

Comparing implicit and synaesthetic number-space associations: visuospatial and verbal SNARC effects

Clare N. Jonas¹, Mary Jane Spiller¹, Ashok Jansari¹, and Jamie Ward^{2,3}

¹School of Psychology, University of East London, London, U. K.

²School of Psychology, University of Sussex, Brighton, U.K.

³Sackler Centre for Consciousness Science, University of Sussex, Brighton, U. K.

Submitted to Quarterly Journal of Experimental Psychology

Short title: Synaesthesia and the SNARC effect

Address correspondence to:

Clare N. Jonas,

School of Psychology,

University of East London,

Stratford Campus,

Water Lane,

London E15 4LZ,

United Kingdom

Tel. : +44 (0) 20 8223 4659

E-mail : c.n.jonas@uel.ac.uk

Abstract

In Dehaene's (1992) theory of the mental number line, number and space are implicitly associated, giving rise to the spatial-numerical association of response codes (SNARC) effect, in which smaller numbers are more readily associated with the left side of space, larger numbers with the right, during a parity judgement task. Others, however, have argued that the SNARC effect is flexible (e.g. Bächtold, Baumüller, & Brugger, 1998) and better explained by verbal rather than spatial associations (Proctor & Cho, 2006). A few single-case studies on the SNARC effect have tested number-space synaesthetes, who make explicit associations between number and space. Here, we present data from experiments conducted on groups of synaesthetes and non-synaesthetes on the classic SNARC parity judgement task with lateralised response keys and a modified version in which they responded to labels appearing on-screen (Gevers et al., 2010). Synaesthetes' behaviour was expected to differ from non-synaesthetes' due to the explicit, fixed nature of their number-space associations, but both experiments show the two groups behaving in the same way, indicating that parity judgement tasks may not be tapping the same representation of number that gives rise to synaesthetic number-space experiences.

Keywords: Synaesthesia; SNARC effect; Parity judgement; Numerical cognition

Introduction

According to the triple-code model of numerical cognition (Dehaene, 1992), number is represented in one of three ways: a visual Arabic number form (e.g. 5), an auditory verbal word frame (e.g. “five”) and an analogue magnitude representation (mental number line) that implicitly links number and space. One presumed behavioural consequence of the mental number line is that native speakers of left-to-right written languages, deciding whether a number is odd or even (a parity judgement task), tend to respond faster to small numbers with the left hand and large numbers with the right hand (Dehaene, Bossini, & Giraux, 1993). In participants whose language reads right to left, the difference in response times between hands is reversed (Shaki, Fischer, & Petrusic, 2009). This effect, termed the spatial-numerical association of response codes, or SNARC, has since been replicated repeatedly (see de Hevia, Vallar, & Girelli, 2008, for a review). Similar behaviours indicating spatial biases have sometimes been found for other ordinal sequences such as months and letters of the alphabet (e.g. Dodd, Van der Stigchel, Leghari, Fung, & Kingstone, 2008; Gevers et al., 2003; Price & Mentzoni, 2008).

The SNARC effect is commonly viewed as the result of a direct, automatic link between mental representations of number and space in the parietal cortex (Hubbard, Piazza, Pinel, & Dehaene, 2005), but it has been argued by Gevers, Verguts, Reynvoet, Caessens, and Fias (2006) and Proctor and Cho (2006) that there is an intermediate step of categorisation into verbally-mediated polarities of, for example, odd and even, or small and large. The concepts of left and right also have polarity, so when stimulus and response-side polarities match, the participant responds more quickly than when they are mismatched. In the case of right-left and

even-odd, right and even are unmarked (positive), left and odd are marked (negative), making these pairs more readily associated than their converse, right-odd and left-even. If the polarity-matching hypothesis is true, then the SNARC effect should be flexible – any polarity-bearing pair of verbal labels for portions of space (e.g. up/down, forward/back, near/far) can allow a SNARC effect to emerge in that dimension. In support of this hypothesis, Gevers, Lammertyn, Notebaert, Verguts and Fias (2006) found a SNARC effect in vertical space, while Santens and Gevers (2008) found one for near/far. Furthermore, Gevers et al. (2010, see also Imbo, De Brauwer, Fias, & Gevers, 2012) showed that the SNARC effect can be reversed when participants in parity and magnitude judgement tasks are asked to respond using buttons labelled ‘left’ and ‘right’ on their respective opposite sides (i.e. ‘left’ on the right and ‘right’ on the left), again indicating a verbal, rather than visuospatial, link between number and space.

Another potential impact on the measurement of the SNARC effect is the trait of number-space synaesthesia, in which numbers take on explicit spatial locations in the mind’s eye or around the body (synaesthetic number forms, Galton, 1880). These explicit spatial layouts may also occur with other linguistic sequences such as days, months, or letters of the alphabet and are collectively referred to as sequence-space synaesthesia (e.g. Eagleman, 2009; Jonas, Taylor, Hutton, Weiss, & Ward, 2011; Price & Mentzoni, 2008). Multiple forms of sequence-space synaesthesia often co-occur in the same individual (Sagiv, Simner, Collins, Butterworth & Ward, 2006), indicating a common underlying mechanism.

Synaesthetic number forms are unlike mental number lines in that they are available to conscious experience, and are idiosyncratic in their shapes; however, they do resemble mental number lines in that both involve a mapping of number onto space. The prevalence of number-

space synaesthesia in the general population is estimated to be between 7% and 12% (Phillips, 1897; Sagiv et al., 2006), though there is some uncertainty over the accuracy of these incidence rates (Brang, Teuscher, Ramachandran, & Coulson, 2010). The majority (63-68%) of synaesthetic number forms increase in magnitude from left to right between 1 and 10 (Sagiv et al., 2006) in a sample mostly composed of Westerners. Therefore, the prevalence of synaesthetic number forms that explicitly resemble the assumed shape of the mental number line in Westerners is likely to be between 4% and 8%.

So far, data on the effect of synaesthetic number forms on tasks tapping implicit associations between number and space are restricted to single case studies with synaesthetes whose number forms do not resemble the mental number line. These studies provide mixed evidence on whether synaesthetic number forms can be interpreted as explicit, idiosyncratic mental number lines. Piazza, Pinel, and Dehaene (2006) report a case in which a synaesthetic number form running in the opposite direction to the mental number line did not interfere with the SNARC effect, suggesting that a synaesthetic number form may have no effect on this test. However, when judging which of a pair of digits was larger in magnitude, the synaesthete was much faster at the task when the digits were presented in a spatial layout compatible with his number form (but incompatible with the presumed mental number line). Gevers et al. (2010) suggested that the findings of Piazza et al. could be explained by the SNARC effect resulting from a verbal link between number and space even in synaesthetes, while the magnitude-judgement task results from a visuospatial link.

Two papers challenge this explanation. Jarick, Dixon, Maxwell, Nicholls, and Smilek (2009) found that a synaesthete with a vertically-oriented number form showed a significant

vertical SNARC effect but no horizontal SNARC effect. Hubbard et al. (2009) also tested vertical and horizontal SNARC paradigms with a synaesthete they predicted would show a vertical SNARC effect based on his self-report, but found no significant vertical or horizontal SNARC effect despite his performance on other tasks, such as cued-detection tasks with numerical cues, indicating that his synaesthesia was perceptually real. These findings are all from single-case studies, however, and are limited because there is known to be variation in the strength of individual SNARC effects (e.g. Bull & Benson, 2006; Fischer, 2008). The current study extends past single-case studies on number-space synaesthesia and the SNARC effect to look at a larger sample of number-space synaesthetes in the SNARC paradigm, much as Price and Mentzoni (2008) investigated the month-SNARC effect in a group of time-space synaesthetes.

In the single-case studies outlined above, synaesthetes' number forms took on shapes that differed from cultural norms about implicit relationships between number and space. By contrast, in our study, synaesthetes' number forms and cultural expectations are aligned. Since most synaesthetes have synaesthetic number forms that resemble the mental number line, the presence of those particular synaesthetes in a group of participants being tested on the SNARC paradigm *may* result in a stronger SNARC effect than a group of non-synaesthetes would have displayed. However, given previous single-case studies on number-space synaesthetes and Price and Mentzoni (2008) showing that the idiosyncratic month-SNARC effects of synaesthetes are no larger than the typical month-SNARC effects of non-synaesthetes, it is also possible that there will be no effect of synaesthesia on the strength of the SNARC effect in this study. The first aim of this study was to determine whether the SNARC effect is stronger in a group of synaesthetes whose number forms resemble the assumed shape of the mental number line

than it is in the general population. In Experiment 1, synaesthetes and non-synaesthete controls completed a straightforward parity judgement task (Figure 1a) – pressing a key on the left side of a keyboard when visually presented with an odd number and a key on the right for an even number (or vice versa). The hypothesis here was that a SNARC effect would appear in both groups, as has been found with non-synaesthete participants many times (e.g. Bull & Benson, 2006; Dehaene, et al., 1993; Fias, Brysbaert, Geypens, & d'Ydewalle, 1996), and that it would potentially be stronger in synaesthetes (though note our caveats above).

A second aim, given the explicit and fixed nature of synaesthetic number forms, was to test whether synaesthetes show a polarity-matching effect as in Gevers et al. (2010). In Experiment 2, participants with and without number forms were given the task created by Gevers et al. (2010). This differs from the classic SNARC paradigm in that, while the buttons remain in the same locations (to the left and right of the participant's midline) for every trial, their meanings ('left' and 'right', assigned by on-screen labels located near the buttons) change (or do not change) at random for each trial (Figure 1b). Such a change means that the effect of the verbal labels 'left' and 'right' can be isolated from their physical locations. More specifically, in each trial a number was visually presented between two lateralised labels, *LEFT* and *RIGHT*. These two labels could appear in the canonical locations (i.e. *LEFT* on the left, *RIGHT* on the right) or in the noncanonical locations, randomised on a trial-by-trial basis. Participants were asked to press the key on the side of the keyboard nearest the *LEFT* label for even numbers and the key nearest the *RIGHT* label for odd numbers (or vice versa). In Gevers et al. (2010), non-synaesthete participants showed a SNARC effect in line with the labels on the screen, rather than one dependent on the side of space on which the response was made, indicating that the

SNARC effect is verbal in nature. In the current experiment, it was predicted that the polarity-matching effect would be replicated in non-synaesthetes. In synaesthetes, this effect might or might not appear. If it did not appear, this would indicate a direct link between number and space (as opposed to the indirect verbal link predicted for non-synaesthetes). If it did appear, this could indicate that the SNARC paradigm does not tap the direct link between number and space that synaesthetes make (Gevers et al., 2010), or that synaesthetes are making verbal links between number and space, despite their phenomenological experience of numbers ‘belonging to’ particular locations in space rather than to verbal descriptions of those locations.

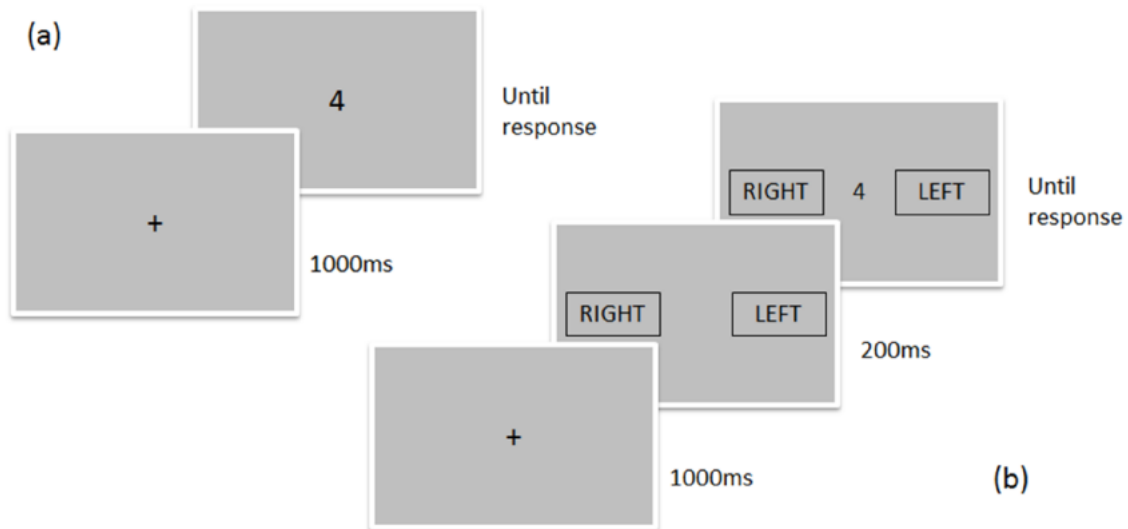


Figure 1: Trial structure in (a) Experiment 1 and (b) Experiment 2). In a task where even numbers require a response designated left, participants would press the backslash key in Experiment 1 and the full stop key in Experiment 2.

Experiment 1

Methods

Participants

Twenty synaesthetes with number forms (recruited from the University of Sussex synaesthesia database) and twenty-six non-synaesthetes (recruited from the colleagues and other contacts of the researchers) took part in this experiment. Only synaesthetes who consistently reported number forms that increased in magnitude from left to right (on the horizontal axis) between 0 and 10 were selected for participation. Before participating in the study, synaesthetes provided drawings of their number forms, and the consistency of the drawings with verbal reports was checked after completion. Synaesthetes had a mean age of 25.50 years (*S.D.* = 9.85, range = 19-62; 14 female) and non-synaesthetes had a mean age of 28.12 years (*S.D.* = 12.89, range = 18-64; 18 female). All participants were native speakers of English. After participating, non-synaesthetes received a brief description of number-space synaesthesia and were asked if they experienced anything similar.

Materials and procedure

Participants were seated in front of a monitor, on which a central fixation cross was presented for 1000ms, followed by a number in the range 1-9 in 24-point Courier New, until a response was made (Figure 1a). Using a standard UK keyboard, participants were asked to press either the backslash (\) key (on the left side of the keyboard) with their left hand or full stop (.) key (on the right) with their right hand to indicate a decision that the presented number was

odd or even, and to do so as quickly and accurately as possible. Numbers were presented in a randomised order. In one version of the experiment, the backslash key was designated 'odd'; in the other, it was designated 'even'. Participants completed both tasks (to control for hand-response assignment), and the order of tasks was counterbalanced across participants (to control for practice effects). In each version of the task, each number was presented 20 times, for a total of 360 trials across versions.

Results

Before analysis, all data were screened for errors and reaction times (RTs) under 300ms. Subsequently, outliers beyond 3 standard deviations (*S.D.*) from each participant's mean were iteratively removed (following Smilek, Callejas, Dixon, & Merikle, 2007).

To determine whether a SNARC effect existed in our two groups of participants, we used the method of Fias et al. (1996). For each participant, a regression slope was taken of the difference in mean RT between right and left hands (dRT) on number magnitude. Slopes were compared against zero (i.e. no dRT) using a one-sample t-test (see Supplementary Table 1 for individual SNARC slopes).

Figure 2 shows regression slopes for grand mean dRTs on magnitude in the synaesthete and non-synaesthete groups. Since Kolmogorov-Smirnoff tests indicated that data were normally distributed in each participant group, we used parametric tests. One-sample t-tests showed that the synaesthetes' slopes were significantly different from zero, $t(19) = 2.19$, $p = .02$ (one-tailed), $d = 0.49$, $M = -6.44$ ms per digit, $S.D. = 13.13$, range = -48.62 to 19.81. Non-synaesthetes' slopes were borderline significant, $t(25) = 1.70$, $p = .05$ (one-tailed), $d = 0.33$, $M =$

-2.44ms per digit, $S.D. = 7.41$, range = -21.13 to 9.35. A between-subjects t-test showed that there was no significant difference between groups, $t(44) = 1.32$, p (two-tailed) = .20, $d = 0.39$.

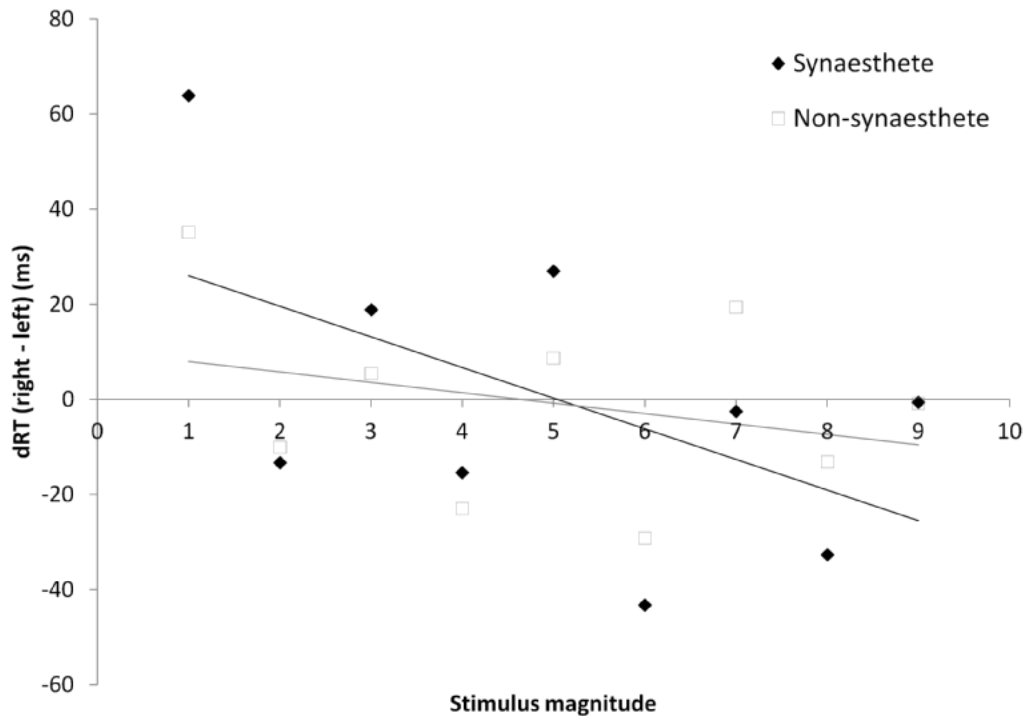


Figure 2: Difference in RT between right and left hand at different stimulus magnitudes for synaesthetes and non-synaesthetes.

Discussion

Experiment 1 was designed to test for SNARC effects in synaesthetes and non-synaesthete groups. Past research did not allow us to make a prediction of the relative strengths of the effects for synaesthetes and non-synaesthetes. In fact, the two groups showed non-significantly different SNARC effects. Interestingly, despite this result, synaesthetes have a much wider range of SNARC slopes than non-synaesthetes do, in both positive and negative

directions. Note, though, that the single largest negative slope in the synaesthete group is --48.62, while the next largest is -22.26, so the removal of the participant with that largest negative slope would render the two groups' ranges more comparable. Even discounting this anomalously large slope, the behaviour of synaesthetes varies substantially, though their experiences are relatively uniform in one respect (i.e. the layout of the number form). This may be due to variation in other aspects of their experiences, such as the strength with which a synaesthetic number form is activated, or whether the SNARC task activates it at all. We return to this point in the general discussion.

The borderline significant result in the non-synaesthete group is unusual given the strong replicability of the SNARC effect. In line with our hypotheses, it may be that the likely presence of at least some synaesthetes with left-to-right number forms in SNARC experiments is driving the SNARC effect to some extent (or at least making the SNARC effect appear stronger than it really is); when synaesthetes are not present, the SNARC effect diminishes. Another possible explanation is that the mainly female participant group has diminished the SNARC effect (see Bull, Cleland, & Mitchell, 2013), though given that the synaesthete group is also largely female we would expect to see a diminished SNARC effect in both groups.

The SNARC effects we found may have similar or different causes in each group. If Dehaene (1992) is correct, then both groups are responding to number lines – one group to an implicit mental version (the mental number line), the other to an explicit synaesthetic version (the synaesthetic number form). However, if the polarity-matching hypothesis (e.g. Santens & Gevers, 2008) is correct, then the non-synaesthete group are using verbal labels to categorise

numbers with the side-effect of a SNARC effect while synaesthetes could be using verbal labels or relying on their synaesthetic number form. This is explored further in Experiment 2.

Experiment 2

Methods

Participants

Nineteen synaesthetes with number forms (recruited from the University of Sussex synaesthesia database) and twenty non-synaesthetes (recruited from among the colleagues and other contacts of the researchers) took part in this experiment. Nine of the synaesthetes had previously taken part in Experiment 1. Again, all synaesthetes had number forms which increased in magnitude between 0 and 10 from left to right in the horizontal axis. Selection criteria and consistency assessments were the same as those used in Experiment 1. Synaesthetes had a mean age of 38.95 years (S.D. = 18.03, range = 20-72; 15 female) and non-synaesthetes had a mean age of 38.00 years (S.D. = 15.56, range = 22-67; 16 female). All participants were native speakers of English.

Materials & Procedure

Participants were seated in front of a monitor, on which a central fixation cross was presented for 750ms, followed by two labels (*LEFT* and *RIGHT*) contained in rectangular boxes to the left and right of the fixation cross. After 200ms, a number in the range 1-9 (excluding 5) appeared between the boxes. All labels and numbers were presented in 12-point Arial. Labels could appear in the canonical positions (i.e. *LEFT* on the left and *RIGHT* on the right) or in the

noncanonical positions (i.e. *LEFT* on the right and *RIGHT* on the left; Figure 1b). Numbers were presented in a randomised order and label locations were randomly assigned for each trial.

Using a standard UK keyboard, participants were asked to press either the backslash (\) key with their left hand or full stop (.) key with their right hand to indicate a decision that the presented number was odd or even, and to do so as quickly and accurately as possible. Half the participants were first given the rule 'press the key nearest the label that says *LEFT* when you see an even number and the key nearest the label that says *RIGHT* when you see an odd number' (see Figure 1). Halfway through the experiment, the participants were asked to switch to the opposite rule (*LEFT*-odd, *RIGHT*-even). The other half of the participants received the rules in the reversed order to control for hand-response assignment and practice effects. In each version of the task, each number was presented 40 times, for a total of 640 trials across versions.

At the beginning of the experiment, all participants received written and verbal explanations of the rule followed by sixteen practice trials with the first rule. A reminder of the rule then preceded four blocks of 80 trials each. This sequence of events was repeated for the second rule, but the verbal explanation was omitted. Participants were warned during the verbal explanation at the beginning of the experiment that the rule would change halfway through the experiment.

Results

Two synaesthete participants were removed from the data set before analysis: one had misunderstood the instructions, and another reported an inconsistent synaesthetic number form. Before analysis, the data were processed in the same manner as in Experiment 1.

To test whether the SNARC effect relied on the location of the on-screen labels, we used a procedure similar to Gevers et al. (2010). Firstly, each participant's trials were split into canonical (*LEFT* on the left and *RIGHT* on the right) and noncanonical (*LEFT* on the right and *RIGHT* on the left). Secondly, mean dRT for left and right hands was calculated for each stimulus magnitude. Thirdly, dRT was regressed on magnitude to obtain a regression slope, as in Experiment 1 (see Supplementary Table 2 for individual SNARC slopes). Synaesthetes' slopes in the canonical condition were non-normally distributed (Kolmogorov-Smirnov $D = .22$, $N = 17$, $p = .04$) and synaesthetes' and non-synaesthetes' slopes in the noncanonical condition were borderline non-normally distributed (respectively, Kolmogorov-Smirnov $D = .20$, $N = 17$, $p = .07$ and Kolmogorov-Smirnov $D = .19$, $N = 20$, $p = .06$), so the data was transformed such that 50 was added to each datapoint (to ensure all datapoints were positive) and the square root was taken. A 2x2 mixed ANOVA was then conducted to test for effects of group (synaesthete, non-synaesthete) and canonicity (canonical labels, noncanonical labels).

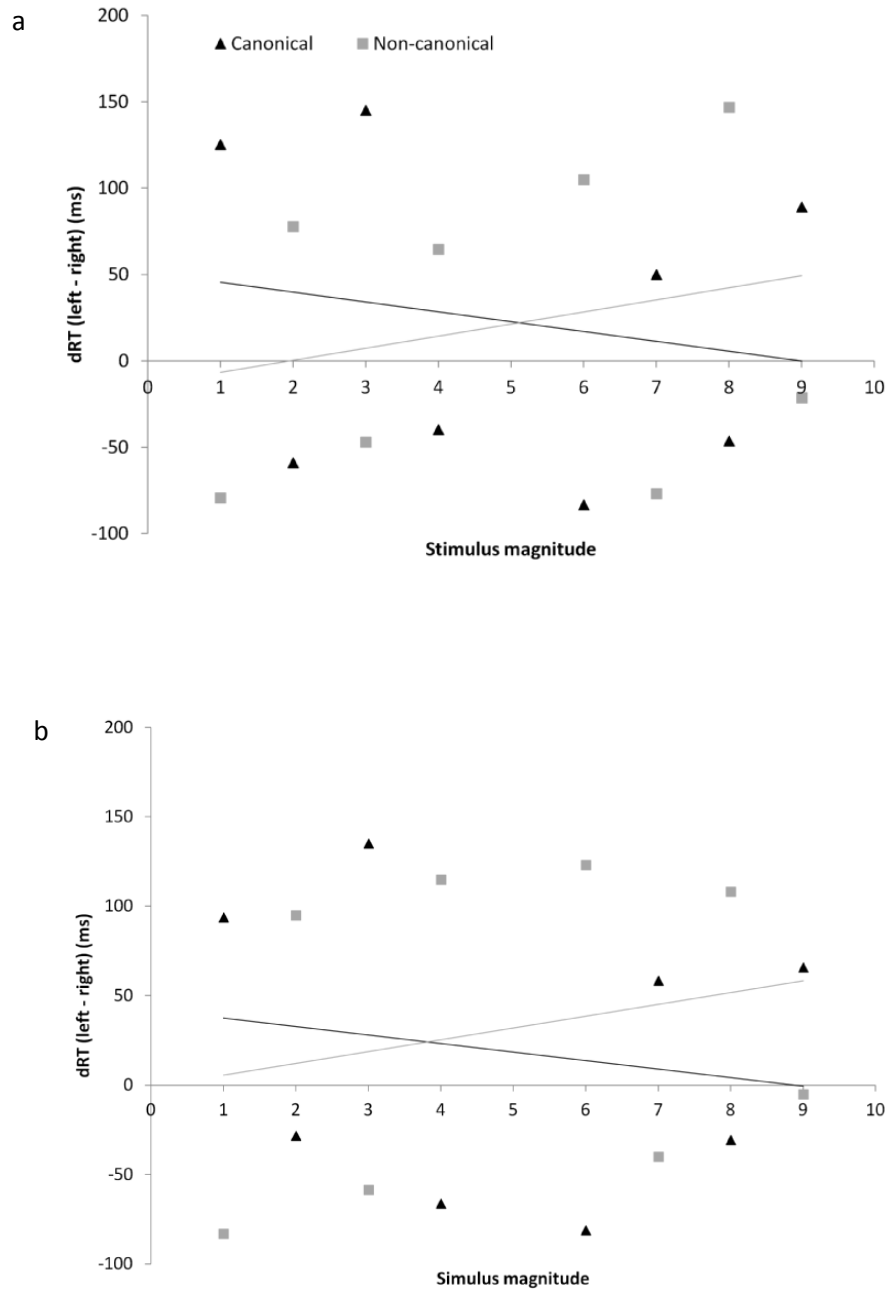


Figure 3: Difference in RT between right and left hand at different stimulus magnitudes in canonical and noncanonical conditions for (a) synaesthetes and (b) non-synaesthetes.

There was a significant main effect of canonicity, $F(1,35) = 10.36$, $p < .01$, $\eta^2 = .22$) but no other main effect or interaction (all $ps > .69$). The direction of the SNARC effect was

influenced by the labels on the screen such that the *LEFT* label always obtained faster responses for small numbers than for large numbers, and vice versa for the *RIGHT* label (mean slope for canonical condition = -5.23ms per digit, for noncanonical condition = 6.79ms per digit; see Figure 3).

Using non-transformed data, one-sample Wilcoxon tests showed that neither of the conditions for either group resulted in a slope that was significantly different from zero (synaesthete canonical $p = .29$, median = -7.89ms per digit; interquartile range = 19.30, range = -47.75 to 23.89; synaesthete noncanonical $p = .06$, median = 5.41, interquartile range = 11.11, range = -21.76 to 34.62; non-synaesthete canonical $p = .12$, median = -6.69, interquartile range = 16.84, range = -27.80 to 19.95; non-synaesthete noncanonical $p = .09$, median = 2.56, interquartile range = 23.82, range = -10.60 to 29.42).

Discussion

As with Experiment 1, similar results are seen in synaesthete and non-synaesthete groups, suggesting that the task activates a similar representation of number in each group, though again, synaesthetes have a wider range of slopes than non-synaesthetes, more obviously so in the canonical condition. Here, several synaesthetes have very large negative slopes in the canonical condition and very large positive slopes in the non-canonical condition, suggesting that large SNARC slopes are indeed a relatively common finding in synaesthete populations.

While the Wilcoxon tests indicate that neither synaesthetes' nor non-synaesthetes' slopes are significantly different from zero in either experimental condition, the ANOVA shows that there is an effect of canonicity. On balance, we are inclined to believe that the effect of canonicity is evident as the parametric ANOVA is more sensitive than the nonparametric Wilcoxon. We conclude that *both* groups are responding to verbal labels rather than to particular sides of space in producing SNARC effects, though more strongly in the noncanonical than in the canonical condition. The findings also support Gevers et al. (2010), indicating that the SNARC effect is accounted for by polarity matching rather than a direct link between number and space. That the synaesthetes and the non-synaesthetes behaved in the same way was unexpected, since synaesthetes report that synaesthetic number forms are inflexible. Further, this similar result in the two groups may indicate that synaesthetic number forms are not automatically activated in every situation, though whether this is the case depends on the underlying mechanism that gives rise to the experience of the number form, an idea we explore in the general discussion.

General discussion

In summary, the results from Experiment 1 show that number-form synaesthetes and non-synaesthetes are both susceptible to the SNARC effect. Experiment 2 shows that for both groups, the SNARC effect can be linguistically mediated. Not only is this a novel finding for synaesthetes, it also replicates Gevers and colleagues' (2010) finding with non-synaesthetes and supports their hypothesis that the SNARC effect has a verbal basis. Following from Bächtold et al. (1998), this could indicate that the SNARC effect in non-synaesthetes is a strategic response to the parity judgement task and that the default response is to categorise small

numbers with left and large numbers with right because it fits in with reading habits (see also Gevers, Verguts, et al., 2006) or finger-counting habits (Fischer, 2008). However, this result must also be explained for the synaesthete group. We discuss three possible explanations.

Firstly, as Gevers et al. (2010) suggest, synaesthetes may have both verbal and visuospatial links between number and space, with the verbal link supporting an implicit number-space association (the mental number line) and the visuospatial link giving rise to explicit synaesthetic experiences. In this view, the task in Experiment 2 taps the non-synaesthetic verbal link, but we cannot be sure from the current study whether Experiment 1 taps the verbal or the visuospatial link. Here, we can turn to single-case studies of vertical synaesthetic number forms conducted by Hubbard et al. (2009) and Jarick et al. (2009), both of which used parity judgement tasks of the same type as our Experiment 1. If the verbal link were activated during this type of task, we would expect to see a horizontal (i.e. culturally typical) (and no vertical) SNARC effect, while an activation of the visuospatial link would lead to vertical (and no horizontal) SNARC effects. In this case, we can argue that viewing a number *may* involuntarily activate synaesthesia, but synaesthesia is visuospatial and does not interact with the SNARC effect. In fact, Hubbard et al.'s participant DG showed no significant horizontal or vertical SNARC effect, while Jarick et al.'s participant L showed no significant horizontal SNARC effect, but did show a significant vertical SNARC effect, indicating that for L the visuospatial link was activated, while for DG neither visuospatial nor verbal link appears to be activated. However, SNARC effects can vary widely at the individual level, making the absence of an effect hard to interpret in these single-case studies. Further experimentation will be needed to determine whether Gevers and colleagues' hypothesis is actually true.

Secondly, synaesthetes who have a synaesthetic number form that resembles the putative mental number line may be special cases. Rather than having a combination of verbal and visuospatial links between number and space, they have only verbal links. Here, the only difference between synaesthetes and non-synaesthetes is that the former have explicit knowledge of the relative positions of numbers in space, while the latter do not. This special-case explanation is compatible with the differing findings of this study, Piazza et al. (2006), Hubbard et al. (2009) and Jarick et al (2009), but remains neutral with respect to the question of synaesthesia's automaticity. However, it is not clear *why* this particular group would differ from other synaesthetes. Once again, further research would be needed to test whether special cases exist.

The final explanation is that *all* synaesthetes make entirely verbal links between number and space, despite their phenomenological experience of numbers as occupying particular locations in space. This hypothesis has been discounted by Gevers et al. (2010), because when Piazza and colleagues' (2006) synaesthete SW carried out a magnitude judgement task with two digits, he behaved in line with his self-reported synaesthetic number form; conversely, when carrying out a SNARC task, he produced a typical SNARC effect, against his synaesthetic number form. Gevers et al. interpreted these results as being caused by visuospatial number-space links in the magnitude judgement task and verbal number-space links in the parity judgement task. However, neither task involved manipulation of verbal labels, so we cannot rule out the possibility that both behaviours were caused by verbal links of different sorts. This explanation does, however, require that SW was able to conceive of small numbers as being of the same polarity as the label 'right' in the magnitude judgement experiment, but of the same as the

label 'left' in the parity judgement experiment. One possible reason for SW being able to do this is based on conflicting information: while his synaesthetic number form links 'right' and 'small', his finger-counting habits or his culture link 'left' and 'small'. These differing behaviours indicate that such a synaesthete would not have an automatically activated number form.

Of course, it is possible that there are individual number-space synaesthetes of each of the three varieties above (and perhaps other varieties), potentially giving rise to the wide range of SNARC effect strengths seen in our synaesthete groups as compared to our control groups. Given that many studies in the area of number-space synaesthesia rely on single-case studies (e.g. Hubbard et al., 2009; Jarick et al., 2009; Piazza et al., 2009) or very small groups of synaesthetes (e.g. Gertner, Limor & Cohen Kadosh, 2009), this raises the question of whether it is appropriate to generalize a particular finding from one or a few number-space synaesthetes to synaesthetes more generally, or even to other number-space synaesthetes. Even within a subtype of synaesthesia, there may be those who perceive their synaesthesia literally and those who experience it as a form of mental imagery (Dixon, Smilek, & Merikle, 2004), or those for whom synaesthesia is driven by concepts and those for whom it is driven by percepts (Ramachandran & Hubbard, 2001). These factors emphasise the importance of larger-scale studies than are typically carried out in this field of research.

Another, more practical concern arises from our findings. Given that synaesthetes do not differ from non-synaesthetes on either of the experiments above, it is pertinent to ask whether tasks tapping the SNARC effect are actually of use in verifying the self-reports of synaesthetes. Price and Mattingley (2013) have recently asked the same question, arguing that SNARC tasks are not particularly sensitive to the subtleties of synaesthetic number forms as

they require participants to make a blunt division into left and right rather than a fine-grained division into (for example) far-upper-left, near-upper-left, near-lower-left, and so on. Price and Mattingley add that the idiosyncratic SNARC effects that some synaesthetes display can be mimicked through intentional mental imagery strategies (see Price, 2009, for an example with a month-SNARC effect), and that synaesthetes' SNARC effects are no stronger than non-synaesthetes', though this was based on a small number of single-case or small-sample studies. As well as strengthening their argument, we can add the finding that, as in non-synaesthetes, synaesthetes' SNARC effects are the result of verbal links between number and space (at least in the version of the SNARC paradigm presented in Experiment 2). Whether this is also the case for other experimental paradigms tapping links between number and space is not yet clear.

Recently, Jonas and Jarick (2013) have discussed behavioural paradigms that may be better able to distinguish sequence-space synaesthetes and non-synaesthetes. Currently, SNARC and SNARC-like tests are used alongside consistency tests and attentional cueing tasks, but each of these tests and tasks has its own problems. For example, consistency and cueing tests are usually carried out in two-dimensional space, while a synaesthete's form may occupy three-dimensional space. Jonas and Jarick suggest some alterations to these tasks to alleviate these problems, for example carrying out each of these tasks in three-dimensional space using body movement tracking to allow synaesthetes to point to the locations of sequence members, and eye-tracking in a virtual three-dimensional environment to capture cued target detection more accurately. They also point out that a combination of tests would be more helpful than a single test in assessing a participant's status as a synaesthete.

Synaesthetes are different from non-synaesthetes in many respects. However, the current study shows that during parity judgment tasks, the two groups behave in a very similar way. This has theoretical implications for the understanding of the synaesthetic number form as a visuospatial coding for number: our findings may indicate that number-space synaesthesia is verbal rather than visuospatial in nature, or alternately that viewing a number does not automatically activate a number form (in agreement with Price and Mattingley, 2013). Consequently, SNARC-type paradigms may not provide a useful means for distinguishing between non-synaesthetes and number-space synaesthetes with a number form that is consistent with the implicit links between space and number made by the cultures around them, though they may still be useful in distinguishing synaesthetes with more idiosyncratic number forms from the general population.

References

- Bächtold, D., Baumüller, M., & Brugger, P. (1998). Stimulus-response compatibility in representational space. *Neuropsychologia*, *36*(8), 731-735. doi: 10.1016/S0028-3932(98)00002-5
- Brang, D., Teuscher, U., Ramachandran, V. S., & Coulson, S. (2010). Temporal sequences, synesthetic mappings, and cultural biases: The geography of time. *Consciousness and Cognition*, *19*, 311–320. doi: 10.1016/j.concog.2010.01.003
- Bull, R., Cleland, A. A., & Mitchell, T. (2013). Sex Differences in the Spatial Representation of Number. *Journal of Experimental Psychology: General*, *142*(1), 181-192. doi: 10.1037/a0028387

Bull, R., & Benson, P. J. (2006). Digit ratio (2D:4D) and the spatial representation of magnitude.

Hormones and Behavior, 50(2), 194-199. doi: 10.1016/j.yhbeh.2006.02.008

de Hevia, M. D., Vallar, G., & Girelli, L. (2008). Visualizing numbers in the mind's eye: The role of

visuo-spatial processes in numerical abilities. *Neuroscience and Biobehavioral Reviews*,

32(8), 1361-1372. doi: 10.1016/j.neubiorev.2008.05.015

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition*, 44(1-2), 1-42. doi: 10.1016/0010-

0277(92)90049-N

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number

magnitude. *Journal of Experimental Psychology: General*, 122(3), 371-396. doi:

10.1037/0096-3445.122.3.371

Dixon, M. J., Smilek, D., & Merikle, P. M. (2004). Not all synaesthetes are created equal:

Projector versus associator synaesthetes. *Cognitive, Affective, & Behavioral*

Neuroscience, 4(3), 335-343. doi: 10.3758/CABN.4.3.335

Dodd, M. D., Van der Stigchel, S., Leghari, M. A., Fung, G., & Kingstone, A. (2008). Attentional

SNARC: There's something special about numbers (let us count the ways). *Cognition*,

108(3), 810-818. doi: 10.1016/j.cognition.2008.04.006

Eagleman, D. M. (2009) The objectification of overlearned sequences: a new view of spatial

sequence synesthesia. *Cortex*, 45, 1266–1277. doi:10.1016/j.cortex.2009.06.012

- Fias, W., Brysbaert, M., Geypens, F., & d'Ydewalle, G. (1996). The importance of magnitude information in numerical processing: Evidence from the SNARC effect. *Mathematical Cognition*, 2(1), 95-110. doi: 10.1080/135467996387552
- Galton, F. (1880). Visualised numerals. *Nature*, 21, 252-256. doi: 10.1038/021252a0
- Gevers, W., Lammertyn, J., Notebaert, W., Verguts, T., & Fias, W. (2006). Automatic response activation of implicit spatial information: Evidence from the SNARC effect. *Acta Psychologica*, 122(3), 221-233. doi: 10.1016/j.actpsy.2005.11.004
- Gevers, W., Reynvoet, B., & Fias, W. (2003). The mental representation of ordinal sequences is spatially organized. *Cognition*, 87(3), B87-B95. doi: 10.1016/S0010-0277(02)00234-2,
- Gevers, W., Santens, S., Dhooge, E., Chen, Q., van den Bossche, L., Fias, W., & Verguts, T. (2010). Verbal-spatial and visuospatial coding of number-space interactions. *Journal of Experimental Psychology: General*, 139(1), 180-190. doi: 10.1037/a0017688
- Gevers, W., Verguts, T., Reynvoet, B., Caessens, B., & Fias, W. (2006). Numbers and space: A computational model of the SNARC effect. *Journal of Experimental Psychology: Human Perception and Performance*, 32(1), 32-44. doi: 10.1037/a0017688
- Fischer, M. (2008). Finger counting habits modulate spatial-numerical associations. *Cortex*, 44, 386-392. doi: 10.1016/j.cortex.2007.08.004

Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interactions between number and space in parietal cortex. *Nature Reviews Neuroscience*, *6*(6), 435-448. doi:

10.1038/nrn1684

Hubbard, E. M., Ranzini, M., Piazza, M., & Dehaene, S. (2009). What information is critical to elicit interference in number-form synaesthesia? *Cortex*, *45*(10), 1200-1216. doi:

10.1016/j.cortex.2009.06.011

Imbo, I., De Brauwer, J., Fias, W. and Gevers, W. (2012). The development of the SNARC effect: Evidence for early verbal coding. *Journal of Experimental Child Psychology*, *111*, 671-

680. doi: 10.1016/j.jecp.2011.09.002

Jarick, M., Dixon, M. J., Maxwell, E. C., Nicholls, M. E. R., & Smilek, D. (2009). The ups and downs (and lefts and rights) of synaesthetic number forms: Validation from spatial cueing and SNARC-type tasks. *Cortex*, *45*(10), 1190-1199. doi: 10.1016/j.cortex.2009.04.015

Jonas, C., & Jarick, M. (2013). Synaesthesia, sequences, and space. In J. Simner & E. Hubbard (Eds.), *Oxford Handbook of Synaesthesia* (pp. 123-148). Oxford: Oxford University Press.

Jonas, C.N., Taylor, A. J. G., Hutton, S., Weiss, P. H., & Ward, J. (2011). Visuo-spatial representations of the alphabet in synaesthetes and non-synaesthetes. *Journal of Neuropsychology*, *5*(2), 302-322. doi: 10.1111/j.1748-6653.2011.02010.x

- Gertner, L., Henik, A., & Cohen, K. R. (2009). When 9 is not on the right: implications from number-form synesthesia. *Consciousness and Cognition, 18*(2), 366. doi: 10.1016/j.concog.2009.02.005.
- Nuerk, H. C., Iversen, W., & Willmes, K. (2004). Notational modulation of the SNARC and the MARC (linguistic markedness of response codes) effect. *Quarterly Journal of Experimental Psychology, Section A: Human Experimental Psychology, 57*(5), 835-863. doi: 10.1080/02724980343000512
- Piazza, M., Pinel, P., & Dehaene, S. (2006). Objective correlates of an unusual subjective experience: A single-case study of number-form synaesthesia. *Cognitive Neuropsychology, 23*(8), 1162-1173. doi: 10.1080/02643290600780080
- Phillips, D. E. (1897). Genesis of number forms. *The American Journal of Psychology, 8*(4), 506-527. Retrieved from <http://www.jstor.org/stable/1411774>
- Price, M. C. (2009). Spatial forms and mental imagery. *Cortex, 45*, 1229-1245. doi: 10.1016/j.cortex.2009.06.013
- Price, M. C., & Mattingley, J. B. (2013). Automaticity in sequence-space synaesthesia: A critical appraisal of the evidence. *Cortex, 49*(5), 1165-1186. doi: 10.1016/j.cortex.2012.10.013
- Price, M. C., & Mentzoni, R. A. (2008). Where is January? The month-SNARC effect in sequence-form synaesthetes. *Cortex, 44*(7), 890-907. doi: 10.1016/j.cortex.2006.10.003

- Proctor, R. W., & Cho, Y. S. (2006). Polarity correspondence: A general principle for performance of speeded binary classification tasks. *Psychological Bulletin*, *132*(3), 416-442. doi: 10.1037/0033-2909.132.3.416
- Ramachandran, V. S., & Hubbard, E. M. (2001). Synaesthesia--a window into perception, thought and language. *Journal of Consciousness Studies*, *8*(12), 3-34. Retrieved from <http://www.imprint-academic.com/rama/synaesthesia.pdf>
- Sagiv, N., Simner, J., Collins, J., Butterworth, B., & Ward, J. (2006). What is the relationship between synaesthesia and visuo-spatial number forms? *Cognition*, *101*(1), 114-128. doi: 10.1016/j.cognition.2005.09.004
- Santens, S., & Gevers, W. (2008). The SNARC effect does not imply a mental number line. *Cognition*, *108*(1), 263-270. doi: 10.1016/j.cognition.2008.01.002
- Shaki, S., Fischer, M. H., & Petrusic, W. M. (2009). Reading habits for both words and numbers contribute to the SNARC effect. *Psychonomic Bulletin & Review*, *16*(2), 328-331. doi: 10.3758/PBR.16.2.328
- Smilek, D., Callejas, A., Dixon, M. J., & Merikle, P. M. (2007). Ovals of time: Time-space associations in synaesthesia. *Consciousness and Cognition*, *16*(2), 507-519. doi: 10.1016/j.concog.2006.06.013

Supplementary Material**Table 1:** Raw SNARC effect slopes for participants in Experiment 1.

Synaesthetes	Non-synaesthetes
-48.62	-21.13
-22.26	-14.40
-13.76	-13.94
-13.22	-9.91
-11.87	-8.07
-9.91	-6.40
-7.32	-6.34
-7.25	-5.69
-7.00	-5.21
-6.60	-3.45
-4.23	-3.25
-2.35	-2.04
-0.94	-1.81
-0.27	-1.32
-0.26	-0.68
0.03	-0.34
0.25	0.02
3.28	1.07
3.72	2.68
13.13	2.93
19.81	3.31
	5.60
	6.20
	7.41
	7.61
	8.36
	9.35

Table 2: Raw SNARC effect slopes for participants in Experiment 2. Canonical and non-canonical slopes for each participant are presented side by side.

Synaesthetes		Non-synaesthetes	
Canonical	Non-canonical	Canonical	Non-canonical
-47.75	33.55	-27.81	29.42
-33.21	9.37	-18.58	-9.26
-13.29	-10.77	-17.03	22.22
-13.05	-9.67	-16.44	7.59
-12.92	34.62	-14.02	-9.96
-8.89	2.64	-13.71	2.77
-8.50	1.00	-13.24	-2.04
-8.47	4.96	-9.88	-1.57
-7.89	15.54	-9.53	21.17
-7.75	-21.76	-9.47	0.82
-0.99	7.11	-3.91	2.34
-0.84	1.69	-0.93	21.28
-0.79	24.86	-0.65	-4.36
13.42	8.67	0.60	-6.41
13.49	4.69	2.51	-10.64
16.99	6.88	4.68	3.67
23.89	5.41	5.63	24.82
		10.03	22.21
		16.25	16.94
		19.95	0.97