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BRIEF REPORT

The SNARC effect is not a unitary phenomenon

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Abstract

Models of the spatial–numerical association of response codes (SNARC) effect—faster responses to small numbers using left effectors, and the converse for large numbers—diverge substantially in localizing the root cause of this effect along the numbers' processing chain. One class of models ascribes the cause of the SNARC effect to the inherently spatial nature of the semantic representation of numerical magnitude. A different class of models ascribes the effect's cause to the processing dynamics taking place during response selection. To disentangle these opposing views, we devised a paradigm combining magnitude comparison and stimulus–response switching in order to monitor modulations of the SNARC effect while concurrently tapping both semantic and response-related processing stages. We observed that the SNARC effect varied nonlinearly as a function of both manipulated factors, a result that can hardly be reconciled with a unitary cause of the SNARC effect.

Keywords SNARC effect · Stimulus–response mapping · Numerical distance effect · Magnitude comparison · Spatial–numerical associations

The spatial–numerical association of response codes (SNARC) effect—faster responses to small numbers using left than right effectors and the converse for large numbers—is probably the most robust and easily replicable evidence of spatial–numerical associations (Cutini, Scarpa, Scatturin, Dell'Acqua, & Zorzi, 2014; Fischer & Shaki, 2014), suggesting that the semantic representation of number magnitude has an intrinsically analogical/spatial nature. According to the dominant view, numbers are coded along a rightward linear vector—the mental number line (Dehaene, Bossini, & Giraux, 1993)—on which small numbers occupy the more leftward positions and large numbers the more rightward positions. This view has been challenged by recent findings hinting at the possibility that the SNARC effect may originate at the level of response selection, owing, for instance, to long-term memory associations between left/right responses with the concepts of small/large (Fias, van Dijck, & Gevers, 2011).

The vast majority of behavioral studies seeking to disentangle these opposing views (extensively reviewed in Fischer & Shaki, 2014; Hubbard, Piazza, Pinel, & Dehaene, 2005; Wood, Nuerk, Willmes, & Fischer, 2008) have relied on the additive-factor logic (Sternberg, 1969) to design paradigms in which the SNARC effect was studied while manipulating semantic or response-related factors. Mapelli, Rusconi, and Umiltà (2003), for instance, employed a speeded manual parity judgment task and displayed digits to the left or right of fixation, in order to also elicit a Simon effect, which is commonly ascribed to processing occurring during response selection (e.g., De Jong, 1994). Both SNARC and Simon effects were observed in this study. The effects were additive, however, leading the authors to conclude that the source of the SNARC effect was functionally independent from response selection. Daar and Pratt (2008) came to opposite conclusions by using a free-choice paradigm and instructing participants to make a left or right keypress when a centrally presented number turned from white to green. Their participants produced more left keypresses in response to digits smaller than 5 and more right keypresses to digits larger than 5, a result that was taken to reflect a direct link between number magnitude and response selection.

Over and above the inconsistency of results and interpretations among these studies, the functional localization of the

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source of the SNARC effect is still controversial (Cipora & Nuerk, 2013; Di Rosa et al., 2017; Ford & Reynolds, 2016; Gibson & Maurer, 2016; Zohar-Shai, Tzelgov, Karni, & Rubinsten, 2017). One possible criticism encompassing the entire class of this type of behavioral reports is related to the structure of the designs employed to date. To our knowledge, there is in fact no documented case in which the SNARC effect has been examined in empirical contexts in which factors tapping both semantic and response-related processing stages have concurrently been manipulated in a single design to assess the presence of multiple origins of the SNARC effect. Crucially, a paradigm that enables to concomitantly monitor additive and interactive combinations of the SNARC effect with both semantic and response-related effects might unveil more comprehensive explanatory models of the SNARC effect than those put forth so far. Producing inferences about the SNARC locus based on interactive effects of SNARC and factors tapping either proposed causal stage, without showing additive effects of SNARC and factors tapping the other stage, may limit the strength of the conclusions that can be drawn.

To overcome the criticism above, we monitored the SNARC effect using a magnitude comparison task. The present design included the requirement to switch stimulus–response mappings upon presentation of a color cue, a manipulation germane to task-switching (e.g., Hirsch, Nolden, & Koch, 2017; Rogers & Monsell, 1995), in which participants are instructed to perform a varying number of trials using one stimulus–response mapping but to switch to a different mapping when prompted by a cue. Switch trials are typically associated with response slowing relative to repetition trials, the so-called *switch cost*, which is widely held to arise at the response selection stage (e.g., Schuch & Koch, 2003). The use of a magnitude comparison task should also elicit a numerical distance effect—namely, the general response slowing observed for numbers closer to the reference, relative to numbers farther away (Moyer & Landauer, 1967). There is wide agreement on the notion that the distance effect is a hallmark of the activation of the semantic representation of number magnitude, for it has been shown to manifest itself even under passive viewing conditions—namely, when no response to Arabic numerals or nonabstract quantities is required (e.g., Ansari, 2008; Ansari, Dhital, & Siong, 2006; but see Van Opstal, Gevers, De Moor, & Verguts, 2008, and Van Opstal & Verguts, 2011, for a different proposal). As in prior works, we analyzed response times (RTs) in the present experiment by considering that the SNARC effect magnitude has been shown to covary with RT length (i.e., the SNARC effect increases as the RT lengthens; Gevers, Caessens, & Fias, 2005; Gevers, Verguts, Reynvoet, Caessens, & Fias, 2006; Mapelli et al., 2003). To this aim, RTs were vincentized (Ratcliff, 1979) in tertiles, so as to explore these expected variations of the SNARC effect across trials associated with short, medium, and long RTs, as well as to explore how such variations are modulated as a function of the aforementioned factors included in the present design.

The predictions can be summarized as follows. An interactive combination of SNARC and distance effects across RT tertiles and an additive combination of SNARC and switch costs would be expected on the basis of models that conceive the SNARC effect as reflecting the intrinsic semantic/spatial nature of numerical magnitude (see Fig. 1, Scenario 1). The opposite pattern of interactive/additive combinations would be expected according to models that conceive the SNARC effect as reflecting a response-related phenomenon (see Fig. 1, Scenario 2). Crucially, an interactive combination of SNARC with both distance effect and switch costs—which is indeed what we found in the present study—would therefore pose a challenge to both classes of models (see Fig. 1, Scenario 3).

Materials and method

Participants

Twenty-six students at the University of Padua (all right-handed, 19 females, seven males; mean age 27 years, range 21–34, all with normal or corrected-to-normal vision) participated in the experiment after providing written informed consent. No participant was color-blind, reported a prior history of neurological/psychiatric disorder, or was under medication at the time of testing.

Stimuli and procedures

During the experiment, each participant was seated in a comfortable chair placed inside a sound-attenuated and dimly lit room, at a distance of 60 cm from a 17-in. LCD monitor with a black background. Participants were instructed to rest their index fingers on the "D" and "K" keys of the computer keyboard throughout the whole experiment. As is shown in Fig. 2, each trial began with the presentation of a fixation cross (1.5°) for 500 ms, followed by the presentation of a dot (0.8°) for 400 ms, and a white digit (2° × 3.5°) ranging from 1 to 9 (except for 5). The color of the dot (equiluminant yellow or blue) indicated the stimulus–response mapping for the magnitude comparison task.

After a yellow dot, participants had to press the "D" key if the following number was smaller than 5, or the "K" key if the following number was larger than 5 (SNARC-compatible trials). After a blue dot, participants had to reverse the SNARC-compatible mapping (SNARC-incompatible trials). The digit was displayed for a maximum of 2 s, and was replaced with a blank screen upon response detection. Following a response, 500 ms elapsed before the presentation of the central fixation cross for the next trial. After 5 min of practice, participants performed a sequence of 320 trials. The design included both repetition trials (i.e., trials in which the same stimulus–response mapping was used as in the preceding trial) and switch

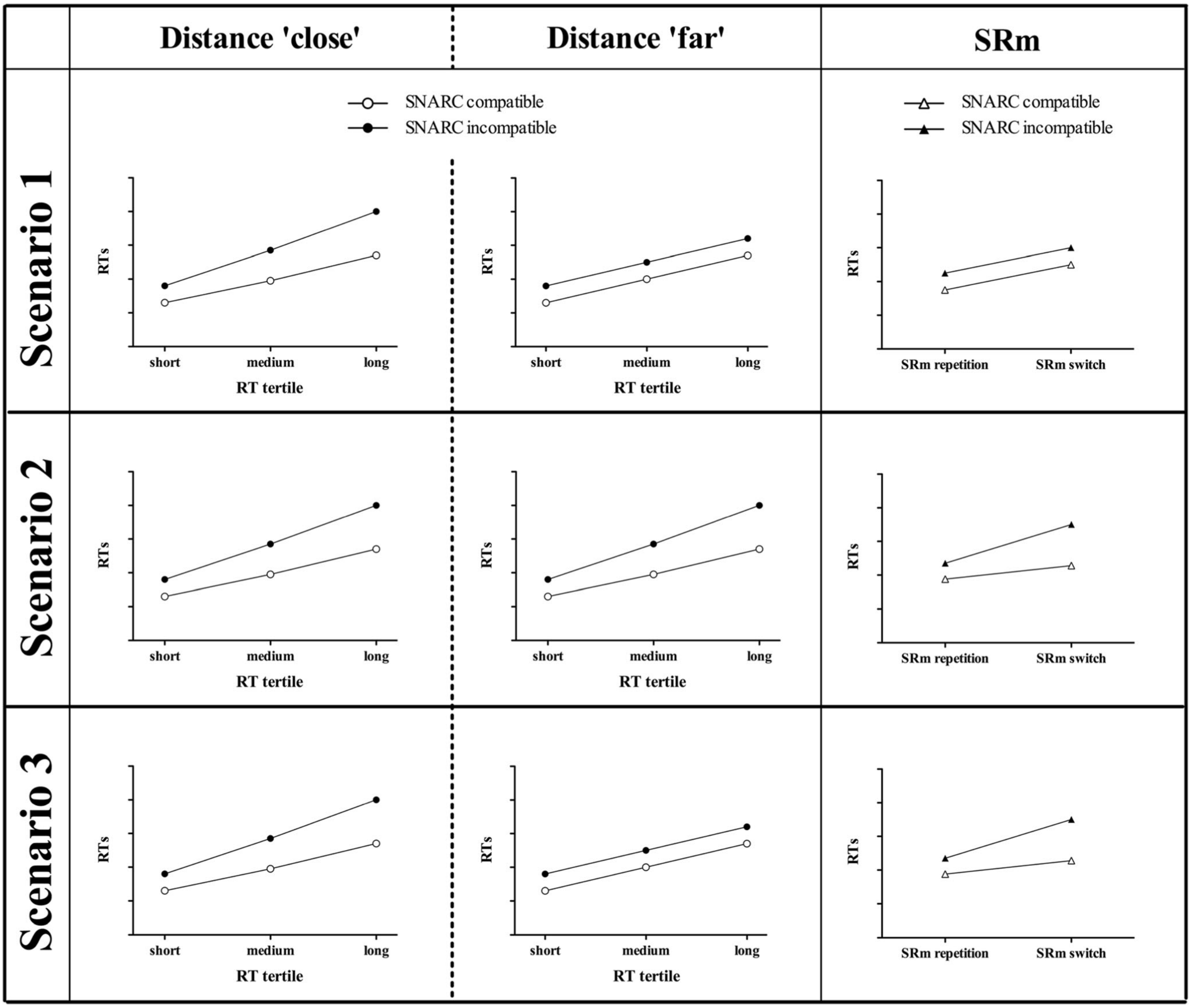

Fig. 1 Hypothetical empirical scenarios (see the text for details) given by interactive or additive combinations of SNARC, distance, and switch costs across mean RT tertiles. Note that the left and middle panels of Scenario 1 and Scenario 3 are meant only to illustrate a plausible interactive combination of numerical distance and SNARC effects across mean RT tertiles. SRm, stimulus–response mapping

trials (i.e., trials in which the stimulus–response mapping rule had to be reversed with respect to the preceding trial). At runtime for each participant, the numbers of repetition and switch trials were balanced, their presentation order was randomized, and the numbers of response repetitions (i.e., trials in which the same response code was used as in the preceding trial) and response alternations (i.e., trials in which the response code had to be changed with respect to the preceding trial) were balanced. Response repetitions and response alternations were equally likely to follow a switch or a repetition trial, so as to minimize to nil the possible influence of the distance effect on response repetitions and alternations (Liefooghe, Verbruggen, Vandierendonck, Fias, & Gevers, 2007). The paradigm was created using E-Prime software (Psychology Software Tools Inc., Pittsburgh, PA, USA).

Results

Participants' responses were scored in terms of both RTs and accuracy. Three out of the 26 participants were excluded from the analyses because their proportions of errors exceeded the mean error rate by more than two standard deviations. Only RTs associated with a correct response were analyzed, following the elimination of outlier RTs (.02 proportion) using the algorithm described by Van Selst and Jolicœur (1994). Individual RT distributions were calculated for each cell of our experimental design and were subsequently divided into tertile bins (see Ratcliff, 1979, for a detailed explanation), each containing an equal number of trials (i.e., 12). The following RT results were obtained using Greenhouse–Geisser-corrected analyses of variance (ANOVAs) and Bonferroni-

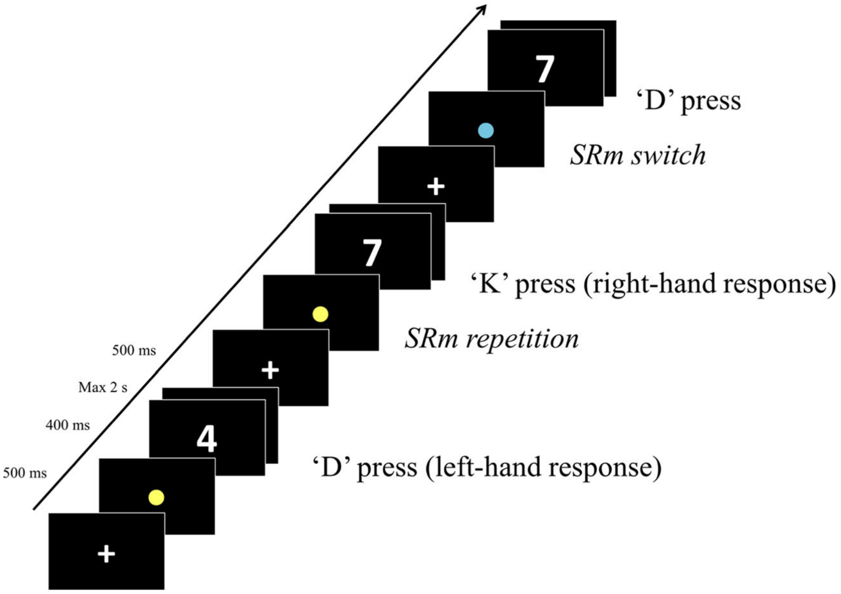

Fig. 2 Schematic illustration of the sequence of events in the present paradigm. The letters shown are the actual keys on the computer keyboard used by participants to respond manually according to a varying stimulus–response mapping (SRm; see the text for details)

corrected *t* tests with SNARC trials (compatible, incompatible), distance (close [3, 4, 6, and 7], far [1, 2, 8, and 9]), stimulus–response mapping (switch, repetition), and RT tertile (short, medium, long) as within-subjects factors.

The ANOVA revealed that each of the aforementioned factors was associated with a significant main effect (min $F = 7.28$, min $\eta_p^2 = .249$, max $p < .001$). A significant interaction was detected between SNARC and stimulus–response mapping, $F(1, 22) = 15.30$, $\eta_p^2 = .410$, $p = .001$, providing statistical support to what Fig. 3 suggests: namely, a more sizable SNARC effect—estimated by subtracting the RTs in compatible trials from the RTs in incompatible trials—in switch than in repetition trials. This pattern was constant across RT tertiles ($F < 1$, $p > .4$).

A significant interaction was detected between SNARC, distance, and RT tertile, $F(1.2, 26.8) = 5.48$, $\eta_p^2 = .199$, $p = .021$. Two ANOVAs with RT tertile and SNARC as factors were separately performed on close and far trials. A significant interaction between SNARC and RT tertile was found for close trials, $F(1.2, 26.8) = 19.77$, $\eta_p^2 = .473$, $p < .001$, but not for far trials, $F < 1$, $p > .3$. As Fig. 4A suggests, in close trials the SNARC effect increased across tertiles [medium vs. short RT: $t(22) = 3.55$, $p = .002$; long vs. medium RT: $t(22) = 4.13$, $p < .001$], whereas in far trials the SNARC effect was constant across tertiles. The lack of a SNARC × Tertile interaction in far trials was further supported by a Bayesian analysis indicating a Bayes factor of 6.63 in favor of the model without the interaction, thereby confirming the different patterns in close and far trials.

In particular, a direct comparison of the SNARC effect between close and far trials indicated that the SNARC effect magnitudes did not differ for the short and medium RT tertiles (max $t = 0.58$, min $p = .570$), but the difference was more pronounced in close than in far trials for the long RT tertile, $t(22) = 2.35$, $p = .028$. One might contend that this pattern was essentially a by-product of the inflation of the variance usually associated with long versus short RTs, and perhaps propose RT normalization as an option to double-check that this was not the case in the present analyses. Though statistically viable, this option is notoriously associated with the loss of information from structurally skewed data, such as RTs (Heathcote, Popiel, & Mewhort, 1991). A different option, however, would be to consider that generic variance increments as RTs lengthen should not alter the relative proportions of SNARC-incompatible versus -compatible trials—for both close and far trials—across RT tertiles. Therefore, if the increase of the SNARC effect on close as compared to far trials

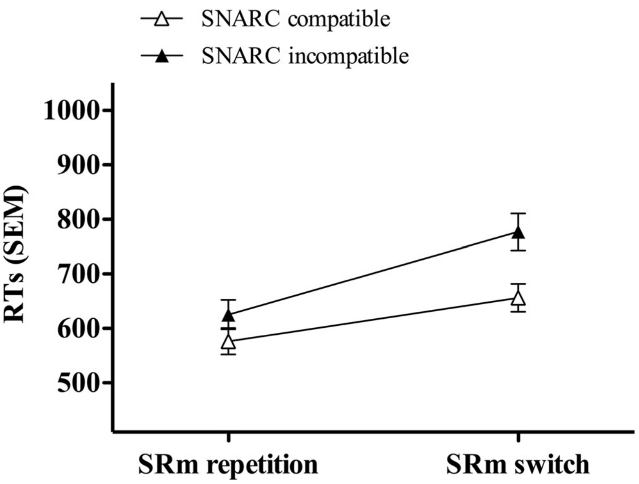

Fig. 3 Modulation of the SNARC effect as a function of trial type. SRm, stimulus–response mapping; *SEM*, standard error of the mean

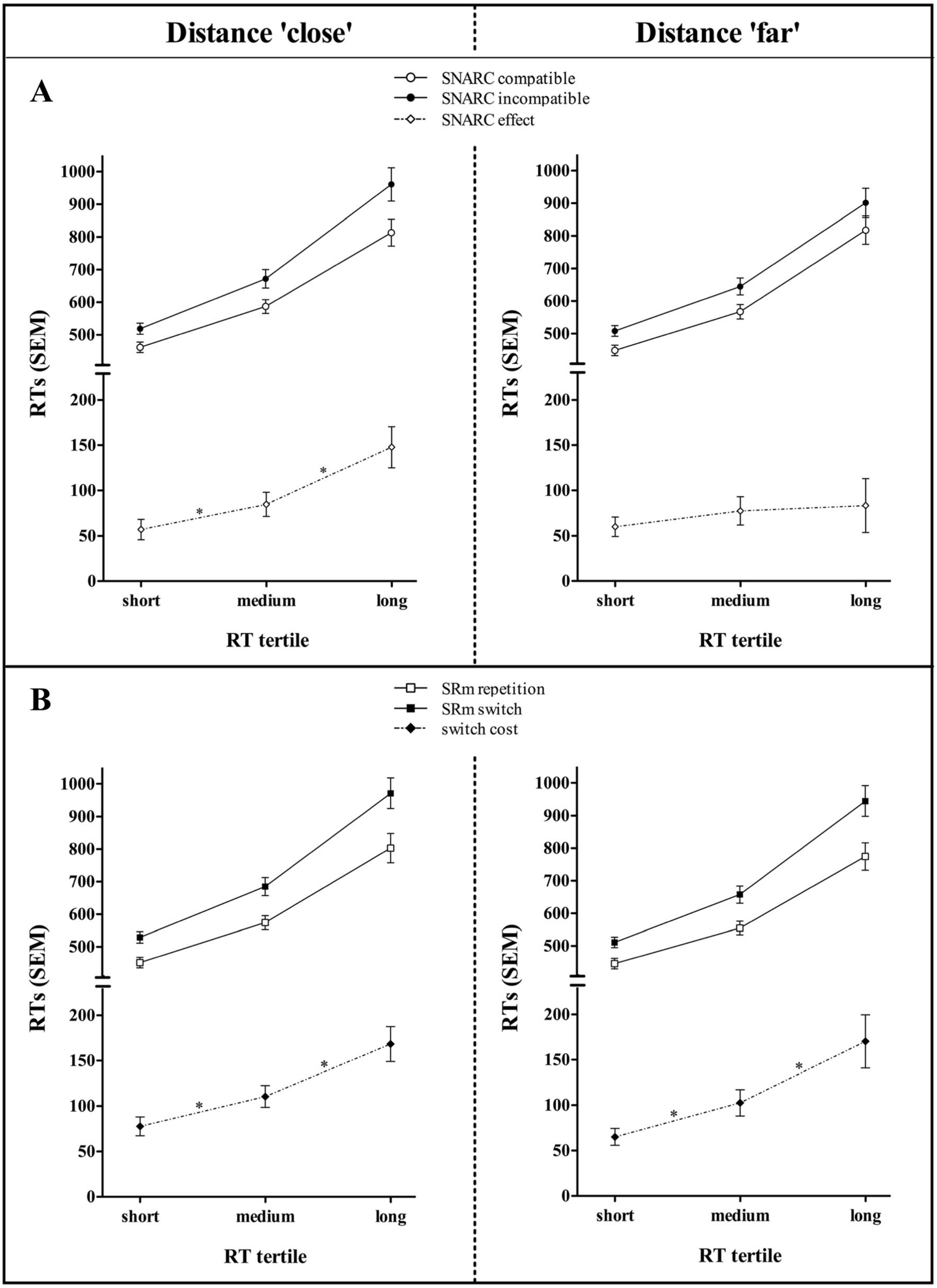

Fig. 4 Modulations of both SNARC effect (A) and switch cost (B) as a function of RT tertile and numerical distance. In the lower portion of each panel, significant differences in the net SNARC effect (A) or switch cost (B) across distance and RT tertile are highlighted with asterisks. SRm, stimulus–response mapping; *SEM*, standard error of the mean

was selectively determined by the present factors' manipulation, then an increment in the proportion of SNARC-incompatible versus -compatible trials as RTs lengthen would be expected for close but not for far trials. To check for this possibility, individual estimates of the ratio between SNARC-incompatible and -compatible trials for each RT tertile were compared via *t* test, separately for close and for far trials. For far numbers, these ratios were in fact similar across the short, medium, and long RT tertiles (1.13, 1.14, and 1.12, respectively; max $t = 0.55$, min $p = .148$). For close numbers, in contrast, the ratios were significantly different between the long versus the medium tertile (1.18 vs. 1.14), $t(22) = 2.23$, $p = .018$, and the long versus the short tertile (1.18 vs. 1.12), $t(22) = 2.06$, $p = .026$, suggesting that RT variance, in and of itself, could hardly be an explanatory factor of RT mean distribution observed in the present circumstances.

Consistent with prior reports on task-switching (De Jong, 2000), Fig. 4B shows that switch costs increased monotonically across RT tertiles, $F(1.1, 24.9) = 19.08$, $\eta_p^2 = .464$, $p < .001$. Furthermore, switch costs were not influenced by numerical distance ($F < 1$, $p > .6$). We found no interaction between stimulus–response mapping and distance, and there were no other interactions between stimulus–response mapping and the other factors considered in the RT analysis (max $F = 0.38$, max $\eta_p^2 = .017$, min $p = .571$) (see the supplementary material for the ANOVA tables of the RT analysis).

The accuracy analysis revealed a pattern of results consistent with those of the analysis carried out on RTs (thus excluding speed–accuracy trade-offs), indicating more correct responses in compatible than in incompatible trials (.95 vs. .92), for far than for close numbers (.95 vs. .93), and in trials with a repeated than in trials with a switched stimulus–response mapping (.97 vs. .91) (min $F = 9.21$, min $\eta_p^2 = .295$, max $p = .006$).

Discussion

The present study was designed to disentangle two opposing models of the SNARC effect, one ascribing its cause to the inherent analogical/spatial structure of the semantic representation of numerical magnitude, and another ascribing its cause to processing taking place at the level of response selection. The paradigm was devised to tap both of these processing stages concurrently, by manipulating the numerical distance of displayed numbers (i.e., 1 to 9, except for 5) relative to a reference number (i.e., 5) using a magnitude comparison task while asking participants to switch or repeat stimulus–response mappings from one trial to the next. The results were clear-cut. The magnitude of the SNARC effect varied as a function of both numerical distance and stimulus–response mapping. The interaction between SNARC and numerical distance was particularly evident when the long portion of the RT distribution was considered (i.e., at the long RT tertile). When considered in full, therefore, the pattern of interactions between SNARC and both semantic and response-related factors is hard to reconcile with models that propose, at least in their current formulations, a functionally unitary locus of the SNARC effect at either of the aforementioned stages. The solution of using color as a cue to switch the stimulus–response mapping allowed us to include unpredictable combinations of compatible and incompatible trials within each trial block in the present design, vis-à-vis the standard design in which different types of trials are segregated in distinct blocks. The added value of this solution is all the more remarkable because within-block manipulations are commonly held to rule out variations of strategy on the part of participants as an issue when interpreting a pattern of results.

An informative aspect of the present results is the way in which numerical distance modulated the distribution of the SNARC effect across RTs. In far trials, the SNARC effect was not contingent on the portion of the RT distribution tested. In contrast, in close trials the SNARC effect magnitude increased as the RT lengthened. A model for this interaction is, in our view, one that relies on two main assumptions. The first assumption is borrowed from the received view on the distance effect, according to which the activation strength of a displayed number can be represented as a Gaussian distribution function centered on the number itself and spreading over a subset of the neighboring numbers. In a magnitude comparison context, the distance effect is proportional to the degree of overlap between the activation functions of the displayed and reference numbers (e.g., Ansari, 2008; Hubbard et al., 2005). When these numbers are close, RTs are inflated by the additional time taken to gather a sufficient signal from overlapping curves. In practice, the longer a displayed number must be processed at this level, the more fine-grained the magnitude information needed by the system prior to activation of a response (Gevers et al., 2006). The second assumption is the linchpin of models based on the principle that the mental number line—a continuous, spatial vector on which small numbers are represented on the left and large numbers on the right (Hubbard et al., 2005)—is rapidly and ballistically activated upon the onset of a displayed number.

By combining these two assumptions, a plausible corollary is that the more fine-grained magnitude information caused by a longer processing time is positively correlated with the activation strength of the spatial codes of the displayed numbers on the mental number line. This chain of events might be at the core of the interaction between SNARC, distance, and tertile. Relative to far numbers, numbers close to the reference elicit stronger activation of the spatial code on the mental number line as a result of the additional time caused by the distance effect. Close numbers displayed in trials associated with long RTs are therefore likely to generate the strongest activation of the spatial code on the number line, due to the more fine-grained magnitude information needed to end the process associated with emission of a (manual, in the present case) response.

This line of reasoning could easily explain why the SNARC effect magnitude increased as RT lengthened. Close trials characterized by long RTs are those with the strongest SNARC effect because the magnitude processing is likely to be extremely fine-grained, with the aforementioned consequences on the activation strength of the spatial codes on the mental number line. In contrast, making a response to numbers far from the reference does not require fine-grained processing of numerical magnitude, a suggestion that comes from our finding of a generally reduced SNARC effect in far trials that, in addition, did not vary with RT length. Overall, our results strongly suggest that the representational strength of number magnitude plays a pivotal role in the emergence of the SNARC effect, and thus dovetail nicely with a recent investigation of the SNARC effect on neglect patients (Zorzi et al., 2012). In magnitude comparison tasks, neglect patients tend to show a stronger SNARC effect for numbers to the right of the reference, a finding that is difficult to reconcile with the view of a SNARC locus solely at response selection.

In conclusion, our results suggest that the two currently opposing accounts of the SNARC effect (e.g., Keus & Schwarz, 2005; Mapelli et al., 2003) should not be seen as mutually exclusive. Rather, the present results strongly suggest a combination of causes that are semantic and response-related in nature, both of which determine the emergence of the SNARC effect. Thus, our findings add an important piece of evidence, suggesting that the root cause of the SNARC effect lies in-between spatial–numerical associations and response-related processes.

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