). At the same time, other results suggest that the mere presentation of numbers can serve to direct attention to the left or right. Fisher et al. (2003) found that presenting a digit as a cue served to direct attention to the left and right, independent of the nature of the response that had to be made. Similarly, Nicholls et al. (2008) found an interaction of laterality and stimulus magnitude in a perceptual judgment task that did not require speeded responses at all. Thus, it seems reasonable to suppose that there is both an early, spontaneous activation component to the SNARC effect, as well as a central, interference component.

Throughout this paper, we have used the term “magnitude-laterality” representations without commitment to the nature of that representation. It is often assumed that this representation is inherently spatial or even analog (e.g., Dehaene et al., 1990). The spatial character of this representation is supported by the finding that spatial working memory load modulates the SNARC effect (Herrara, Macizo, & Semenza, 2008). Similarly, visual neglect patients who exhibit a rightward bias in bisecting physical lines also show a corresponding bias in selecting midpoints of numerical ranges (Rossetti, Jacquin-Courtois, Rode, Michel, & Boisson, 2004). In contrast, Santens and Gevers (2008) asked subjects to make close/far judgments of digits relative to a standard and found no evidence for an effect of whether the response movement was close or far. Thus, they concluded that the SNARC effect depends on the activation of abstract spatial codes for left and right rather than a direct correspondence with a notional number line (see also Notebaert, Gevers, Verguts, & Fias, 2006). In a related proposal, Proctor and Cho (2006) argued that stimuli and responses are marked in terms of polarity and that the SNARC effect arises because left responses and small numbers share negative polarity and right responses and large numbers share positive polarity. The present results do not bear on this issue but are rather directed to the question of when and how such representations are activated. In particular, the present results demonstrate that magnitude-laterality codes, whatever their nature, are generated in the course of accessing number information in memory.

Résumé

L'effet SNARC (*Spatial Numerical Association of Response Codes*) repose sur l'observation selon laquelle les petits nombres mènent à des réponses plus rapides à gauche qu'à droite et les grands nombres génèrent des réponses plus rapides à droite qu'à gauche. Cet effet suggère que les nombres activent des codes latéralisés en fonction de leur magnitude et que ceux-ci interagissent avec la sélection de la réponse gauche-droite. Dans la présente recherche, les participants jugeaient de l'égalité de nombres à un chiffre (Expérience 1) et à deux chiffres (Expérience 2), et nous avons examiné l'effet de la répétition du stimulus sur l'effet SNARC. Avec les stimuli à un chiffre, les réponses étaient plus rapides et l'effet SNARC était éliminé lorsque deux stimuli identiques étaient présentés lors de deux essais successifs. Avec les stimuli à deux chiffres, les réponses étaient plus rapides lorsque le chiffre des unités était répété mais l'effet SNARC était observé peu importe que le chiffre soit répété ou non. Nous avançons que les codes magnitude-latéralité sont activés lors du processus d'accès à l'information du nombre en mémoire et que ce processus peut être court-circuité si le stimulus visuel correspond à celui de l'essai précédent. Ainsi, l'effet SNARC n'est pas observé dans l'Expérience 1 lorsque des stimuli identiques sont présentés lors d'essais successifs. Cependant, ce résultat n'est pas observé dans l'Expérience 2 car les stimuli successifs ne correspondent pas même si le chiffre des unités est répété.

Mots-clés : effet SNARC, effet de répétition

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