Simmons, FR, Gallagher-Mitchell, T and Ogden, R

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Response-irrelevant number, duration and extent information triggers the SQARC effect: Evidence from an implicit paradigm

Fiona Simmons[1], Thomas Gallagher-Mitchell[2] and Ruth S. Ogden[1]

[1]School of Natural Sciences and Psychology, Liverpool John Moores University,

Liverpool, UK, L3 5AF.

[2]Department of Psychology, Hope Park, Liverpool Hope University,

Liverpool, UK, L16 9JD

f.r.simmons@ljmu.ac.uk

mitchet@hope.ac.uk

r.s.ogden@ljmu.ac.uk

Correspondence concerning this article should be addressed to Dr Fiona Simmons, School of Natural Sciences and Psychology, Liverpool John Moores University,

Liverpool, UK, L3 5AF.

Tel.: +44 (0)151 904 6343. Email address: f.r.simmons@ljmu.ac.uk

Abstract:

Spatial–Numerical Association Of Response Codes (SNARC) and Spatial–Quantity Association Of Response Codes (SQARC) effects are evident when people produce faster left-sided responses to smaller numbers, sizes and durations and faster right-sided responses to larger numbers, sizes and durations. SQARC effects have typically been demonstrated in paradigms where the explicit processing of quantity information is required for successful task completion. The current study tested whether the implicit presentation of task-irrelevant magnitude information could trigger a SQARC effect as has been demonstrated previously when task-irrelevant information triggers a SNARC effect (Mitchell, Bull & Cleland, 2012). In Experiment 1 participants (*n* = 20) made orientation judgments for triangles varying in numerosity and physical extent. In Experiment 2 participants (*n* = 20) made orientation judgments for triangles varying in numerosity and for a triangle preceded by a delay of varying duration. SNARC effects were observed for the numerosity conditions of Experiment 1 and 2 replicating Mitchell et al., (2012). SQARC effects were also demonstrated for physical extent and for duration. These findings demonstrate that SQARC effects can be implicitly triggered by the presentation of the task-irrelevant magnitude.

Introduction

It is becoming increasingly clear that there are commonalities in the way in which different domains of magnitude (e.g., time, space, numerosity) are perceived. Representations of time, size and number are interrelated from the first days of life (de Hevia, Izard, Coubart, Spelke & Streri, 2014), share similar development trajectories (Droit-Volet, Clement, & Fayol, 2008; Feigenson, 2007, however see Odic, 2018) and are exhibited in non-human animals (De Corte, Navarro & Wasserman, 2017). Neuroimaging studies show comparable, and at times overlapping (Kaufmann et al., 2005), parietal activation during the processing of number (Dehaene, Piazza, Pinel, & Cohen, 2003), duration (Pouthas et al., 2005), and space/length (Pinel, Piazza, Le Bihan, & Dehaene, 2004). Behaviour tasks suggest that judgements of magnitude show similar output features (e.g., conformity to Weber's Law) (Dehaene & Brannon, 2011; Dormal & Pesanti, 2012; Droit-Volet, 2010, 2013). Furthermore, on tasks in which multiple domains of magnitude are presented simultaneously, congruency between the magnitude domains facilitates task performance (Wühr & Seegelke, 2018) whereas incongruence impairs performance (e.g., Coull, Charras, Donadieu, Droit-Volet, & Vidal, 2015, Xuan, Zhang, He, & Chen, 2007).

These findings can be taken as evidence for shared processing theories such as A Theory of Magnitude (ATOM; Bueti & Walsh, 2009; Walsh, 2003). ATOM proposes that different domains of magnitude (e.g., time, space, numerosity) share a common neural processing system located in the parietal cortex. This processing system is thought to have developed to facilitate action-control through the integration of size, duration and numerosity information from the environment. Within this system, magnitude representations are thought to be monotonically mapped, so that changes in one magnitude domain (e.g., increased number) correspond with changes in other domains (e.g., increased size). Interference effects, in which judgements of the relevant magnitude domain are influenced by task-irrelevant magnitude information from another domain, can be argued to result from this mapping (see Walsh, 2003 and Pinel et al., 2004).

However, a shared magnitude processing system is not the only plausible explanation for the interference effects observed (see Van Opstal & Verguts, 2013 for critique). Interference effects could instead reflect competition for shared response or decision processing systems (see and Van Opstal & Verguts, 2013; Reike & Schwarz, 2017, Tagliabue, Zorzi, Umilta & Bassignani, 2000 for discussion). Furthermore, as Van Opstal & Verguts (2013) highlight, comparable neural activity during the processing of different magnitude domains may not reflect the underlying stimulus representation itself, but may reflect activation from comparable decision processing or response systems.

SNARC Effects

Within the field of numerical cognition it has been argued that numerosity is represented on an internal directional spatial continuum in which “few” is represented on the left and “large” is represented on the right (Dehaene, 1992; Fias, Brysbaert, Geypens, & d’Ydewalle 1996; Hoffman, Martin, Schiltz, 2013). This suggestion is supported by findings demonstrating the Spatial–Numerical Association Of Response Codes (SNARC) effect (see Wood, Wilmes, Nuerk & Fischer, 2008 for a meta-analysis). The SNARC effect is demonstrated by faster left-sided responses to smaller numbers and faster right-sided responses to larger numbers. This pattern is consistent with a left-to-right orientated association between number and space.

In humans SNARC effects are observed in neonates (de Hevia, Veggiotti, Streri & Bonn, 2017), pre-verbal (Rugani & de Hevia 2017) and verbal children (Yang, Chen, Zhou, Xu, Dong & Chen, 2014), as well as adults (Mitchell, Bull, & Cleland, 2012). Although human SNARC effects are generally considered robust (Cutini, Scarpa, Scatturin, Dell’Acqua, & Zorzi, 2012; Fischer & Shaki, 2018; Wood et al., 2008), they can be influenced by task manipulations

(Fischer, Mills, & Shaki, 2010; Pfister, Schroeder, & Kunde, 2013). There is also limited evidence of SNARC-like effects in non-human animals (Rugani, Vallortigara, Priftis & Regolin, 2015), although this is debated (Drucker & Brannon, 2015). SNARC has been demonstrated cross-modally (e.g., for Arabic numbers, number words, auditory numbers, and canonical representations) (Mitchell et al., 2012; Nuerk, Wood, & Willmes, 2005) and occurs even when the numerical information presented is irrelevant or incidental to the task. For example, it occurs for parity judgements, phoneme monitoring, and judging shape orientation where irrelevant digits are presented inside the shape (e.g., Dehaene, et al., 1993; Fias et al., 1996; Fias, Lauwereyns, & Lammertyn, 2001; Mitchell, et al., 2012). SNARC has also been demonstrated cross-culturally (Gobel, Shaki & Fischer, 2011) with some studies suggesting that reading direction may influence the direction of the SNARC effect (Shaki, Fischer, & Petrusic, 2009) indicating a cultural basis for the effect. However, recent demonstrations of left-right SNARC effects in Hebrew speakers question this conclusion (Zohar-Shai, Tzelgov, Karni & Rubinsten, 2017).

Competing theories differ in their explanations of SNARC effects (see Fischer & Shaki, 2018, Moro, Dell'Acqua & Cutini, 2018 for discussion). Dehaene et al., (1993) proposed that numerosity is represented in semantic memory on a mental number line in which small is located on the left and large is located on the right. The number line is automatically activated when quantity is processed and SNARC effects result from congruency between the spatial location of a quantity on the number line and the spatial code of the response (i.e., left or right). Others suggest a response level account in which congruency in the long-term memory associations between the numerosity (e.g., small) and the response side (i.e., left) speeds responding (e.g., Fias, van Dijck & Gervers, 2011, Gervers, Verguts, Reynvoet, Caessens & Fias, 2006). Furthermore, it has recently been suggested that SNARC may be influenced by working memory encoding wherein the ordinal position in which stimuli are encoded into working memory results in the spatial code upon which SNARC effects emerge (e.g., Dixon, 2017, van Dijck & Fias, 2011).

SQARC Effects

Given that ATOM suggests that different domains of magnitude share a common processing system (Bueti & Walsh, 2009; Walsh, 2003) it would be logical to suggest that *all magnitudes* are associated with a directional left to right spatial continuum. Indeed, Walsh (2003) identified "*Does the spatial numerical association of response codes generalize to other magnitudes?*" (p. 487) as a core question for future research. This widening of the SNARC effect to other domains of magnitude is often referred to as Spatial–Quantity Association Of Response Codes effects (SQARC). Although SQARC effects could be explained in terms of the shared *representation* of magnitude outlined within ATOM, they could also be consistent with a response code account (e.g., Fias et al., 2011, Gervers et al., 2006) with a range of quantities (e. g., physical extent, duration) having associations with spatial orientation.

SQARC effects have been demonstrated with stimuli varying in physical size and conceptual size (Ren, Nicholls, Ma & Chen, 2011; Sellaro, Treccani, Job & Cubelli, 2014). In both instances, faster left responses were associated with smaller sizes and faster right responses were associated with larger sizes. SQARC-like effects have also been demonstrated with changing stimulus luminance (Fumarola, Prpic, Da Pos, Murgia, Umilta & Agostini, 2014) and contrast (Ren et al., 2011). However, task-specific conditions appear to influence whether dark is located on the left or right of space. Furthermore, not all findings are consistent. For example, Bulf et al., (2014) found that luminance did not produce attentional shifts to the left or right sides of space in the same manner that spatial extent and number did. This led them to conclude that not all continuous dimensions are equally mapped onto space.

Behavioural findings are also suggest that time is associated with left-to-right spatial continuum (see Bonato, Zorzi & Umilta, 2012 for a review). Metaphorical representations of time display spatial representations consistent with a left-right spatial continuum (Boroditsky & Gaby, 2010; Ouellet, Santiago, Funes Lupiáñez, 2010; Ouellet, Santiago, Israeli & Gabay, 2010; Santiago, Lupanez, Perez & Funes, 2007; Weger & Pratt, 2008) as do symbolic representations of time in musical notation (Prpic, Fumarola, De Tommaso, Luccio, Murgia, & Agostini, 2016). Furthermore congruency effects are evident when response or presentation duration is manipulated. Kiesel & Vierck (2009) used an odd/even parity judgement in which response duration was manipulated. Participants responded more quickly to smaller numbers when the required response key-press was short and more quickly to larger numbers when the required response key press was long. Vallesi, Binns & Shallice, (2008) and Vallesi, McIntosh & Stuss, (2011) asked participants to classify the length of a presented duration as short or long. In both studies, left sided responses were quicker in response to short durations and right sided responses are quicker in response to long durations.

SQARC effects are not consistently observed in infants. Although de Hevia et al., (2017) observed SNARC-like effects (i.e., small-left and large-right associations) for numerical information, they were not observed for duration or length. Similarly, Bulf, de Hevia and Cassia (2016) observed that, in 8 and 9 month old babies, attentional orientation could be cued to the left or the right by numerical information (few or many dots) but not size (large or small). Furthermore, spatial representations of duration appear absent in pre-schoolers, although they develop during the initial school years (Coull, Johnson & Droit-Volet, 2018; Tillman, Tulagan, Fukuda & Barner, 2018). This perhaps suggests that numerical processing has a privileged status at birth and that other magnitude domains may be “mapped on to this” during development (de Hevia et al., 2017).

The present study

A key issue with existing literature on SQARC effects is that studies to date often involved the explicit presentation of magnitude information relevant to task completion (see

Macnamara et al., 2018 for a review). For example, participants make decisions about, about time based verbs and adverbs rather than non-time associated stimulus features. This explicit presentation and processing of numerical information may therefore have triggered unintentional processing of the task-irrelevant dimension, contributing towards the SQARC effects observed (see Mitchell et al., 2012 for a discussion of the impact of explicit presentation). Where SQARC effects have been established using an implicit paradigm the effect sizes are smaller than those using an explicit paradigm (Macnamara et al., 2018). It is therefore important to establish whether SQARC effects are also present when task-irrelevant magnitude is presented (Mitchell et al., 2012).

The activation of SNARC using an implicit paradigm was examined by Mitchell et al., (2012). This study used a modified version of the neural-overlap paradigm developed by Fias et al., (2001) in which participants were asked to make judgements about the orientation of shapes. Task-irrelevant magnitude information was provided by manipulating the number of shapes in an array. Despite the number of the shapes presented being irrelevant to the orientation judgments, a SNARC effect was demonstrated; faster left responses were associated with small quantities and faster right responses were associated with large quantities. Therefore, whilst it is clear that SNARC effects can be elicited implicitly, it is unclear whether this is also true of SQARC effects.

The current studies used the same implicit paradigm as Mitchell et al., (2012) to test whether the presentation of task-irrelevant magnitude information could trigger a SQARC effect for physical extent (Experiment 1) and duration (Experiment 2) similar to the SNARC observed in Mitchell et al. (2012). In Experiment 1 we tested for SQARC effects for physical extent. The stimuli consisted of single triangles that varied in physical extent and were either pointing upwards or downwards. Participants had to judge the orientation of the triangle (pointing upwards or pointing downwards). If physical extent elicits a SQARC effect when quantity is irrelevant to the task, we would expect faster left responses to smaller stimuli and faster right responses to larger stimuli. In Experiment 2 we tested for a SQARC effect for duration. Participants were presented with a single triangle pointing either upwards or downwards. Duration was manipulated by varying the duration of the delay between the offset of the fixation cross and the presentation of the triangles display. Again, participants had to judge the orientation of the triangle. If duration elicits a SQARC effect when duration is irrelevant to the task, we would expect quicker left responses to short durations and quicker right responses to long durations. In both Experiment 1 and 2, participants also completed the implicit SNARC test, developed in Mitchell et al., (2012) to test whether we could replicate the SNARC effect they observed for number i.e., faster small-left large-right responses. The demonstration of implicit SQARC effects for duration and physical extent would support the argument that these quantities automatically trigger spatial associations in a similar manner that number automatically triggers spatial associations.

Experiment 1

Method

Participants

Twenty participants took part in the study (5 males, mean age 22.50, *SD* =7.75). All participants were between the ages of 18 and 65. Participants outside of this age range or with health conditions that impacted on their response times were excluded. The study was approved by Liverpool John Moores University Research Ethics Committee and all participants gave informed written consent. The study was conducted in accordance with the principles expressed in the Declaration of Helsinki.

Materials

The experiment was conducted using E-Prime2 software using a Dell Optiplex 5040 at a standardised screen resolution of 1600x900 pixels with a refresh rate of 60Hz and 32 bit colour quality. The stimuli were developed using Microsoft Publisher. The triangle or triangles were always presented in green (coded 362C in the PANATONE^{TM} colour wheel).

Procedure

The basic experimental procedure was a replication of that used in Mitchell et al., (2012) in which participants made judgements about the orientation of triangles. Participants completed two tasks 1) a numerosity manipulation in which the number of triangles displayed varied between trials and 2) a physical extent manipulation in which a single triangle was displayed but its physical extent varied between trials. The order of these tasks was counterbalanced across participants.

The numerosity manipulation: At the start of the experiment participants were told that they would be presented with images of triangles and that their task was to indicate, as quickly and accurately as possible, the orientation of the triangles. The task instructions displayed were as follows: “Your task is to judge the orientation of the triangle. On each trial you should press the z/m key if you see an inverted triangle and the z/m key if you see an upright triangle.” Participants responded using the Z and M keys on the keyboard and the response key was counterbalanced across participants.

At the start of each trial a fixation cross was presented for 1000ms. This was followed by a single array of triangles presented in the centre of the screen. The array contained 1, 2, 3, 4, 6, 7, 8, or 9 triangles. These array sizes were selected because Mitchell et al., (2012) successfully elicited SNARC effects using 1-9 items. All triangles in an array were presented in the same orientation; either upright or inverted. The array was presented until the participant responded (Z or M) to indicate orientation. An ISI of 1000ms was then interposed before the next trial. Across trials, the total surface area of the triangle or triangles displayed remained constant (at 4.5cm^2). So, for example, in trials with one triangle would be a single triangle of 4.5cm^2 whereas in trials with nine triangles each triangle would vary in size but subtend the same total surface area. The spatial location of the triangles varied between numerosities but was fixed within numerosities. See Figure 1 for schemata of trial structure.

Participants performed 16 training trials, in which performance feedback was provided. These trials were designed to ensure that the participant was familiar with the task and understood the correct response keys. Data from these trials was recorded but not analysed. Participants then completed 128 experimental trials, 8 for each numerosity with an inverted display and 8 for each numerosity with an upright display. The order of presentation was randomised by the computer for each participant. In experimental trials no performance feedback was provided.

The physical extent manipulation: the experimental procedure was identical to that used in the numersosity manipulation except that the stimuli was always a single isosceles triangle with the base and height of equal length. To provide a manipulation of physical extent, the length of the sides varied from trial to trial. There were eight different sizes of triangles with base and height lengths of 1, 2, 3, 4, 6, 7, 8 and 9 centimetres respectively.

[Insert Figure 1 about here]

Results

Across manipulations, the presence of a significant influence of task-irrelevant magnitude on motor response time to stimulus orientation was captured using regression analysis. Response times for each numerosity display responded to with the left and right key were collated and the median response time calculated (correct responses only). The difference in the time to respond to each numerosity display with the right and left hand was then calculated (right hand RT – left hand RT). The nature of the SNARC and SQARC effect was captured by regression analyses (Lorch & Myers, 1990, Method 3; for a detailed discussion see Fias et al., 1996). A regression equation was computed for each participant, with array numerosity or stimulus size as the predictor variable (dependant on task condition) and RT difference as the criterion variable. The regression weight (standardised beta) was recorded for each participant, and one sample t-tests were conducted to determine whether the regression weight was significantly different from 0 (a flat line).

[Figure 2 about here]

[Table 1 about here]

Table 1 shows mean reaction times, error rates and standardised beta weights for the numerosity and physical extent manipulations. Examination of Table 1 suggests that mean reaction times and error rates were similar across the two manipulations. This was confirmed by analysis using paired samples t-tests which showed no significant difference in error rates for the numerosity and physical extent manipulations, t (19) = 1.33, p = .20. There was also no significant difference reaction times during the numerosity and physical extent manipulations, t (19) = .98, p = .34.

Analysis of the standardised beta weights indicated that, for the numerosity manipulations, the standardised beta weight was -.23 (SD = .29), with a negative slope which was significantly different from 0, t (19) = -3.51, p = .002 and indicative of a SNARC effect (see Figure 2). For the physical extent manipulations the mean standardised beta weight was -.16 (SD = .31), with a negative slope which was significantly different from 0, t (19) = -2.38, p = .03 and indicative of a SQARC effect. Comparison of the mean standardised beta weights for number and physical extent showed no significant difference between the two, t (19) = .76, *p* = .45, suggesting the size of the SNARC and SQARC effects did not differ significantly between the modalities. However participants' beta weights for the numerosity manipulation was not correlated with their beta weights for the physical extent manipulation, *r*(18) = .22, *p* = .35.

Discussion

The results of Experiment 1 confirm Mitchell et al's. (2012) observation that SNARC effects can be elicited when task-irrelevant numerical information is presented. They also extend this finding by demonstrating that SQARC effects can be observed when task-irrelevant physical extent information is presented. This suggests, that like number, physical extent is also represented on a spatial continuum in which small is represented on the left and large on the right.

Experiment 2

Experiment 2 examined whether SQARC effects could also be observed for when task-irrelevant duration information is presented. Although SQARC like effects have previously been shown for duration (Vallesi et al., 2008; Vallesi et al., 2011) they have involved explicit classification of duration in that participants had to classify the presented durations as long or short. It is unclear whether SQARC effects for duration can be observed when the presented durations are task-irrelevant and duration classification is not a requirement of the task. To test this, we use a modified version of the paradigm used in Experiment 1; single triangles were presented in an upward or inverted orientation. Their presentation was preceded by a delay of or 100-900ms to provide implicit duration information. As in Experiment 1, participants were instructed to judge the orientation of the triangle. The presence of SQARC effects for task-irrelevant duration information would support the suggestion that duration processing automatically triggers spatial representations.

Participants

Twenty participants took part in the study (11 males, mean age 21.55, *SD* = 5.24). All participants were between the ages of 18 and 65. Participants outside of this age range or with health conditions that impacted on their response times were excluded. The study was approved by Liverpool John Moores University Research Ethics Committee and all participants gave informed written consent. The study was conducted in accordance with the principles expressed in the Declaration of Helsinki.

Materials

As in Experiment 1.

Procedure

The basic experimental procedure was identical to that used in Experiment 1. Participants were informed that they would complete two tasks in which they needed to make judgements about the orientation of triangles: 1) a numerosity manipulation in which the number of triangles displayed varied between trials and 2) a duration manipulation in which the duration of the delay between the offset of the fixation cross and the presentation of the triangles varied from trial to trial. The order of these tasks was counterbalanced across participants.

The numerosity manipulation: The experimental procedure was identical to numerosity task in Experiment 1.

The duration manipulation: At the start of the task participants were told that they would be presented with images of a triangle and that their task was to indicate, as quickly and accurately as possible, the orientation of the triangle. Participants responded using the Z and M keys on the keyboard and the response key was counterbalanced across participants.

At the start of each trial a fixation cross was presented for 1500ms. This was followed by a blank screen presented for either 100, 200, 300, 400, 600, 700, 800 or 900ms. This was followed by the presentation of a single isosceles triangle, with a base and height of 3 centimetres, located in the centre of the screen, in either an upright or inverted orientation. The triangle was presented until the participant responded (Z or M) to indicate orientation. An ISI of 1000ms was then interposed before the next trial. Participants completed 16 training trials to familiarise themselves with the experimental procedure. Feedback was provided during the training trials. They then completed 128 experimental trials during which no feedback was provided. Only data from the experimental trials was analysed. See Figure 2 for schematic diagram of the method.

[Insert Figure 2 about here]

Results

As in Experiment 1, individual regressions were conducted for each participants and each task. Standardised beta weights were then analysed to assess for SNARC and SQARC effects.

[Table 2 about here]

[Figure 4 about here]

Table 2 shows mean reaction times, error rates and standardised beta weights for the numerosity and duration tasks. Examination of Table 2 suggests that mean reaction times and error rates were similar across the two tasks. This was confirmed by analysis using paired samples t-tests which showed no significant difference in error rates for the numerosity and duration, t (19) = 1.18, p = .25. There was also no significant difference in the reaction times for the numerosity and duration tasks, t (19) = .1.24, p = .23.

Analysis of the standardised beta weights indicated that, for the numerosity manipulation, the standardised beta weight was -.23 (SD = .41), with a negative slope which was significantly different from 0, *t* (19) = -2.49, *p* = .02 and indicative of a SNARC effect. For the duration manipulation the mean standardised beta weight was -.19 (SD = .39), with a negative slope which was significantly different from 0, *t* (19) = -2.23, *p* = .038 and also indicative of a SQARC effect. Comparison of the mean standardised beta weights for number and duration showed no significant difference between the two, *t* (19) = .24, *p* = .81, suggesting the physical extent of the effect did not differ between the modalities. However participants' beta weights for the numerosity manipulation was not correlated with their beta weights for the physical extent manipulation, *r*(18) = -.30, *p* = .20.

Discussion

The results of Experiment 2 show a SQARC effect for duration can be elicited when task-irrelevant duration information is presented. This suggests that like number, implicit duration processing can trigger spatial representations in which short is represented on the left and long is represented on the right.

General Discussion

The study aimed to replicate Mitchell et al.'s (2012) finding that task-irrelevant numerosity variation generates a SNARC effect during an orientation task, and furthermore extend these findings by determining whether task-irrelevant duration and physical extent information generates a SQARC effect.. Mitchell et al.'s findings were replicated as smaller numbers of shapes were associated with faster left-sided responses whereas larger numbers were associated with faster right-sided responses. The results also indicated that SQARC effects were generated when task-irrelevant information varied in terms of physical extent and pre-stimulus presentation duration

The findings for physical extent are consistent with those of Ren et al., (2011) who demonstrated a SQARC for physical extent when participants were asked to make explicit magnitude judgements (i. e., they were asked to indicate which of two circles was larger). These results extend Ren et al.'s findings by demonstrating that a SQARC effect is triggered by physical extent even when it is irrelevant to the task performed. This is consistent with the argument that the spatial association with physical extent is triggered automatically even if there is no conscious plan to analyse this information.

The findings for duration are consistent with studies showing spatial mapping for metaphorical representations of time (e.g., past and future) (Boroditsky & Gaby, 2010; Ouellet et al., 2010; Ouellet et al., 2010; Santiago, et al., 2007; Weger & Pratt, 2008), with studies that have demonstrated spatial mappings when participants engage in the classification of presented durations (Vallesi et al., 2008; Vallesi et al., 2011) and with neuropsychological studies showing that left-hemispatial neglect patients have difficulties representing "past" on mental time lines (Saj, Fuhrman, Vuilleumier & Boroditsky, 2013). Together, these findings suggest that spatial associations are generated both by durations that are perceived and by durations that are generated by particular response type.

Together, the presence of SNARC and SQARC effects for number, physical extent and duration suggests that both continuous and discontinuous domains of magnitude can trigger the generation of directional (left-right) spatial continuum, even when the quantity presented is incidental to the task. These findings are consistent with the suggestion that different domains of magnitude share a common underlying processing system (Walsh, 2003), which can be activated implicitly rather than explicitly. If this theoretical account is accepted numerosity, physical extent and duration trigger the activation of a common spatial magnitude system that facilitates left-sided responses when small and right-side responses when large. However, they could also be accounted for by shared response systems (see Daar & Pratt, 2008,Van Opstal &

Verguts, 2013; Reike & Schwarz, 2017, Tagliabue et al., 2000). If a response system account is accepted smaller and larger numerosity, physical extent and duration are associated with left *responses* and larger with right *responses*. Such pre-existing response associations could produce the pattern of findings we report. The origins of SNARC and SQARC effects therefore remains controversial.

When considering the findings three key methodological issues must be acknowledged. First, we controlled for total physical extent in our numerosity manipulation. This meant that although the total shaded area was constant across numerosity trials, the physical extent of the individual triangles was inversely related to the number of triangles presented. This *may* have reduced the magnitude of the SNARC effect as the physical extent of the *individual* triangles was smaller in the more numerous numerosity trials. Future studies would need to investigate whether the SNARC effect is facilitated when *individual* shape area, rather than total area is kept constant. Second we used fixed arrays for all trials with the same numerosity. So, for example, the position of the triangles in all trials with a numerosity of three was constant. Although unlikely, it is possible that the fixed arrays may have influenced the size of the SNARC effect. Replicating the findings with the arrays being randomly generated would further strengthen the conclusions. Third, participants experienced two manipulations (in Experiment 1 physical extent and numerosity and in Experiment 2 duration and numerosity). Task order was counterbalanced so it is therefore unlikely that the SQARC effects identified in the physical extent and duration manipulations are influenced by the numerosity manipulation. However it would be interesting to replicate the study with participants experiencing a single manipulation to further investigate the robustness of the implicit SQARC effects.

These findings suggest that the presentation of number, physical extent and duration information all implicitly trigger spatial associations in adults even when they are not directed to focus on them and they do not need to be processed for successful task completion. However, three core issues require further investigation. The first is the developmental time course over which these spatial associations develop. de Hevia et al., (2017) reported evidence of non-symbolic SNARC effects in neonates, before the emergence of similar SQARC effects for length and duration. It may therefore be that SNARC effects develop first, and that spatial associations for symbolic numbers and other magnitudes (such as duration, physical extent and length) are parasitic on pre-existing spatial associations for non-symbolic magnitudes. To test this hypothesis longitudinal studies tracing the development of SNARC and SQARC effects from infancy through the early years of formal schooling are required.

The second issue is the extent that the position of magnitudes is flexible and updated dependent on their relative magnitude when compared to recently perceived stimuli. Recent findings suggest that SNARC effects are disrupted with working memory load (Herrera et al., 2008, van Dijck et al., 2009, van Dijck & Fias, 2011). These findings are consistent with the spatial associations between number and space being constructed within working memory as the stimuli are perceived. Further studies examining the extent that working memory load disrupts SQARC effects will inform our understanding of whether SQARC effects stem from a fixed internal spatial representation of magnitude or are flexibly constructed within working memory in response to the stimuli perceived.

The third issue is the extent that individual differences in SNARC and SQARC effects are related. If the effects emerge from common underlying processing system (Walsh, 2003) then one would expect individual differences in the effects to be correlated. Although SNARC and SQARC effects were evident in all three magnitudes (numerosity, duration and physical extent) in our study, individual differences in SQARC and SQARC effects did not correlate at a statistically significant level. Our sample is too small to confidently conclude that individual differences in such effects are unrelated. Therefore, investigating the relationships between individual differences in such effects in larger and more powerful samples is an important avenue for future research. Such research will further inform our understanding of the extent that they stem from a core underlying numerosity system or different coding networks (see Georges, Hoffmann, Schiltz, 2017; Schroeder, Nuerk, & Plewnia, 2017 for a discussion).

In summary, these results suggest that the perception of numerosity, physical extent and duration triggers an internal spatial association even when the task does not demand that the quantity information is analysed or retained.

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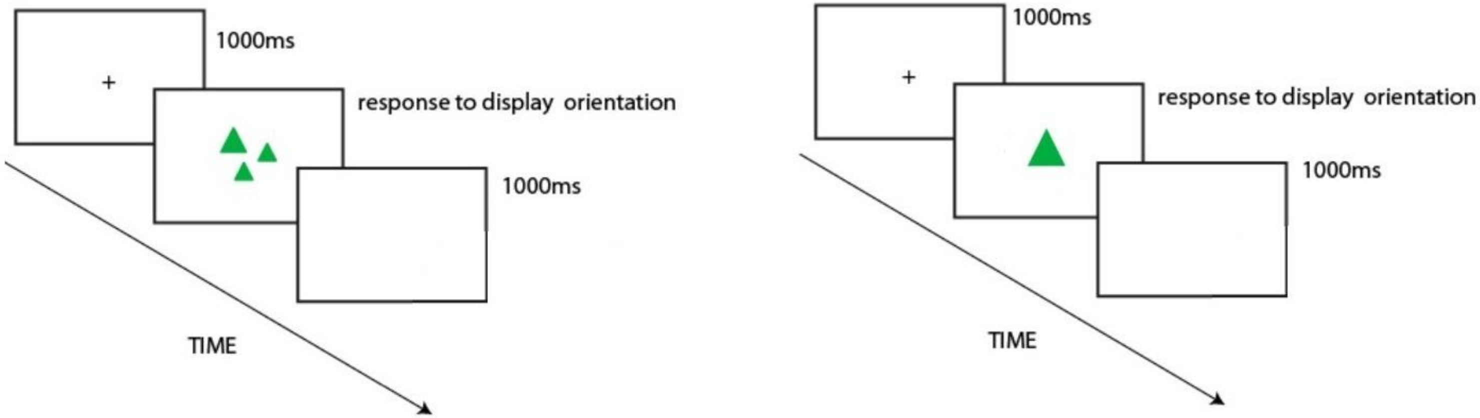
Table 1: Mean reaction time, error rate and standardised beta weights for the numerosity and physical extent tasks.

Task	*Mean reaction time ms (SD)*	*Mean error rate (SD)*	*Mean standardised beta weight (SD)*	*Mean unstandardized beta (SD)*
Numerosity	464.33 ms (87.39)	3.21 (0.02)	-.23 (.29)	-3.50 (5.33)
Physical extent	437.48 ms (63.01)	5.90 (0.09)	-.16 (.31)	-2.62 (6.39)

Table 2: Mean reaction times, error rates and standardised beta weights for the numerosity and duration task.

	Mean reaction time ms (SD)	*Mean error rate % (SD)*	*Mean standardised beta weight (SD)*	*Mean unstandardized beta (SD)*
Numerosity	505.53 ms (84.71)	2.85 (0.02)	-.23 (.41)	-4.29 (8.53)
Duration	487.11 ms (97.73)	4.24 (0.04)	-.19 (.39)	-5.13 (6.81)

Figure 1: Time course of the experiment. Numerosity trials illustrated in Panel A, physical extent trials in Panel B. The images show that in each task, following a 1000ms fixation cross, the stimulus was presented and participants responded as quickly and accurately as possible during presentation. There was then a 1000ms delay, followed by the start of a new trial.



A B

Figure 2: Difference in reaction times (dRT) between left- and right-hand responses as a function of display numerosity (left panel) and display physical extent (right panel). The line depicts predicted reaction time differences from the regression analysis. Bars represent +1 standard error of the mean values.

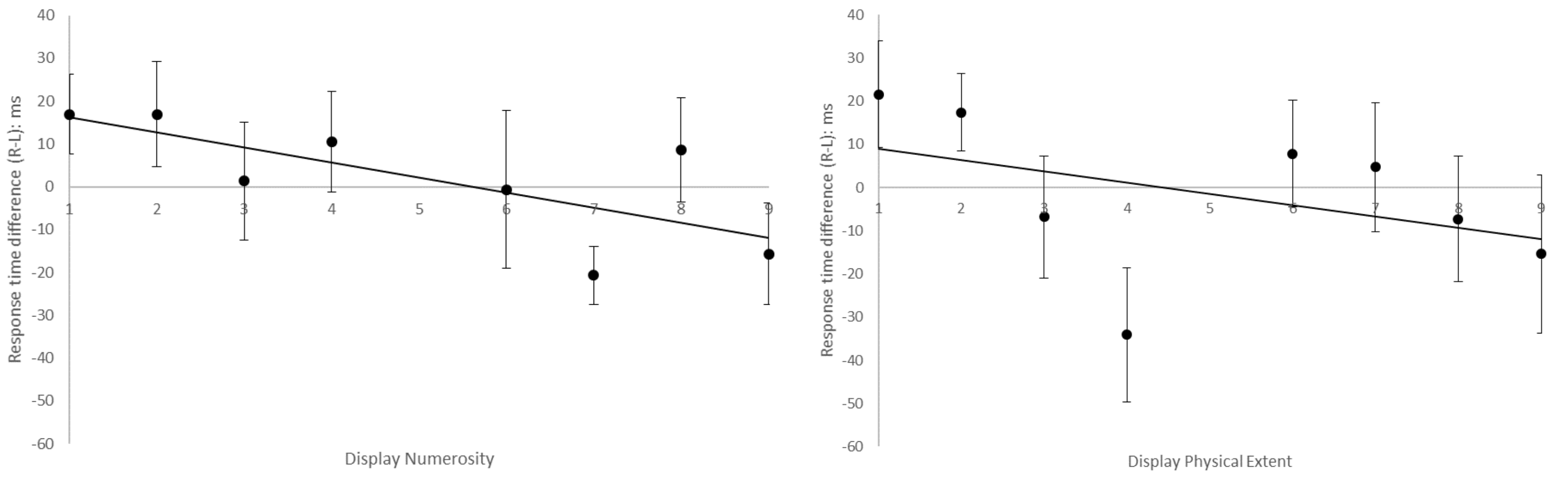


Figure 3: Time course of the experiment. Numerosity trials illustrated in Panel A, Duration trials in Panel B. The images show that in the nuerosity task, following a 1000ms fixation cross, the stimulus was presented and participants responded as quickly and accurately as possible during presentation. There was then a 1000ms delay, followed by the start of a new trial. In the duration task, following a 1000ms fixation cross, there was a variable delay of 100-900ms. The stimulus was presented and participants responded as quickly and accurately as possible during presentation. There was then a 1000ms delay, followed by the start of a new trial.

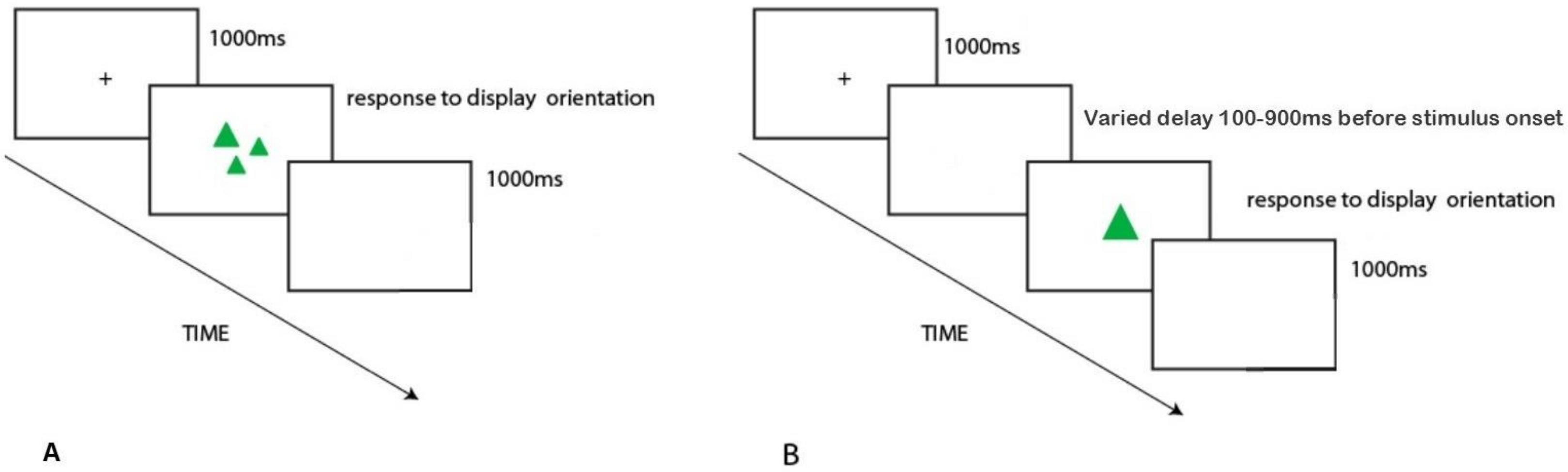


Figure 4: Difference in reaction times (dRT) between left- and right-hand responses as a function of display numerosity (left panel) and display duration (right panel). The line depicts predicted reaction time differences from the regression analysis. Bars represent +1 standard error of the mean values.