Non-symbolic numerosities do not automatically activate spatial-numerical associations: Evidence from the SNARC effect.

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Abstract

The SNARC (spatial numerical association of response codes) effect is the finding that people are generally faster to respond to smaller numbers with left-sided responses and larger numbers with right-sided responses. The SNARC effect has been widely reported for responses to symbolic representations of number such as digits. However, there is mixed evidence as to whether it occurs for non-symbolic representations of number, particularly when magnitude is irrelevant to the task. Mitchell et al. (2012) reported a SNARC effect when participants were asked to make orientation decisions to arrays of one-to-nine triangles (pointing upwards versus pointing downwards) and concluded that SNARC effects occur for non-symbolic, non-canonical representations of number. They additionally reported that this effect was stronger in the subitizing range. However, here we report four experiments that do not replicate either of these findings. Participants made upwards / inverted decisions to one-to-nine triangles where total surface area was either controlled across numerosities (Experiments 1, 2 and 4) or increased congruently with numerosity (Experiment 3). There was no evidence of a SNARC effect either across the full range, or within the subset of the subitizing range. The results of Experiment 4 (in which we presented the original stimuli of Mitchell et al.) suggested that visual properties of non-symbolic displays can prompt SNARC-like effects driven by visual cues rather than numerosity. Taken in the context of other recent findings, we argue that non-symbolic representations of number do not offer a direct and automatic route to numerical-spatial associations.

Keywords: SNARC, non-symbolic number

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Numerical information can be represented in a multitude of ways; Arabic or Roman symbols, written or spoken words, finger positions, dot patterns, beads on an abacus, or graphical figures can all convey the same quantity in different ways. However, the dominant view is that, however numerical information is represented externally, it is likely that there is a notation-independent abstract representation of number associated with structures in the intraparietal sulcus (e.g., Dehaene, 1992; McCloskey, 1992; see Hubbard, Piazza, Pinel, & Dehaene, 2005 for a review; but cf. Cohen Kadosh & Walsh, 2009). One source of behavioural evidence for such accounts comes from tasks where quantitative information influences performance regardless of the specific form of notation or representation, perhaps most notably the spatial numerical association of response codes (or SNARC) effect (for reviews see e.g., Fischer & Fias, 2005; Gevers & Lammertyn, 2005; van Dijck, Ginsburg, Girelli, & Gevers, 2015).

The SNARC effect is the finding that people are generally faster to respond to small quantities with a left-sided response and to larger quantities with a right-sided response. In their seminal paper, Dehaene, Bossini and Giraux (1993) asked participants to respond to the parity of numbers using left- and right-hand key presses, and reported a SNARC effect that they attributed to a “mental number line”. Dehaene et al. found the strongest effect for Arabic numerals, with weaker effects for verbal numerals. They interpreted this finding in the context of Dehaene’s (1992) triple-code model, which postulates three concrete representations for number: a visual Arabic number form, an auditory verbal word frame, and an analogue magnitude representation. They argued that the stronger SNARC effect for Arabic numbers reflects an automatic pathway to the analogue magnitude representation, with verbal numbers following a less automatic pathway. The finding that SNARC effects vary by notation has been reported elsewhere. For example, Hung, Hung, Tzeng, and Wu (2008) found a SNARC effect for parity decisions to digits, but not to Chinese numerical words. However, others have found the SNARC effect to be relatively unaffected by notation; for example, Nuerk, Wood, and Willmes (2005) reported similar SNARC effects for parity decisions to auditory number words, visual Arabic numerals, visual number words and visual dice patterns and concluded that the SNARC effect reflects automatic access to an amodal semantic magnitude representation that is unaffected by number form.

Whereas the SNARC effect for symbolic number has been reported multiple times and using multiple numerical formats, (see Wood, Willmes, Nuerk, & Fischer, 2008, for a meta-analysis), there are only a handful of reported studies that investigate SNARC (or SNARC-like) effects for non-symbolic, non-canonical representations of number (see Buijsman & Tirado, in press, for a review), and the majority of these studies use tasks where numerical magnitude is relevant to the task. Patro and Haman (2012) asked pre-schoolers (aged between 2 years 8 months and 4 years 11 months) to indicate which of two "plates of sweets" (two sets of coloured rectangles on a touch-screen) had more or fewer sweets. Children were faster to make "more" responses on the right and there was a trend for them to be faster to make "less" responses on the left. Ebersbach, Luwel, and Verschaffel (2014) asked children (mean age 5 years 11 months) to indicate whether arrays of 5, 10, 40 or 80 dots contained more or fewer than 20 dots in the context of deciding whether they had more or fewer "cookies" (brown dots) than "guests" (blue dots). Children were faster to respond to 40 or 80 dots with their right hand and faster to respond to 5 or 10 dots with their left hand. In adults, Nemeh, Humberstone, Yates and Reeve (2018) reported a SNARC effect when performing referent-to-target judgements. Participants who judged whether arrays of dots (e.g., 45 or 15 dots) were more or less numerous than a referent array of 30 dots were faster to respond to smaller non-symbolic magnitudes with their left hand and to larger non-symbolic magnitudes with their right hand. Zhou, Shen, Li, Li and Cui (2016) used a numerosity matching task, where adult participants were asked to judge whether two sequentially presented dot arrays had the same or different numbers of dots; the numerosities used (11, 14, 17, 20, 23, 26, and 29) meant that this was an approximation task. They found a SNARC-like effect such that participants were faster to respond to large numerosities with the right hand and faster to respond to smaller numerosities using the left hand. They did not find a similar effect for judgements of continuous magnitude (when participants matched area or dot density), and concluded that there is an autonomous mental numerosity line associated with the approximate number system.

Notably, in all of these studies, magnitude was relevant to the task. This stands in contrast to the literature on SNARC effects for symbolic representations of number, where magnitude is very often *ir*relevant to the task. Indeed, there is evidence from studies of SNARC effects in symbolic number that the SNARC effect for parity and magnitude judgement may reflect different processes, with SNARC effects for magnitude more categorical in nature and SNARC effects for parity more continuous (e.g., Gevers, Verguts, Reynvoet, Caessens, & Fias, 2006; Wood et al., 2008). Furthermore, the processing of parity versus magnitude is differentially affected by working memory demands (van Dijck, Gevers, & Fias, 2009), and differentially predicted by arithmetic performance and visualization profile (Georges, Hoffmann, & Schiltz, 2017). In other words, a direct comparison between spatial-numerical associations for symbolic and non-symbolic number is not complete without tasks that require only implicit magnitude processing. However, comparatively few studies have examined tasks where numerical magnitude is irrelevant to the task. Mitchell, Bull, and Cleland (2012) asked participants to indicate with left- and right-hand key presses whether arrays of one-to-nine triangles were presented pointing upwards or downwards, and found a significant SNARC effect that was most marked for the subitizing range (i.e., one to four triangles). They interpreted their results along the lines of Fias, Lauwereyns, and Lammertyn’s (2001) “neural overlap” account. Fias et al. had reported a SNARC effect for orientation decisions to single triangles superimposed upon digits, but not for colour decisions to digits, and attributed this to the overlapping parietal structures that process orientation and magnitude. In a similar pattern of findings, Mitchell et al. did not find a SNARC effect for colour decision to circles, and therefore proposed that non-symbolic representations of number *can* trigger “automatic” access to semantic representations, but potentially only when the neural structures underlying the task overlap with magnitude (note that colour processing is not believed to rely substantially on parietal areas, e.g., Chao & Martin, 1999). Mitchell et al. further suggested that the increased SNARC effect in the subitizing range could reflect an approximate number system that represents numerosity with increasing representational overlap, either due to increasing noise with increasing magnitude (Gallistel & Gelman, 1992), or logarithmic compression of the representation with fixed noise (Dehaene, 2003; Verguts & Fias, 2004). Either possibility would suggest less spatial precision for magnitudes in the higher range. Simmons, Gallagher-Mitchell, and Ogden (in press) replicated the SNARC effect for the same set of stimuli, although they do not report whether they replicated the enhanced SNARC effect in the subitizing range.

Further evidence of SNARC effects for task-irrelevant non-symbolic number comes from Bulf, Macchi Cassia and de Hevia (2014), who used a task based on Fischer, Castel, Dodd and Pratt’s (2003) visual detection task. Participants were presented with either the digits 2 or 9, or with two or nine dots presented centrally on a screen. This was then followed by a to-be-detected target presented either on the left or right of the screen. For both representations, participants were faster to detect a target on the right following larger numerical magnitudes and the left following smaller numerical magnitudes. Bulf et al. argued that these findings are consistent with abstract numerical representations and with the view that numerical information is spontaneously associated with space. Furthermore, they argued that these spontaneous spatial associations are not driven by experience with external representations of number such as rulers or graphs. This conclusion is supported by their subsequent finding that two- and nine-dot arrays orient preverbal infants' visual attention towards the left and right respectively (Bulf, de Hevia, & Macchi Cassia, 2016).

Mitchell et al.'s (2012), Simmon et al.'s (in press), and Bulf et al.'s (2014) findings suggest that non-symbolic number could offer at least as strong a route to spatial associations as symbolic number. However, there are no other reports, to our knowledge, of SNARC effects for non-symbolic number when magnitude is irrelevant to the task. More problematically, these effects have only been reported for a limited range of stimuli. Mitchell et al. and Simmon et al. used the same stimuli set (personal communication), and Bulf et al. only used arrays of two and nine dots. Furthermore, Cleland and Bull (2019) reported no evidence of a SNARC effect for responses to arrays of circles. In this study, participants made binary colour decisions to arrays of one to nine circles presented on a computer screen. The arrays either appeared immediately in colour, or were displayed in black for 200 ms or 400 ms before changing colour. Importantly, a parallel experiment in the same series used an identical procedure but with coloured digits, allowing a direct comparison between symbolic and non-symbolic representations. Whereas there was strong evidence for a SNARC effect in the experiment using digits, there was no evidence of a SNARC effect in the experiment using circles, despite reaction times for the two tasks being similar (440 ms for colour decisions to digits and 436 ms for decisions to circles). Cleland and Bull concluded that non-symbolic number differs from symbolic number in that it does not provide a direct and automatic route to spatial associations with magnitude.

The current studies

The SNARC effect for orientation to non-symbolic numerosities has only been reported with one set of stimuli (Mitchell et al., 2012; Simmons et al., in press). Furthermore, only one array of each numerosity was used during these experiments, meaning that each numerosity always looked the same and was seen repeatedly by each participant (Mitchell et al. presented each array 16 times upright and 16 times inverted, and Simmons et al. presented each array eight times upright and eight times inverted). The repeated use of identical arrays raises at least two issues. Firstly, it is possible that participants memorised the arrays over the course of the study and began to assign them verbal labels (either numerical labels, or simply “small” versus “large”), which might account for the SNARC effect, particularly under conceptual or verbal coding accounts of the SNARC effect (e.g., Gevers, Verguts, Reynvoet, Caessens, & Fias, 2006; Proctor & Cho, 2006). Secondly, seemingly insignificant visual properties of the array (e.g., placement of individual items) might influence participants’ responses, a risk that is amplified by repeated viewing of the same arrays. The initial aim of the current studies was to establish whether the SNARC effect for orientation decisions to non-symbolic number replicated with a wider range of stimuli, and whether this might be modulated by visual cues to magnitude unrelated to numerosity (specifically, the aggregate surface area of the triangles, and their subtended area).

In Experiment 1, participants made orientation decisions to arrays of between one and nine triangles, with multiple arrays for each numerosity. If the SNARC effect is indeed triggered by response-irrelevant magnitude (as argued by Mitchell et al., 2012), we would expect to find a SNARC effect in this study regardless of the change in stimuli. In Experiment 2, each participant saw only one version of each numerosity but across the participants these arrays were varied; this allowed us to test the hypothesis that repeated use of the same arrays contributed to the SNARC effect in Mitchell et al.

The aggregate surface area (i.e., the summed total surface area) of the triangles in any given array was held constant in Experiments 1 and 2. Controlling such non-numerical visual cues in the stimuli can create a conflict between different potential cues to magnitude (see e.g., Gebuis, Cohen Kadosh, & Gevers, 2016; Gebuis & Reynvoet, 2012). Visual properties such as aggregate surface area have been demonstrated to affect performance on tasks with a spatial component; for example, Cleland and Bull (2015) reported that participants performing a bisection task to a line flanked by numerosities were at least as influenced by subtended area and aggregate surface area as they were by number of items. Ren, Nicholls, Ma, and Chen (2011) found SNARC-like effects when participants made relative judgments of the physical sizes of two disks such that responses with the right hand were faster for large than small targets. This finding is particularly relevant, given that controlling the aggregate surface area of the triangles meant that the mean surface area of the individual triangles decreased as numerosity increased. Furthermore, there is a large literature on the "size congruity effect", where physical size interferes in semantic magnitude comparisons (e.g., Banks & Flora, 1977), including for digit magnitude (e.g., Henik & Tzelgov, 1982). There is also evidence that conflicting cues to magnitude might eliminate the SNARC effect under certain conditions; for example, Holmes and Lourenco (2013) found that placing a weight on participants' left wrists eliminated the SNARC effect. Taking together these disparate findings, it would be reasonable to predict that over-controlling visual cues to magnitude might eliminate any potential SNARC effect in Experiments 1 and 2. Therefore, in Experiment 3, we allowed the aggregate surface area and subtended surface area to vary congruently with magnitude. This was to test the hypothesis that the lack of a SNARC effect in Experiments 1 and 2 might be prompted by the conflict between numerosity itself and the visual cues that would normally co-vary congruently with magnitude.

Finally, Experiment 4 was designed to address two crucial differences between Experiments 1-3 and Mitchell et al.'s (2012) original study. The first was that the stimulus sets in Experiments 1-3 all included an array of five triangles, whereas Mitchell et al. did not include a five-triangle array. It is possible that the omission of a five-triangle array made participants more likely to allocate each array to either a "small" (1-4) or "large" (6-9) label. Under a verbal coding account, this might explain why Mitchell et al. found a SNARC effect. However, given the fact that there was only one array for each numerosity, it is also possible that some visual property of the arrangement of the triangles prompted the SNARC effect. In order to distinguish these possibilities, Experiment 4 was a direct replication of Mitchell et al. (2012) using two versions of the original set of stimuli; one that was the same as that used by Mitchell et al., and another where the stimuli were flipped on the vertical axis. If the omission of the five-triangle array caused the SNARC effect, we would expect to see a SNARC effect across both sets of stimuli. However, if Mitchell et al.'s finding was prompted by visual properties of the stimuli we would expect to see a SNARC effect for the original set of stimuli that subsequently reversed for the flipped stimuli.

Experiment 1

Method

Participants. Sixty-four participants took part in the study (12 men, 51 women, one chose not to specify; mean age 22 years, SD = 5.68, two declined to provide ages; 56 right-handed based on self-report, seven left-handed, one declined to report). A further three participants were excluded from the analysis based on making excessive errors on the task (13% and above).

Stimuli and Procedure.

Stimuli. The stimuli were arrays of 1-9 equilateral black triangles, which could appear either upright or inverted. The total surface area of the triangles in each array was 500 mm^2, with the surface area of individual triangles varied within this. Four different arrays were created for each numerosity above one, with the surface area of individual triangles and the arrangement of the triangles within the array varied for each different array. The triangles were displayed such that they occupied a notional circle 50 mm in diameter, with an area of 1963 mm^2. So far as possible, this subtended area was kept constant across stimuli (although note that in the lower range this was not practical, with stimuli inevitably occupying a smaller convex hull). Upright and inverted versions of each array were created; as such, there were eight different possible stimuli for each of the numerosities above one.

Procedure. Participants were instructed that they should indicate whether the triangles presented onscreen were upright or inverted. Response mapping was counterbalanced across participants; half of the participants responded to upright triangles with the *M* key and inverted triangles with the *Z* key of a QWERTY keyboard, and half responded with the reverse mapping. On each trial, a fixation cross was presented centrally for 1000 ms. This was then replaced by the array of triangles, which remained onscreen for 2000 ms or until the participant made a response. This was followed by a blank screen for 1000 ms before the fixation point for the next trial. The experimental session consisted of 288 trials in total (32 presentations of each numerosity, 16 upright and 16 inverted), presented in two blocks of 144 trials with a rest break in between. The main experimental session was preceded by a practice block of 18 trials, during which participants were provided with feedback on accuracy and reaction time. No feedback was provided during the experimental block. The experimental stimuli were presented on a Dell 19” flat panel monitor using a Dell PC running Windows 7, with key presses recorded from a Dell keyboard. Stimuli were presented and reaction times recorded using E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA).

Results and Discussion

In all experiments, reaction times for each numerosity responded to with the left and right key were collated and the median reaction time calculated (correct responses only). The difference in time to respond to each numerosity with the right and left hand was then calculated (right hand reaction time – left hand reaction time). The nature of the SNARC effect was captured by regression analyses (Lorch & Myers, 1990, Method 3; for a detailed discussion, see Fias, Brysbaert, Geypens, & d'Ydewalle, 1996). A regression equation was computed for each participant, with numerosity as the predictor variable and reaction time difference as the criterion variable. The regression weight (standardised β) was recorded for each participant, and a one-sample *t*-test conducted to determine whether the regression weights across participants differed significantly from 0 (a flat line).

The mean error rate was 3.43%, and the mean reaction time for correct trials was 455 ms. A one-sample *t*-test revealed that the regression weight did not differ significantly from 0, mean $\beta = .0009$, $t\ (63) = .02$, $p = .984$, $d = .003$, CI[-.088, .09]. A Bayesian one-sample *t*-test using a Cauchy prior width of 1.0 (see, e.g., Rouder, Speckman, Sun, Morey, & Iverson, 2009) yielded a Bayes Factor (BF_{10}) of 0.098, suggesting moderate evidence for the null hypothesis. The mean response time differences across the numerosities are displayed in Figure 1.

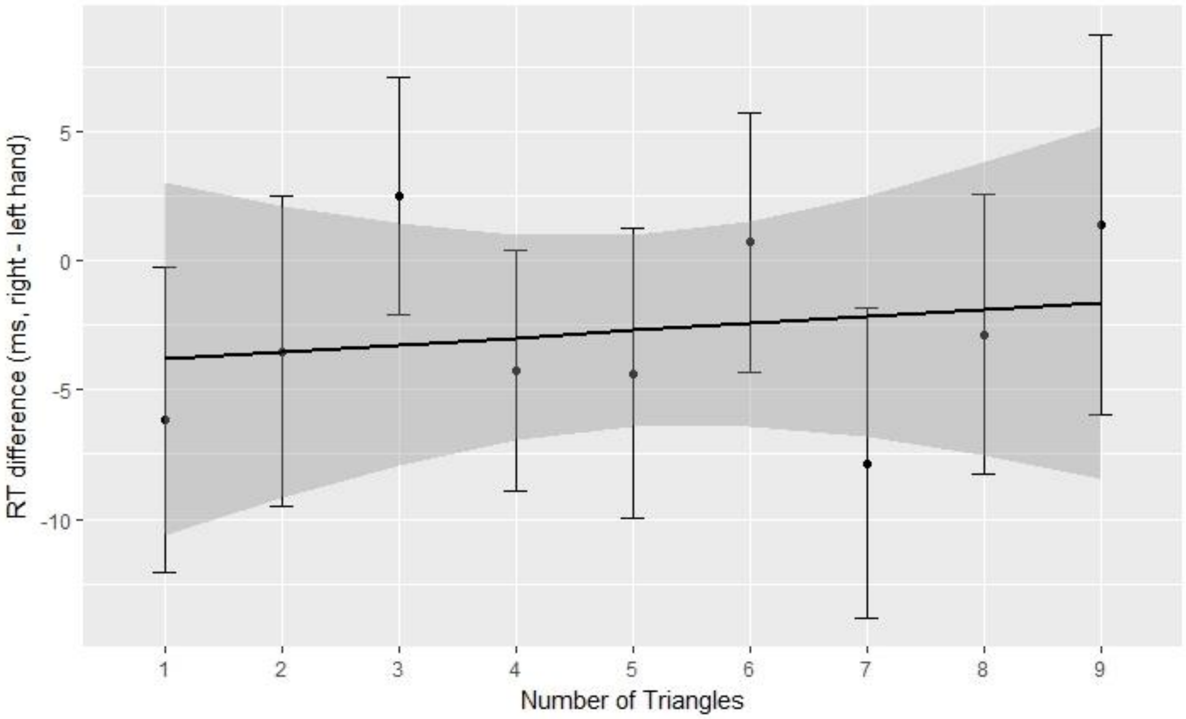

Figure 1. Mean reaction time differences for each numerosity in Experiment 1. Errors show +/- 1 standard error. The shaded area show the 95% confidence interval for the trend line. All graphs were generated using ggplot 2 (Wickham, 2009) in R (R Core Team, 2016).

An additional analysis was run solely on the subitizing range. As with the full range, there was no evidence of a SNARC effect, mean β = .090, *t* (63) = 1.18, *p* = .242, *d* = .148, CI[-.062 ,242], BF_{10} = .194.

To summarise, there was no evidence of a SNARC effect in Experiment 1. This may point to a Type I error in Mitchell et al.'s original study, but it is necessary to rule out other explanations. One issue is that participants in Experiment 1 saw a range of different stimulus arrays for each of the numerosities (with the exception of the one-triangle array, which remained constant). However, in Mitchell et al.'s study, participants only saw one version of each numerosity, with each participant viewing each numerosity 32 times (16 times upright and 16 times inverted). It is possible that participants started to recognise the stimuli over the course of the experiment and began to label them verbally. Over the course of the study we might therefore expect to see participants develop a stronger association between each non-symbolic display and its magnitude and spatial associations. Alternatively, the repetition of arrays might make it easier for participants to build a stable ordinal representation of the stimuli in working memory, thus producing a SNARC effect (see e.g., van Dijck, & Fias, 2011). These explanations might also account for the enhanced SNARC effect reported in the subitizing range, if we assume that the smaller numerosities are more distinctive and easier to remember. If repetition of the stimuli was the cause of the SNARC effect in Mitchell et al., we would expect to see a SNARC effect for repeated use of non-symbolic displays regardless of the individual stimulus set. To test this hypothesis, in Experiment 2 each participant saw only one version of each numerosity array. We varied the numerosity arrays across participants in order to eliminate the possibility that the visual properties of individual arrays might influence responses.

Experiment 2

Methods

Participants. Sixty-four participants took part in the study (14 men; mean age 21 years, SD = 4.12; 58 right-handed based on self-report). One further participant was excluded from the analysis based on having made an excessive number of errors (15%).

Stimuli and Procedure. The stimuli and procedure were identical to Experiment 1 with one exception. Rather than seeing multiple versions of each numerosity, each participant only saw one version throughout the experiment (the inverted stimuli was a flipped version of the upright version). In order to rule out the influence of visual properties specific to any one arrangement of items, different participants saw different items (with four different arrangements of each counterbalanced across participants). As with Experiment 1, half of the participants responded to upright triangles with the *M* key and inverted triangles with the *Z* key, with the response mapping reversed for the other half.

Results and Discussion

The mean error rate was 3.40%, and the mean reaction time for correct trials was 440 ms. A one-sample *t*-test revealed that the regression weight did not differ significantly from 0, mean β = .038, $t(63) = .733$, $p = .466$, $d = .092$, CI[-.066, .142]. A Bayesian one-sample *t*-test using a Cauchy prior width of 1.0 yielded a Bayes Factor (BF_{10}) of .128, suggesting moderate evidence for the null hypothesis. The mean response time differences across the numerosities are displayed in Figure 2.

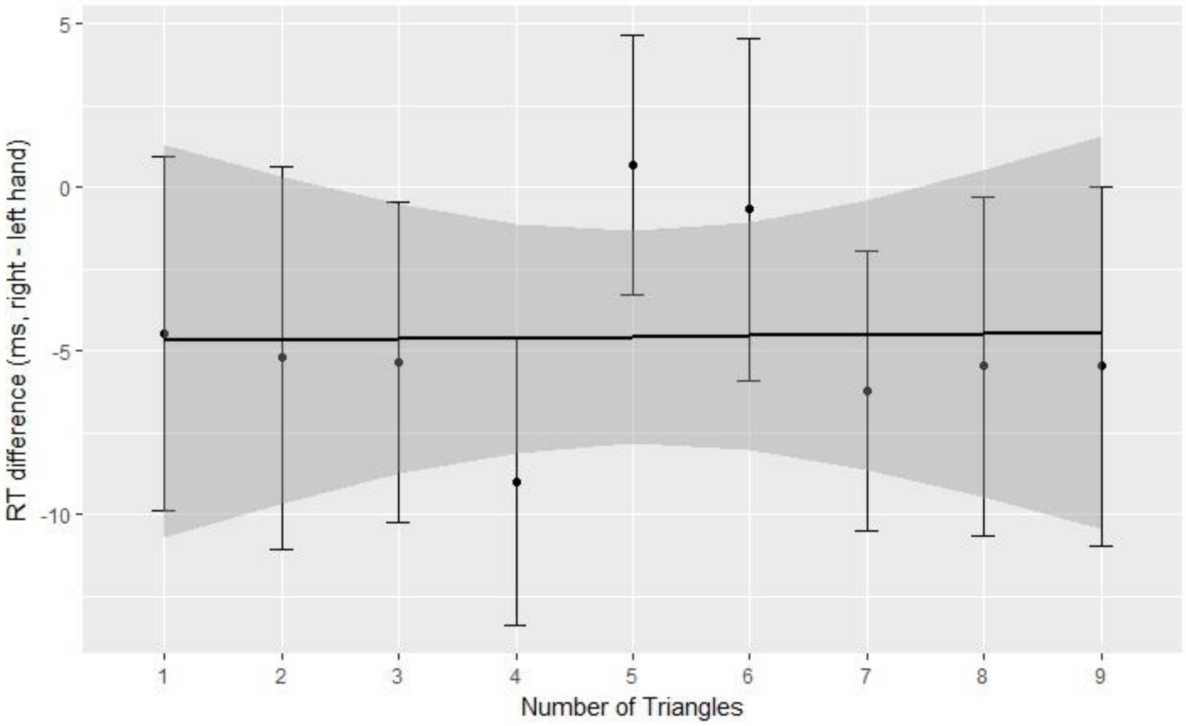

Figure 2. Mean response time difference for each numerosity in Experiment 2. Errors bars show +/-1 standard error. The shaded area shows the 95% confidence interval for the trend line.

An additional analysis was run solely on the subitizing range. As with the full range, there was no evidence of a SNARC effect, mean $\beta = -.011$, t (63) = -.151, p = .881, d = .019, CI[.152, .130], BF_{10} = .099.

In Experiment 2, we found no evidence for a SNARC effect even though participants saw the same arrays of stimuli repeatedly across the course of the experiment. We conclude therefore that it is unlikely the SNARC effect in Mitchell et al. (2012) was driven by repeated exposure to the same non-symbolic arrays. There remain two differences between Experiment 2 and Mitchell et al; the omission of a five-triangle array in Mitchell et al., and the specific stimuli used. We return to this issue in Experiment 4.

In Experiments 1 and 2, we controlled visual cues to magnitude unrelated to numerosity, specifically aggregate surface area and, so far as possible, the area subtended by the stimulus. However, as discussed in the Introduction, this sets up a conflict between numerosity and visual cues that would normally be informative as to magnitude. While such controls ensure that we are tapping numerosity rather than other visual cues, such control is in many ways artificial; in real life, objects do not get smaller because there are more of them (see e.g., Gebuis & Reynvoet, 2012, for discussion). In Experiment 3, we allowed aggregate surface area and the area subtended by the stimulus to vary congruently with numerical magnitude. This allowed us to test the hypothesis that removing the conflict between numerical and non-numerical cues to magnitude might prompt a SNARC effect.

Experiment 3

Method

Participants. Sixty-four participants took part in the study (10 men; mean age 20 years, SD = 1.49; 59 right-handed based on self-report). Three further participants were excluded from the analysis based on having made an excessive number of errors (10% and above).

Stimuli and Procedure. In Experiment 3, each individual triangle had a surface area of 100 mm^2 for all numerosities. In other words, the aggregate surface area of the triangle stimuli ranged from 100 mm^2 for the one triangle display up to 900 mm^2 for the nine triangle display. The spacing between triangles was kept constant so that the convex hull of the displays increased with numerosity. For example, nine triangle displays subtended a circle of approximately 4901 mm^2. As in Experiment 1, four different arrays were created for each numerosity above one, with the arrangement of the triangles within the array varied for each different array. These were then flipped to create the inverted versions of each array. In all other respects, the stimuli and procedure were the same as Experiments 1 and 2.

Results and Discussion

The mean error rate was 3.24%, and the mean reaction time for correct trials was 469 ms. A one-sample *t*-test revealed that the regression weight did not differ significantly from 0, mean β = -.020, *t* (63) = -.463, *p* = .645, *d* = .058, CI[.-.105, .065]. A Bayesian one-sample *t*-test using a Cauchy prior width of 1.0 yielded a Bayes Factor (BF_{10}) of .109, suggesting moderate evidence for the null hypothesis. The mean response time differences across numerosities are displayed in Figure 3.

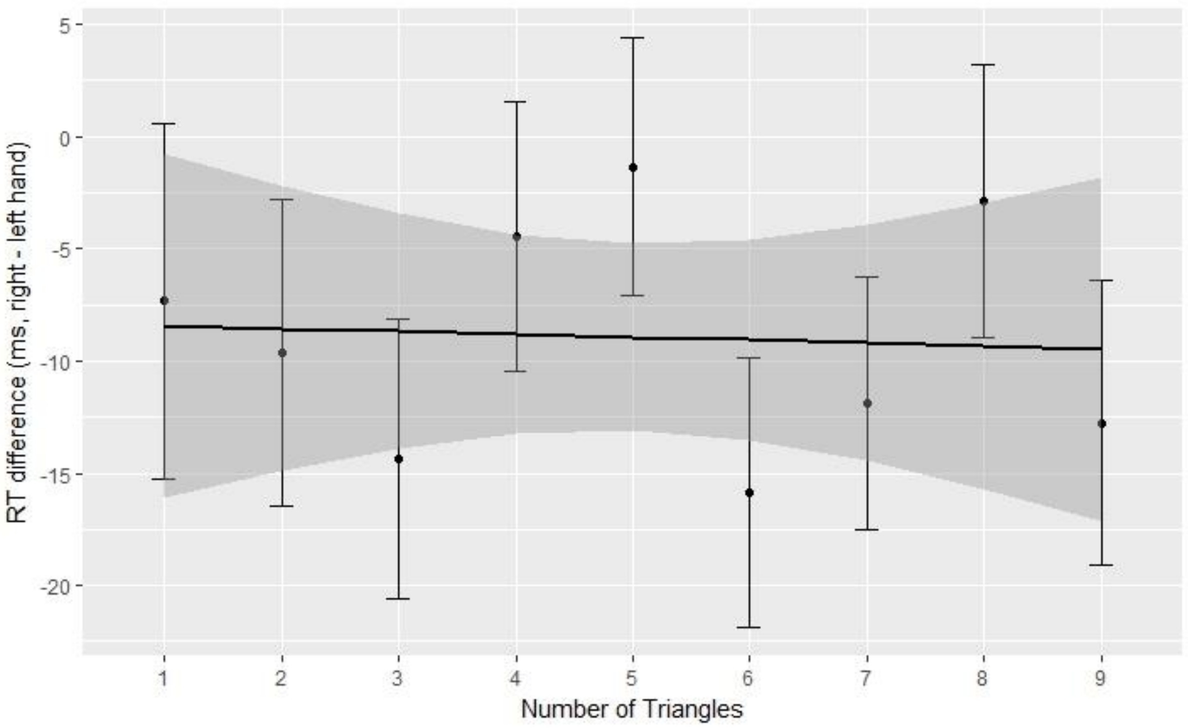

Figure 3. Mean response time difference for each numerosity in Experiment 2. Errors bars show +/-1 standard error. The shaded area shows the 95% confidence interval for the trend line.

An additional analysis was run solely on the subitizing range. As with the full range, there was no evidence of a SNARC effect, mean β = -.011, *t* (63) = -.151, *p* = .881, *d* = .148, CI[-.152, .130], BF_{10} = .103.

In Experiment 3, we did not find evidence of a SNARC effect, despite the fact that numerical and non-numerical cues to magnitude were entirely congruent. On the basis of this finding, we do not believe that the lack of a SNARC effect in Experiments 1 and 2 was due to the conflict in visual cues to magnitude.

Experiment 4 was a more direct replication of Mitchell et al. (2012). In Experiments 1-3, we included a five-triangle array, whereas Mitchell et al. presented either 1-4 or 6-9 triangles. It is possible that this made participants more aware of a “smallness” or “largeness” to the numerosities displayed on the screen, and more likely to assign them a verbal code or polarity (following accounts such as e.g., Gevers, Verguts, et al., 2006; Proctor & Cho, 2006). Another possibility is that some visual property of the placement of the triangles on the screen prompted participants to respond in a SNARC-like manner. A straightforward replication of Mitchell et al. would not allow us to distinguish these possibilities; however, reversing the stimulus set for half of the participants in Experiment 4 allowed us to investigate which was more likely. If the omission of the five-triangle array caused the SNARC effect, we would expect to see a SNARC effect across both sets of stimuli. However, if visual properties of the stimuli caused the effect, we would expect to see a SNARC-like effect for the original stimuli but potentially an eliminated or directionally opposite effect for the reversed stimuli.

Experiment 4

Method

Participants. Sixty-four participants took part in the study (20 men; mean age 23 years, SD = 6.74; 56 right-handed based on self-report). Two further participants were excluded from the analysis based on having made an excessive number of errors (12% and above).

Stimuli and Procedure. The stimuli were arrays of 1 – 9 (excluding 5) equilateral green triangles, which could appear either upright or inverted. The images displayed were taken from the original .bmp files used by Mitchell et al. (2012, Experiment2). The total surface area of the triangles in each array was 452 mm^2, with the surface area of individual triangles varied within this. The triangles occupied a notional circle 60 mm in diameter and were displayed in a green shade selected from the PANTONE^{TM} colour-wheel, green (362C). Whereas Mitchell et al. only displayed one version of each numerosity, we reversed the stimuli on the vertical axis for half of the participants.

Response mapping and stimuli set were counterbalanced across participants such that 16 participants responded to the original set of stimuli using the *M* key for upright triangles and the *Z* key for inverted triangles, and 16 responded to the same stimuli with the reverse mapping. A further 16 participants responded to the reversed set of stimuli using the *M* key for upright triangles and the *Z* key for inverted triangles, and the remaining 16 responded to the reversed stimuli with the reverse response mapping.

The timing of stimulus presentation was identical to Experiments 1 – 3. The experimental session consisted of 256 trials in total (32 presentations of each numerosity, 16 upright, 16 inverted), presented in one block. The rest break was omitted to keep the procedure similar to Mitchell et al.’s Experiment 2. The main experimental session was preceded by a practice block of 16 trials, during which participants were provided with feedback on accuracy and reaction time. No feedback was provided during the experimental block.

Results and Discussion

The mean error rate was 9.25 %, and the mean reaction time for correct trials was 428 ms. A one-sample *t*-test revealed that the regression weight did not differ significantly from 0, mean β = -.018, *t* (63) = -.335, *p* = .739, *d* = .042, CI[-.122, .087]. A Bayesian one-sample *t*-test using a Cauchy prior width of 1.0 yielded a Bayes Factor (BF_{10}) of .104, suggesting moderate evidence for the null hypothesis. The mean response time differences across numerosities are displayed in Figure 4.

An additional analysis was run solely on the subitizing range. As with the full range, there was no evidence of a SNARC effect, mean β = .141, *t* (63) = 1.958, *p* = .055, *d* = .245, CI[-.003, .285]. The Bayesian one-sample *t*-test yielded a Bayes Factor of .616 suggesting only anecdotal evidence for the null hypothesis; however, it should be noted that the regression weight was positive rather than the negative value we would normally expect to see in a SNARC study.

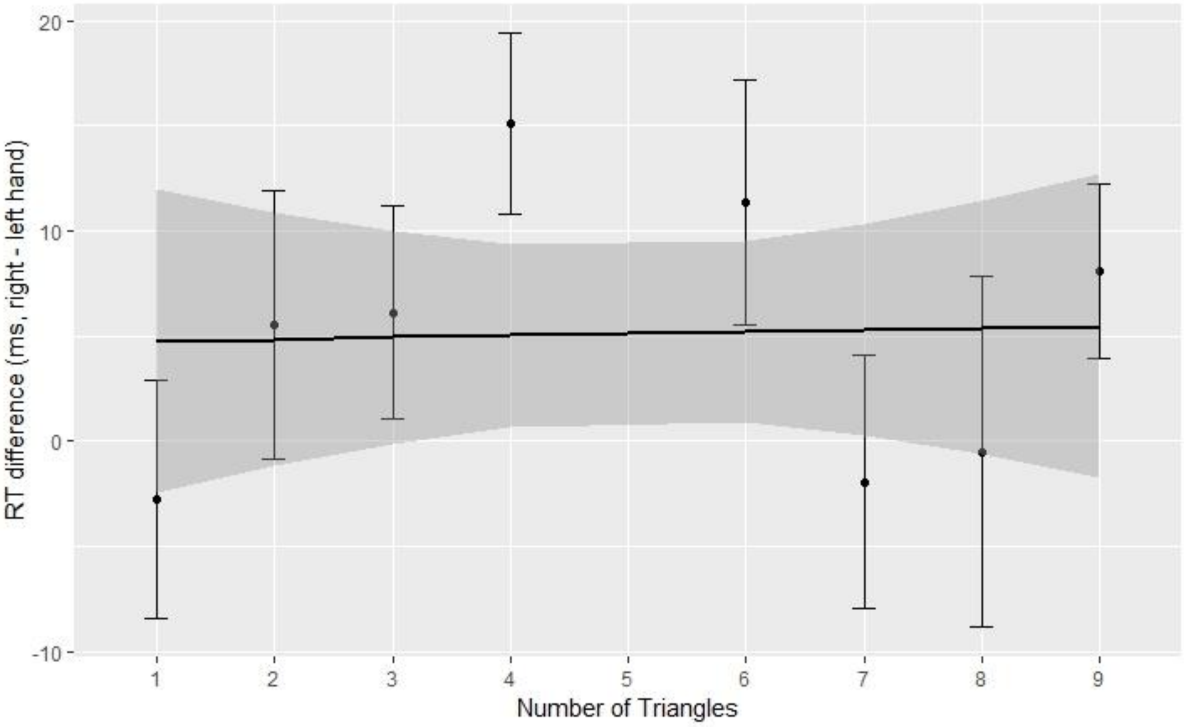

Figure 4. Mean response time difference for each numerosity in Experiment 4. Errors bars show +/-1 standard error. The shaded area shows the 95% confidence interval for the trend line.

An independent samples *t*-test revealed that the regression weight for the original stimuli set ($\beta = -.226$) differed significantly from the regression weight for the reversed stimuli set ($\beta = .191$), *t* (62) = -4.562, *p* < .001, *d* = 1.141, CI [-.599, -.234], BF_{10} = 816.770 (indicating extreme evidence for the hypothesis). When considered alone, the original set of stimuli yielded a negative regression weight that differed significantly from 0, mean $\beta = -.226$, *t* (31) = -3.333, *p* = .002, *d* = .589, CI[-.364, -.088], BF_{10} = 13.998, whereas the reversed set of stimuli yielded a positive regression weight that differed significantly from 0, $\beta = .191$, *t* (31) = 3.116, *p* = .004, *d* = .551, CI[.066, .316], BF_{10} = 8.411. Mean response time differences across all numerosities and split by stimuli condition are presented in Figure 5.

Mitchell et al. (2012) reported the strongest SNARC effect in the subitizing range using this set of stimuli. In order to test whether this finding replicated, we analysed the subitizing range alone for each version of the stimulus set. There was no evidence of a SNARC effect in the subitizing range for the original set of stimuli, mean β = -.040, *t* (31) = -.414, *p* = .681, *d* = .073, CI[-.235, .156], BF_{10} = .149. However, the positive regression weight did differ significantly from 0 for the reversed stimuli in the subitizing range, mean β = .322, *t* (31) = 3.252, *p* = .003, *d* = .575, CI[.012, .524], BF_{10} = 11.542.

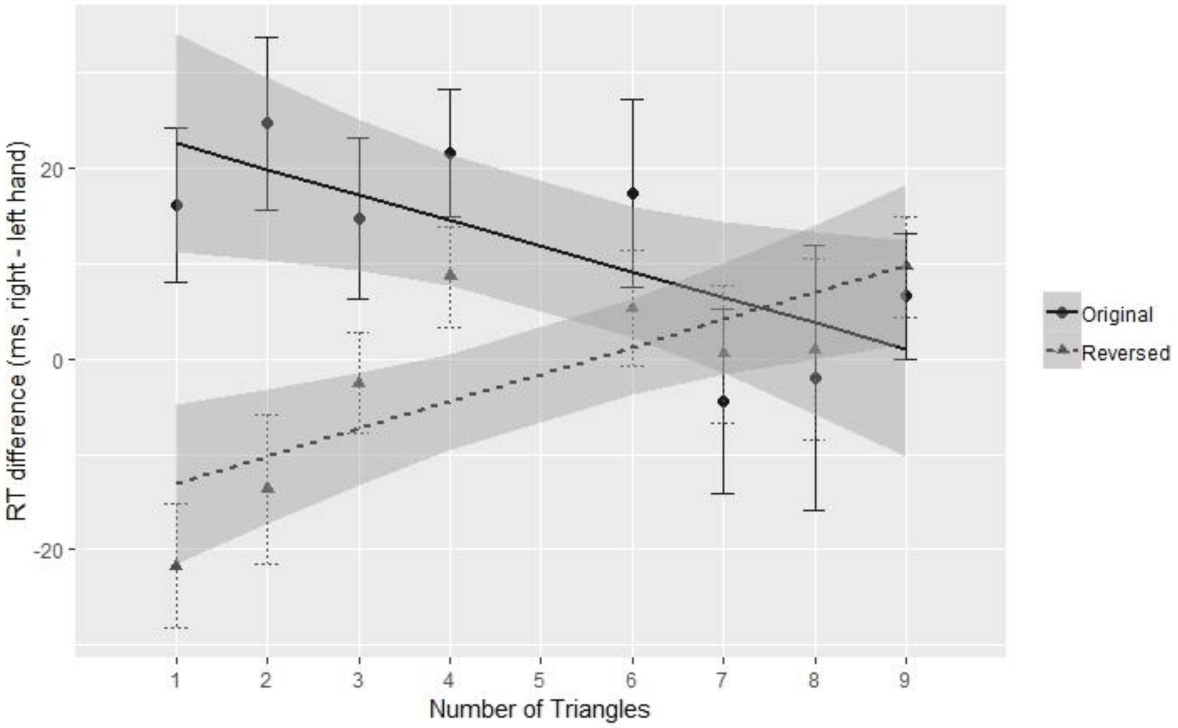

Figure 5. Mean response time difference for each numerosity in Experiment 4 when broken down by the stimuli originally used in Mitchell et al. (2012) (“Original”) and the reversed versions (“Reversed”). Errors bars show +/-1 standard error. The shaded area shows the 95% confidence interval for the trend lines.

To summarise, we did not find an overall SNARC effect in Experiment 4. However, there was an apparent SNARC effect for the original set of stimuli, that was cancelled out by a reverse-SNARC effect in the mirror-reversed stimuli. This finding provides us with strong evidence that the finding of a SNARC effect in Mitchell et al. (2012) was driven by the visual properties of the stimuli rather than by participants coding the 1-4 triangle arrays as “small” and the 6-9 triangle arrays as “large” (had this been the case, we would expect to see a SNARC effects across both stimulus types).

General Discussion

Across four experiments, we found no evidence for a SNARC effect for orientation decisions to non-symbolic representations of number, regardless of whether stimuli were repeated across trials, regardless of whether visual cues to magnitude (in other words, subtended area and aggregate surface area) increased congruently with numerosity, and regardless of whether we focussed solely on the subitizing range. In other words, we did not replicate Mitchell et al.’s (2012) and Simmons et al.’s (in press) findings of a SNARC effect for orientation decisions to non-symbolic number, using a wide range of stimuli, a large sample size, and across four separate studies.

The one exception across our studies was when we used the original stimuli from Mitchell et al. (2012); in this case, we found what appeared to be a left-to-right oriented SNARC effect. However, when participants viewed the same stimuli reversed on the vertical axis, we found a right-to-left oriented effect. This strongly suggests that the visual properties of the stimuli used in Mitchell et al. (2012) may have prompted the SNARC effect. It is difficult to say exactly what it is about the stimuli that could have driven the effect. The most obvious possibility would be that something about the distribution of the shapes influenced responses, for example if more of the triangles appeared to one side of fixation than the other it might cause a SIMON-like effect where left-handed responses were faster. This might create an apparent SNARC effect if all 1-4 arrays had larger triangles on the left and all 6-9 arrays had larger triangles on the right. The stimuli were presented within a notional circle 60 mm in diameter (i.e., 2827 mm^2), and the triangles themselves had a total aggregate surface area of 452 mm^2. On close inspection, we found that some arrays appeared to be slightly off-set to the left within the display circle area. However, upright and inverted versions of the stimuli were mirrored versions of one another (see example of the two- and three-triangle arrays in Figure 6).

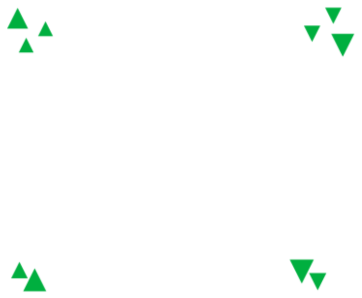

Figure 6. The two- and three-triangle arrays from Mitchell et al.'s (2012) original experiment.

For the upright three-triangle array, we can see that there is more total triangle area towards the left of the array, and that the largest of the three triangles is positioned towards the left of the array. On viewing experimental trials, the stimuli give the impression of being leftwards of the fixation cross. However, the inverted version of the same stimulus is a mirror image and so there is now more total triangle area towards the right, with the largest of the three triangles on the right edge of the array. As such, any influence of stimulus placement should in theory be balanced out across the upright and inverted trials. The two-triangle array has a larger triangle towards the left in the inverted version, but the upright version of the same array has the larger triangle on the right. What does remain constant between the upright and inverted versions of the two-triangle array is that the triangles appear on a diagonal axis running from top left to bottom right, but it seems unlikely that this would matter given findings that suggest a bottom-right to top-left diagonal for the SNARC effect (Gevers, Lammertyn, Notebaert, Verguts, & Fias, 2006). In short, it is hard to say exactly what it is about the stimulus placement that prompted the effect, but it is likely that any effect was exacerbated by the repeated presentation of the same stimuli. This finding underlines the critical importance of presenting a range of stimuli when investigating spatial-numerical associations in non-symbolic stimuli.

Taken together, the general pattern of findings reported here leads us to conclude that non-symbolic, non-canonical representations of number alone are not sufficient to trigger a SNARC effect. We did not run a parallel study with digits to compare across numerical form, but SNARC effects for orientation decisions in digit-based tasks have been reported elsewhere. Fias et al. (2001) reported a SNARC effect for orientation decisions to shapes superimposed upon digits. Similarly, Lammertyn, Fias and Lauwereyns (2002) reported a SNARC effect for orientation decisions to digits that were presented either upright or tilted 10 degrees to the right. The contrasting pattern of findings for non-symbolic number and digits in orientation decision is similar to the pattern for colour decision reported by Cleland and Bull (2019), who found a SNARC effect for colour decisions (when colour onset was manipulated) to digits, but not circles. Taking these results together, the emerging message is that it is unlikely that non-symbolic number spontaneously activates spatial associations with number. More broadly, this finding is generally consistent with research from other forms of numerical notation that indicate that the SNARC effect does not consistently emerge for symbolic number either, and may reflect the nature of the task rather than some inherent and universal cognitive strategy of spatial associations. For example, Shaki and Fischer (2018) reported that spatial-numerical associations do not arise in a parity task when there is no explicit activation of either spatial-directional processing or magnitude processing, and SNARC effects do not arise for colour decision to numbers under the simplest conditions (Cleland & Bull, 2019; Fias et al., 2001).

How do we reconcile the lack of a SNARC effect with the existing literature? If we exclude Mitchell et al. (2012) and Simmons et al. (in press), then (to our knowledge), Bulf et al. (2014) is the only report of SNARC-like effects in adults for non-symbolic number when magnitude is completely irrelevant to the task. Participants detected targets on the right faster when they were preceded by larger numbers (either digits or dot arrays) and faster on the left when preceded by smaller numbers. However, Bulf et al. only used arrays of either two or nine dots; given the findings of Experiment 4 in the current series of studies, we would very much like to see Bulf et al.'s paradigm repeated with a wider range of numerosities. Other findings in adults have used tasks where magnitude is relevant to the task (e.g., Nemeh et al., 2018; Zhou et al., 2016), suggesting a distinction between how magnitude is associated with space (or how those spatial associations are accessed) for implicit and explicit tasks.

While there has been comparatively little research into SNARC effects for non-symbolic number in adults, there are a number of studies that report SNARC (or SNARC-like) effects in young children (e.g., Aulet & Lourenco, 2018; Bulf et al., 2016; de Hevia, Girelli, Addabbo, & Macchi Cassia, 2014; Ebersbach et al., 2014; Patro & Haman, 2012). In many of these studies, magnitude is relevant to the task (Aulet & Lourenco, 2018; Ebersbach et al., 2014; Patro & Haman, 2012), but some have used tasks that did not require magnitude processing. In a modified version of the cueing paradigm used by Bulf et al. (2014) in adults, Bulf et al. (2016) found that two-dot arrays oriented 8-9 month olds' visual attention to the left side of space and nine-dot arrays to the right. De Hevia, Girelli, et al. (2014) found that 7-month-old infants show a preference for a left-to-right orientation for increasing numerosities. Indeed, there is evidence that even non-human animals may associate small numerosities with left-sided space and larger numerosities with right-sided space, including day-old chicks (e.g., Rugani, Vallortigara, Priftis, & Regolin, 2015), rhesus monkeys (Drucker & Brannon, 2014), and chimpanzees (Adachi, 2014; see Rugani & de Hevia, 2017, for a review of number-space associations in preverbal infants and non-human animals). Patro and Haman (2012) used a magnitude decision task, but noted that spatial associations were most apparent in children who were classified as “precounting” on the basis of a pre-test (mean age 3 years 11 months). For the children who understood counting (mean age 4 years 1 month), there was some evidence of an association with space but it only held for the 2-4 range. Taken together, these studies raise the possibility that very young children (and, potentially, non-human animals) hold stronger spatial-numerical associations with non-symbolic number than older children or adults. A speculative hypothesis would be that infants are predisposed to associate number with space (see de Hevia, Izard, Coubart, Spelke, & Streri, 2014, for evidence from neonates), and this underlies early findings of number-space associations in infants and children. However, as children’s daily experience with number shifts from predominantly non-symbolic to predominantly symbolic, their spatial associations may make a corresponding shift and be additionally shaped by factors such as finger counting preferences and writing direction (see, e.g., Fischer, 2012, for discussion of finger counting and SNARC).

Finally, we turn to how our findings might be incorporated into current models of SNARC effects. The most extreme interpretation of a differing pattern for SNARC effects across numerical forms, as advocated by Cohen Kadosh and Walsh (2009), is that it provides evidence against an abstract numerical representation. For example, Cohen Kadosh and Walsh cite Hung et al. (2008) as evidence for non-abstract representations, as Hung et al. found a SNARC effect for parity decision to digits but not to Chinese numerical words. The logic that a notation-independent SNARC effect is evidence for abstract representations has been proposed elsewhere; for example, Nuerk et al. (2005) concluded that “the SNARC effect indexes the existence of an automatic pathway to an amodal semantic magnitude representation” (p. 191), and Bulf et al. (2014) argued that their results supported “the view of an abstract representation of numerical representation" (p. 6). The logic inverse of this would be that a modality-dependent SNARC effect is evidence against abstract representations. However, alternative explanations are possible. It is possible that the difference in SNARC effects for different numerical forms reflects the automaticity of pathways to magnitude (as argued by Dehaene et al., 1993). Under such an account, symbolic and non-symbolic number might access the same shared magnitude representations but differ in the automaticity with which they are accessed. This automaticity could reflect the skill with which people can extract numerical information (e.g. Cantlon, Cordes, Libertus, & Brannon, 2009; Dehaene, 2009; Ganor-Stern, 2009) from different representations of magnitude, or be influenced by the external representations of a given number format that people experience on a day-to-day basis (e.g., rulers, numbers on a QWERTY keyboard).

Under working memory accounts of the SNARC effect, the SNARC effect arises from the spatial coding of ordinal information in working memory (e.g., Fias, van Dijck, & Gevers, 2011; Fischer, Mills, & Shaki, 2010; van Dijck & Fias, 2011; see Fias & van Dijck, 2016 for a review). Short-term numerical-space associations underlie the SNARC effect rather than an explicit and permanent "mental number line". This account is well-supported by findings of apparent spatial associations with different kinds of ordinal information (e.g., Gevers, Reynvoet, & Fias, 2003; van Dijck & Fias, 2011). For example, Gevers et al. reported SNARC-like effects for both months and letters (based on position in the alphabet). Van Dijck and Fias (2011) asked participants to memorise sequences of fruit and vegetables, and then perform a fruit-vegetable categorization task. They found that items presented at the beginning of the memory sequence were responded to faster and more accurately with the left hand than the right hand, whereas items presented towards the end were responded to faster and more accurately with the right hand. We believe that the current findings are consistent with such working memory accounts under the assumption that non-symbolic, non-canonical representations of number are more difficult to conceptualise as an ordinal sequence. This would certainly explain why canonical non-symbolic number in the form of dice patterns (Nuerk et al., 2005) elicit SNARC effects whereas our stimuli do not. It may also explain why SNARC-like effects might arise for some stimulus arrays but not others, if we assume that some arrays are more distinctive. Under this account, we predict that any manipulation that would make the stimuli more memorable might make participants more likely to form a temporary spatial representation of non-symbolic stimuli. This may explain why experiments that use a limited range of stimuli (specifically two-dot and nine-dot, as in Bulf et al., 2014) report a SNARC effect for non-symbolic number.

Conclusion

There is evidence to suggest that people will make spatial associations with non-symbolic number when they process non-symbolic quantities. This is supported by the fact that SNARC-like effects have been reported for magnitude decisions to non-symbolic number in children (e.g., Ebersbach et al., 2014; Patro & Haman, 2012) and adults (Nemeh et al., 2018) and a SNARC effect has been reported for parity decision to dice patterns (Nuerk et al., 2005). However, in a series of four experiments, we do not find any evidence that people *automatically* access spatial-numerical associations when presented with non-symbolic, non-canonical quantities.

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