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A cross-sectional developmental examination of the SNARC effect in a visually-guided grasping task

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ABSTRACT

The present study documents the influence of numerical processing on hand and space use during a reach-to-grasp task. Three questions regarding the SNARC (spatial–numerical association of response codes) effect were asked: (1) would the SNARC effect influence hand and/or space preference for grasping?; (2) would the SNARC effect be demonstrated during the processing of one-digit numbers, two-digit numbers, or both?; and (3) would developmental age influence the strength of the SNARC effect? A total of 84 participants in three age/school level groups (Primary, Secondary, and Post-secondary) took part in the study. Two identical sets of small wooden blocks numbered from 0 to 19 were used. Each set was presented to the right and to the left of each participant. A number was called and participants were asked to find and grasp a block with the corresponding number as fast and accurately as possible. Hand and space used (L/R) was recorded for each grasp. Number magnitude was shown to influence the selection of hand and hemi-space in accordance with the SNARC effect. In the small percentage of trials where the left hand was used, it was more commonly recruited to grasp blocks displaying low numbers than high numbers. Participants grasped blocks from left and right space with equal frequency, but respectively left/right space was accessed more often for blocks displaying low/high numbers. Regression analyses revealed that developmental age is a powerful predictor of the SNARC effect on hand and space selection for grasping. This study provides the first description of the SNARC effect on hand and space preference for the reach-to-grasp action. Results are discussed with relevant literature of numerical processing in the human brain.

1. Introduction

The notion that numbers are mentally represented as occupying locations in space, i.e. situated in ascending order on a left-to-right number line, was first introduced by Dehaene, Bossini, and Giraux (1993) paper describing the "SNARC" effect (Spatial Numerical Association of Response Codes). In a bi-parity judgement task of single-digit numbers, participants were faster to respond (with a key press) to lower numbers when using their left hands and to higher numbers when using their right hands. The authors suggested that the relative magnitude of each presented digit was automatically processed by the participant and associated with left or right space, leading to movement priming in that direction.

Studies have expanded on Dehaene and colleagues' discovery, using their parity judgement/key-pressing paradigm to document the SNARC effect for spoken numbers (Wood, Nuerk, & Willmes, 2005; Fias, Brysbaert, Geypens, & d'Ydewalle, 1996; Fias, 2001) and negative numerals (Fischer & Rottmann, 2005). Moving beyond key presses, researchers confirmed the presence of a SNARC effect in a pointing task (Fischer, 2003) and at the level of visual perception; seeing a higher digit quickened detection of circles in the right visual field and seeing a lower digit sped detection in the left visual field (Fischer, Castel, Dodd, & Pratt, 2003). These examples illustrate that after its initial discovery, the SNARC effect has been demonstrated across presentation modalities (visual vs. auditory) and across response forms (e.g. key press, point, gaze). However, it is important to note that the tasks in the aforementioned studies were not free-choice: either a specific response was required (e.g. for odd numbers point left) or post-priming stimuli was presented in one hemi-field only. Thus, the main variable of interest across all of these studies was reaction time.

Daar and Pratt (2008) investigated the effects of number magnitude in a free-choice task. They presented either a low digit (1, 2) or a high digit (8, 9) and asked participants to choose between two manual key-press responses, one on the left and one on the right side of a keyboard. The results showed that low digits produced more left responses while high digits produced more right responses. The authors concluded that numerical information influenced the response that would be selected for action. One action that we perform hundreds of times a day is reaching and grasping. Several studies have shown that numerical processing can

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affect the kinematics of the grasp (e.g. Moretto & di Pellegrino, 2008; Andres, Ostry, Nicol, & Paus, 2008; Namdar, Tzelgov, Algom, & Ganel, 2013) and they have revealed a powerful association between number magnitude and grasp size, but they have not shed light on the SNARC effect—biases in response side/direction. It seems that no study has investigated how number magnitude may affect the selection of hand and space use during reach-to-grasp movements. The first goal of the present study therefore, was to investigate this question. To this end, participants attended to a verbally presented number and were required to find and grasp a wooden block labelled with the corresponding number from an array of blocks. Within the array, numbered blocks were equally represented in right and left space. No instruction as to what hand or side of space to use was provided to the participants. This unique setup allowed researchers the opportunity to test free-choice hand- and space-selection in a reach-to-grasp task.

A second goal of the current study was to investigate whether the SNARC effect is exhibited during the processing of one-digit numbers, two-digit numbers, or both; a question that has produced mixed answers in the literature (see Fischer & Fias, 2005 for a review; see also Zhou, Chen, Chen, & Dong, 2008). To achieve this goal, numbered blocks with digits that ranged from 0 to 19 were used.

The design and setup of the current task also provided the opportunity to examine the developmental trajectory of the SNARC effect; this was the third and final goal of the study. Some researchers have argued that space-number associations are not innate, but rather products of one's culture (Dehaene et al., 1993; Zebian, 2005; Ristic, Wright, & Kingstone, 2006). Assuming that a mental number line is acquired through cultural reinforcement, its behavioural effects should increase with age and associated years of schooling. Indeed, some studies have found that the SNARC effect is displayed by children in third grade but not earlier (Berch, Foley, Hill, & Ryan, 1999; van Galen & Reitsma, 2008), while others have found the effect in children as young as kindergarten-age (Hoffman, Hornung, Martin, & Schiltz, 2013; Yang et al., 2014). However, these few developmental studies had participants make specific key presses, and did not investigate free choice response selection or the reach-to-grasp movement. The current study tested participants across a broad age range (varying levels of education) in the block grasping task.

The current study only involved right-handed participants, as Dehaene et al. (1993) original study found virtually no differences in the SNARC effect between left- and right-handers' behaviour. However, it is known that within the right-handed population there is still variability in strength of right hand preference (Oldfield, 1971). Hence, the impact of preference strength was considered during analysis.

When exploring the developmental trajectory of the SNARC effect, a related aspect of motor development to consider is midline crossing. Midline crossing is exhibited when one hand is spontaneously used in contralateral space, i.e. on the opposite side of the body. While children and adults are more likely to make hand movements in ipsilateral (same side) space (Gabbard, Helbig, & Gentry, 2001), midline crossing is noted in children as young as 2 years of age and the frequency of this behaviour has been shown to progressively increase from 2 to 12 years of age (Schofield, 1976; Cermak, Quintero, & Cohen, 1980; Stilwell, 1987; Carlier, Doyen, & Lamard, 2006; Hill & Khanem, 2009). Researchers have suggested that the development of this phenomenon could follow the development of hand preference (Carlier et al., 2006). In other words, as a child comes to rely more consistently on one hand, he/she will more frequently use that hand in contralateral space. In the current study, every digit labelled block was equally represented on the left and right sides of space. We explored the possibility that participant's hand use becomes more lateralized and more likely to cross the midline by documenting contralateral grasps in all age groups.

Table 1
Participant demographics. Number of male and female participants, and total number of participants, in each of the three participant groups and in each year of age tested.

GROUP	AGE (years)	Male (n)	Female (n)	Total (n)
Primary $n=40$	5	4	7	11
	6	4	4	8
	9	6	9	15
	10	5	1	6
Secondary $n=23$	12	3	1	4
	13	3	3	6
	14	2	6	8
	15	1	4	5
Post-secondary $n=21$	18–30	7	14	21

2. Methods

2.1. Participants

A total of 84 participants of various developmental ages took part in the study. Participants were split into 3 groups based on age/level of education; Primary – comprised of children aged 5–6 and 9–10 ($n=40$), Secondary – comprised of adolescents aged 12–15 ($n=23$), and Post-secondary – comprised of adults aged 18–30 ($n=21$). See Table 1 for a detailed summary of participant groups.

We tested children of the ages 5–6 and 9–10 years, but not 7–8 years, as various studies have shown that 7–8 years of age may be an important transitory time in the development of not only numerical processing (Miller, 1992; Lemaire & Fayol, 1995; Berch et al., 1999), but also midline crossing (Carlier et al., 2006), hand

Table 2
All Chi-square analysis results for hand use (2A) and space use (2B) by participant group.

	Low: 0–9 High: 10–19		Low: 0–4 High: 5–9		Low: 10–14 High: 15–19	
	$X^2(1)$	p	$X^2(1)$	p	$X^2(1)$	p
2A: Hand use						
Group						
Primary	5.90	0.01**	0.21	0.64	0.62	0.43
Secondary	1.03	0.31	0.20	0.64	0.26	0.60
Post-secondary	0.72	0.39	3.68	0.05*	1.58	0.21
2B: Space use						
Group						
Primary	0.84	0.35	2.56	0.10	0.09	0.76
Secondary	0.13	0.70	6.20	0.01**	0.43	0.51
Post-secondary	0.61	0.43	12.88	0.00***	0.68	0.40

* $p > 0.05$
** $p > 0.01$
*** $p > 0.001$

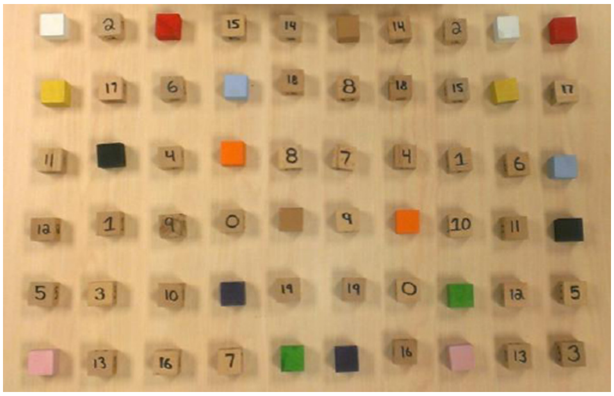

Fig. 1. The lay-out of the 40 numbered and 20 coloured blocks. Two identical sets of blocks – one set on the right and one set on the left side of the table – were placed in near-symmetric positions (in a pseudo-random configuration 10 columns wide by 6 rows deep) that remained consistent across participants. The midline of the array was not marked in any way. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

preference (Hill & Khanem, 2009), and reach-to-grasp coordination (Schneiberg, Sveistrup, McFadyen, McKinley, & Levin, 2002). However, upon statistical analysis (performance of all Chi-square tests described in the Results), we found no significant differences between these two age groups, save for one. When blocks were grouped into low digits (0–9) and high digits (10–19), 9–10 year olds show a significant SNARC effect for hand use, and though the trend was in the same direction, the effect did not reach significance in 5–6 year olds ($p = 0.1$).

Table 2 Primary age children were recruited from the general public, Secondary age students were contacted through their participation in a Science Fair hosted at the University of Lethbridge, and Post-secondary adults were undergraduate psychology students recruited from the University of Lethbridge. The studies were approved by the local ethics committee and all participants or caregivers gave written informed consent before participating in the study. Participants were naïve to the purposes of the study.

No participants were neurologically compromised, and all were right-handed (Primary and Post-secondary individuals assessed with the Edinburgh Handedness Inventory, while Secondary students self-reported handedness). Participants' sex was not counter-balanced, as it has not been shown to affect hand or space use in a block grasping task (Gonzalez & Goodale, 2009). However, during preliminary data analysis the impact of sex on space use for grasping was investigated. Repeated measures ANOVAs were conducted, with numbered block (0–19) as within-subject factor and sex as between-subjects factor. Neither a main effect of sex ($p > 0.4$) nor a block by sex interaction ($p > 0.1$) was found in any of the age groups or in the participant group as a whole. As such, subsequent analyses did not include sex as a factor.

2.2. Materials and procedure

On a tabletop (60 cm deep × 80 cm wide for children aged 5–6, and 120 cm deep × 120 cm wide for all other participants) a total of 40 numbered and 20 coloured blocks (2.54 cm^3) were arranged in a rectangular array of 6 rows and 10 columns (see Fig. 1). Blocks were placed approximately 6.35 cm apart, creating a grid approximately 33 cm deep × 61 cm wide. The grid was notionally divided into right and left space. Within one set of blocks (presented on one side of the tabletop), twenty blocks labelled with the numbers 0–19 and ten blocks of different colours were placed. In the other half of space, a replicate set of blocks was placed. Paired numbered blocks (e.g. the two "19" blocks) were either equally distanced from the midline (in mirror-image columns) or near-equally distanced (one column away from mirror-image), with the exception of the "9" blocks which were placed two columns away from mirror-image due to experimental error. Near-symmetry was used so as not to alert the participant to our interest in space selection, while ensuring that left and right "options" for each number called were equally accessible from where the participant sat. To further lessen the likelihood of participants studying the array of numbers and realizing the duplication of each number, the coloured blocks served as visual distractors. The placement of all 60 blocks was pseudo-random and consistent across participants (see Fig. 1).

Participants sat in a chair without armrests in front of the table. They were instructed to find and pick up one and only one of each numbered and coloured block when called, and to place the block into a box located at the top of the array (see Fig. 2). To reduce the amount of "free" time participants had to scan the array of numbers, participants were not asked to returned to a home position. Instead, just as the participant placed a block in the box, the experimenter would call upon the next number. Participants were also encouraged to be as fast as possible. These manipulations were made to reduce the likelihood that participants would detect symmetry within the block array, and to encourage them to follow their 'first instinct'.

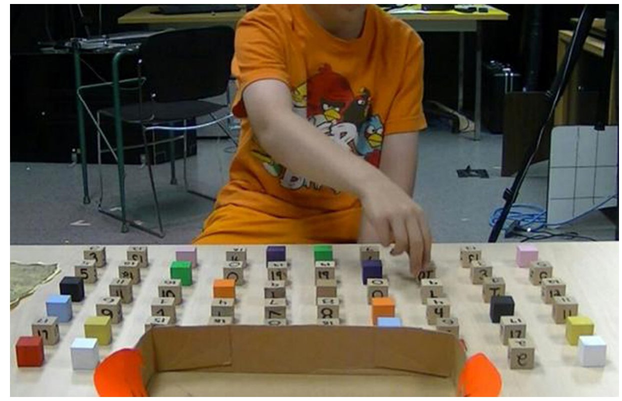

Fig. 2. Experimental set-up. The participant sat in a chair without armrests directly in front of the array of blocks, aligned with the unmarked midline of the array. The box in which participants deposited blocks was also aligned with the midline and placed at the top of the array. The video camera was positioned directly in front and facing the participant.

This speeded number calling may have exerted a slight effect on participants' space use, as the hand dropping the block could have momentarily obstructed view of certain blocks on the table. If, for example, a participant preferred to use her right hand, depositing blocks could partially obstruct her view of the right side of the table. This factor was considered during analysis.

Every number (0–19) and 8 colours were called out once (28 requests total) in a pseudo-random order that remained consistent across participants. The task lasted no more than five minutes, for any age group. Each testing session was recorded with a JVC Everio HD video camera and scoring was performed offline.

2.3. Analysis

For all grasps made by each participant, hand used (L or R) and space used (i.e. side of the table: L or R) was recorded, and arbitrarily converted into zeros (left) and ones (right).

2.3.1. Chi-square analysis

Chi-square analyses were performed to determine if participant' grasps were influenced by number magnitude. Because one of the goals of the study was to establish if the SNARC effect arises during the processing of one digit numbers, two digit numbers, or both, we performed separate analyses on the following block spans: (I) Low (0–9), High (10–19); (II) One-Digit low (0–4) and high (5–9); (III) Two-Digit low (10–14) and high (15–19). These analyses were performed for each of the three developmental groups (Primary, Secondary, and Post-secondary). Statistics were conducted using Statistical Package for the Social Sciences (SPSS) v. 19 with an alpha of 0.05 as significant.

2.3.2. Correlation analysis

We tested whether the effect of number-space association on hand- and space-use increased with age. For this, a measure of SNARC effect strength (proportion of right side (hand) use high-numbered blocks minus proportion of right side (hand) use for low-numbered blocks) was computed for each participant. The resulting values ranged from -1 to $+1$, with $+1$ indicating the highest conformation to a SNARC pattern of hand (space) use, and -1 indicating an inverted SNARC effect: right hand (space) use for relatively low numbers and vice-versa. Pearson r correlations with the variables SNARC effect strength and age (years) were conducted for each block span.

2.3.3. Regression analysis

To further explore the contribution that age has on the strength of the SNARC effect, we conducted linear regression analyses.

2.3.4. Effect of handedness

To explore whether or not strength of handedness modulates the SNARC effect, we examined the relationship between hand preference – as measured by a handedness questionnaire – and hand/space use exhibited during the block grasping task. We also inspected the relationship between hand use and space use during the task. Lastly, we investigated frequency of contralateral grasping (i.e. midline crossing) in the three age groups, to see whether age-related changes are present (and potentially modulating the SNARC effect).

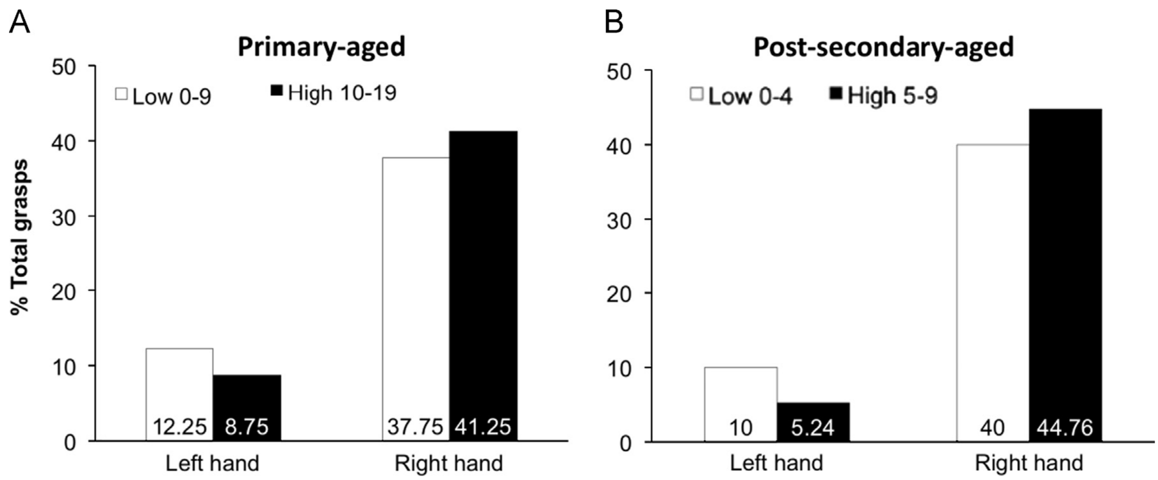

Fig. 3. Hand use for low and high numbers. Please note the two different legends. (A) Primary age children's hand use. Percent of total grasps made with each hand, for each block span (low and high end of an all-inclusive line from 0 to 19), when Primary age children's data was pooled. A grand total of 800 grasps are represented (40 children, each grasping 20 blocks numbered 0–19). Participants were significantly more likely to grasp low blocks when using the left hand, and high blocks when using the right hand. (B) Post-secondary age adult's hand use. Percent of total grasps made with each hand, for each block span (One-Digit low and high), when Post-secondary age adult's data was pooled. A grand total of 210 grasps are represented (21 adults, each grasping 10 blocks numbered 0–9). Participants were significantly more likely to grasp low blocks when using the left hand, and high blocks when using the right hand.

3. Results

Only significant results are reported.

3.1. Chi-square analysis

3.1.1. Hand use

Primary age children: Low (0–9), High (10–19).

A chi-square test demonstrated a significant relationship between hand-use and number magnitude ($X^2(1)=5.9$; $p<0.01$). Children used their right hand more often to pick up blocks associated with higher numbers (10–19) and their left hand for blocks with lower numbers (0–9) (see Fig. 3A).

Secondary age children: No significant relationships between hand-use and number magnitude were found in any of the analyses.

Post-secondary age adults: One-Digit low (0–4) and high (5–9).

A chi-square test for the One-Digit numbers revealed a significant relationship between hand-use and number magnitude ($X^2(1)=3.68$; $p<0.05$). Participants used their right hand more often to grasp the blocks with high numbers (5–9) and their left hand for blocks with low numbers (0–4) (see Fig. 3B).

3.1.2. Space use

Primary age children: No significant relationships between space-use and number magnitude were found in any of the analyses.

Secondary age children: One-Digit low (0–4) and high (5–9).

A chi-square test for the One-Digit numbers revealed a significant relationship between space-use and number magnitude ($X^2(1)=6.2$; $p<0.01$). Participants grasped more blocks from the right side of space if the number was between 5 and 9, and they grasped more from the left side of space if the number was between 0 and 4 (see Fig. 4A).

3.1.3. Post-secondary age adults

One-Digit low (0–4) and high (5–9).

A chi-square test for the One-Digit numbers revealed a significant relationship between space used and number magnitude ($X^2(1)=12.8$; $p<0.0001$). Participants grasped more blocks from the right side of space if the number was between 5 and 9, and they grasped more from the left side of space if the number was between 0 and 4 (see Fig. 4B).

3.2. Correlation analysis

3.2.1. Hand use

A significant positive correlation was found for the One-Digit numbers ($r=0.28$; $p<0.01$), indicating that older age is associated with a stronger SNARC effect on hand use for grasping (Fig. 5A).

3.2.2. Space use

A significant positive correlation was found for the One-Digit numbers ($r=0.45$; $p<0.0001$), indicating that older age is associated with a stronger SNARC effect on space use for grasping (Fig. 5B).

3.3. Regression analysis

3.3.1. Hand use

The model accounted for 6.7% of the variance and significance was noted ($F=7.0$; $p=0.010$). An examination of the coefficients showed that age was a significant predictor of hand use SNARC-effect strength ($\beta=0.011$).

3.3.2. Space use

The model accounted for 19.3% of the variance and significance was noted ($F=20.88$; $p<0.0001$). An examination of the coefficients showed that age was a significant predictor of space use effect strength ($\beta=0.026$).

3.4. Effect of handedness

3.4.1. Primary age children

Primary age children's handedness was assessed using a modified version of the Edinburgh/Waterloo Handedness Inventory (EWHI; Oldfield, 1971; Brown et al., 2006), in which scores can range from 0 points (indicating total left hand preference) to 11 points (indicating total right hand preference). On average, primary age children scored 10.4 ± 1.01 points. 12/40 (30% of) primary age children did not use their left hand to grasp any numbered blocks. All primary age children grasped at least one

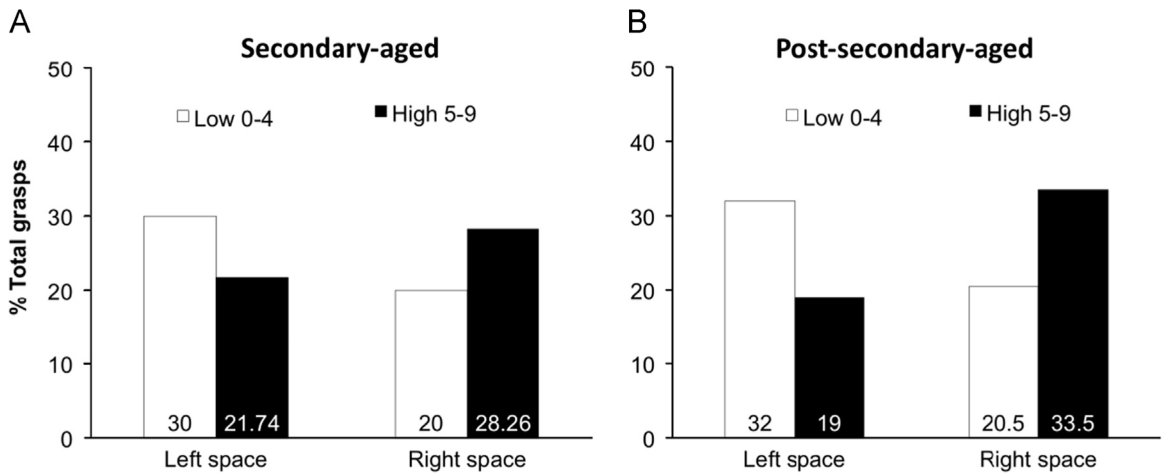

Fig. 4. Space use for low and high numbers. (A) Secondary age children's space use. Percent of total grasps made to each side of space, for each block span (One-Digit low and high), when secondary age children's data was pooled. A grand total of 230 grasps are represented (23 children, each grasping 10 blocks numbered 0–9). Participants were significantly more likely to grasp low blocks when using left space, and high blocks when using right space. (B) Post-secondary age adult's space use. Percent of total grasps made to each side of space, for each block span (One-digit low and high), when Post-secondary age adult's data was pooled. A grand total of 210 grasps are represented (21 adults, each grasping 10 blocks numbered 0–9). Participants were significantly more likely to grasp low blocks when accessing left space, and high blocks when accessing right space.

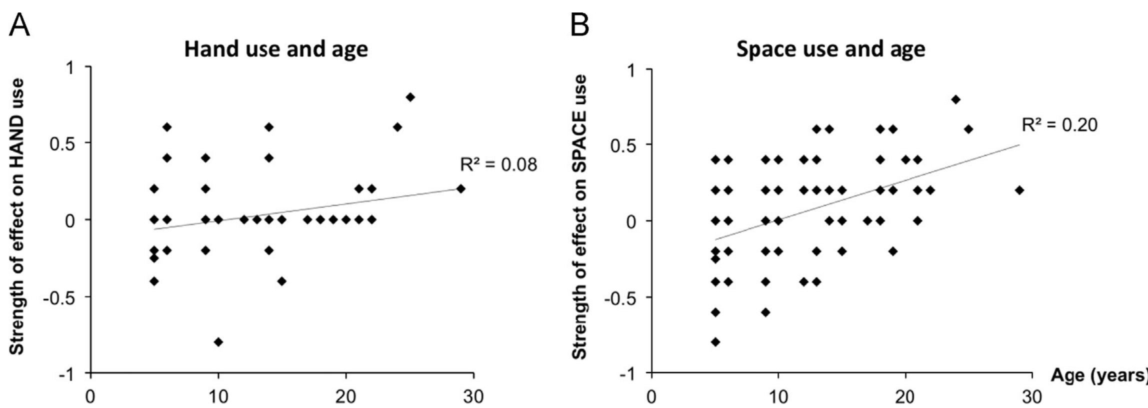

Fig. 5. Effect of age on SNARC effect for the One-Digit block span (0–9). (A) Effect of age on hand use SNARC effect. Each participant's hand use SNARC effect strength (range: -1 to $+1$) plotted as a function of chronological age. (B) Effect of age on space use SNARC effect. Each participant's space use SNARC effect strength (range: -1 to $+1$) plotted as a function of chronological age.

block from the left side of space. In fact on average, children grasped 10.07/20 ($\sim$50% of) blocks from left space, confirming that no space biases arose from participants' hands visually obstructing blocks. Correlation analyses revealed no significant relationship between EWHI score and the total number of blocks grasped with the left hand ($r=0.21$; $p>0.1$) nor total number of blocks grasped from left space ($r=-0.09$; $p>0.5$). Correlation analyses were also conducted between EWHI score and the strength of the SNARC effect exhibited; no significant correlations were found in either hand use ($r=-0.15$; $p>0.3$) or space use ($r=0.23$; $p>0.1$) for the One-Digit block span (where the SNARC effect was detected). Additionally, a correlation analysis revealed no significant relationship between total number of blocks grasped with the left hand and total number of blocks grasped from left space ($r=0.13$; $p>0.3$).

3.4.2. Secondary age children

Secondary age children were not able to complete handedness questionnaires as only a short time frame was allowed for their visit to our laboratory. However, all children self-identified as right-handed. 13/23 (56.5% of) secondary age participants did not use their left hand to grasp any numbered blocks. All secondary age children grasped at least 5/20 blocks from the left side of space. On average, secondary age children grasped 10.04/20 ($\sim$50% of) blocks from left space. As was the case in the Primary group, it seems that no space biases resulted from participants' hands visually obstructing the table. In this group, a correlation analysis again revealed no significant relationship between total number of blocks grasped with the left hand and total number of blocks grasped from left space ($r=0.02$; $p>0.9$).

3.4.3. Post-secondary age adults

Post-secondary age adult's handedness scores were obtained with the standard EWHI (Oldfield, 1971; Brown et al., 2006), in which scores can range from -44 points (indicating total left hand preference) to $+44$ points (indicating total right hand preference). On average, adults scored $+29.1\pm7.96$ points. 13/21 (61.9% of) Post-secondary age participants did not use their left hand to grasp any numbered blocks. All adults grasped at least 6/20 blocks from the left side of space. On average, adults grasped 10.09/20 ($\sim$50% of) blocks from left space, again demonstrating that possible obstruction caused by the reaching hand did not bias space use. Correlation analyses revealed no significant relationship between EWHI score and the total number of blocks grasped with the left hand ($r=0.154$, $p>0.5$) nor total number of blocks grasped from left space ($r=0.08$, $p>0.8$). Correlation analyses were also conducted between EWHI score and the strength of the SNARC effect exhibited; no significant correlations were found in either hand use ($r = -0.082$, $p > 0.7$) or space use ($r = -0.081$, $p > 0.7$) for the One-Digit block span. Again, correlation analysis revealed no significant relationship between total number of blocks grasped with the left hand and total number of blocks grasped from left space ($r = 0.02$; $p > 0.9$).

3.4.4. Contralateral grasps

For each participant, total number of contralateral (CL) grasps made while picking up the 20 numbered blocks was calculated. On average, Primary participants made 8.08 CL grasps, Secondary made 8.70, and Post-secondary made 7.90. Independent samples T-tests confirmed that the three age groups did not significantly differ from each other ($p > 0.1$). In other words, we did not find age-related changes in frequency of midline crossing; it seems that this factor did not play a role in the emergence of the SNARC effect.

4. Discussion

While many studies have documented the effect of numerical magnitude on spatial representation using a variety of manual responses, this study provides the first description of the SNARC effect on hand and space preference for the reach-to-grasp action. Furthermore, hand and space use biases associated with number magnitude were investigated for one- and two-digit numbers. Finally, the study employed a free-choice grasping task that allowed for a cross-sectional developmental characterization of the SNARC effect. For the task, an array comprised of two identical sets of wooden blocks was presented to the participant. Each set contained blocks labelled with the digits 0–19, and one set was presented on each side of a table top (the participant's left and right). Participants attended to spoken number words and reached for one correspondingly labelled block as quickly as possible. Three age/school level groups (Primary, Secondary, and Post-secondary) completed the task and their hand and space use for grasping was recorded. It was hypothesized that if lower numbers are associated with left space and higher numbers associated with right space, then patterns of hand and space use for grasping should reflect this bias. The results showed: (1) a significant hand use bias in the Primary and Post-secondary group and a space use bias in the Secondary and Post-secondary groups conforming to the SNARC effect; (2) limited evidence to support the SNARC effect for two-digit numbers; and (3) a positive and predictive relationship between age and hand and space use; the older the individual the stronger the SNARC effect.

4.1. The effect

The first goal of this study was to investigate whether the SNARC effect emerges for hand and space use in a natural reach-to-grasp task. Results revealed that number magnitude significantly affected hand selection. When children used their left hands (in a small proportion of trials), it was more often to grasp one-digit numbers (0–9). When children used their right hands, it was more often to grasp two-digit numbers (10–19). Hand use in adult participants was also influenced by number magnitude but only for one-digit numbers. Adults used the left hand more often for blocks labelled 0–4, than for blocks labelled 5–9. The results of space selection showed that (Secondary) adolescent and adult participants were strongly influenced by numerical magnitude (again, for one digit numbers only), in accordance with the SNARC effect. These findings expand the current knowledge of numerical processing and highlights its influence on response selection in a free-choice grasping task.

All participants were categorized as right-handed, either through self-identification or through the use of the EWHI (Oldfield, 1971; Brown et al., 2006). We determined that degree of right hand preference (as measured with the EWHI in the Primary and Post-secondary groups) did not correlate with hand use, space use, or the strength of the SNARC effect exhibited in either age group. This result might not be surprising given Dehaene et al., 1993 discovery that the SNARC effect is replicated in left-handers, and the finding that right- and left-handers often exhibit similar patterns of hand use for grasping (Gonzalez, Whitwell, Morrissey, Ganel, & Goodale, 2007). Furthermore, various researchers have shown that handedness questionnaires may not accurately predict hand preference for grasping in experimental tasks (Carlier et al., 2006; Gonzalez & Goodale, 2009) and that the nature of the task can modulate the expression of handedness (Fagard & Lockman, 2005). In the current study, we did not detect age-related changes in midline crossing (in contrast to, for example, Schofield, 1976). Thus we determined that this factor did not play a role in the emergence of the SNARC effect.

Some studies have demonstrated the SNARC effect in other free-choice behaviours (not reaching and grasping). For example, Fernandez, Rahona, Hervas, Vazquez, and Ulrich (2011) found that the direction of first gaze during free visual exploration is sensitive to the SNARC effect. In another study, Perrone, de Hevia, Bricolo, and Girelli (2010) observed a shift in handwriting location that was predicted by the magnitude of the digit being written. When given the freedom to use either hand in a key pressing task, Daar and Pratt (2008) noted a hand bias that varied with digit magnitude—respectively, the left/right hand was selected more often when responding to lower/higher numbers (see also Vicario, 2012). With respect to grasping, it appears that studies examining grasp responses during numerical processing have focused only on movement kinematic effects rather than the SNARC effect (left/right biases). For example, Andres, Davare, Pesenti, Olivier, and Seron (2004) asked participants to respond to digit parity with either a grip closure or opening, and observed that movement initiation time varied according to number magnitude (i.e. closure was initiated faster in response to smaller numbers while opening was primed by larger numbers). Other studies, in which participants responded to digits with either a precision or power grip, demonstrated that precision grips were initiated faster after small numbers while power grips were facilitated by large numbers (Lindemann, Abolafia, Girardi, & Bekkering, 2007; Moretto & di Pellegrino, 2008). In a free-choice study, Andres et al. (2008) had participants reach for digit-labelled objects and discovered that grip aperture was sensitive to label magnitude (i.e. seeing higher digits induced larger grip apertures while seeing lower digits induced smaller). Recently, Namdar et al. (2013) found that grip aperture was affected by magnitude even when individuals were asked to ignore that information. Despite this breadth of research establishing the interaction between number and grasp size, no other study has demonstrated the impact of numerical processing on hand/space selection for grasping. It is reasonable to speculate that motor responses, and in particular reaching-to-grasp, would be influenced by number processing. Research has shown that overlapping regions of the parietal lobe are implicated in space-processing, number-processing (see Hubbard, Piazza, Pinel, & Dehaene, 2005 for a review, Bueti & Walsh, 2009), and visuomotor control—reaching and grasping, specifically (Culham, Cavina-Pratesi, & Singhal, 2006; Olivier, Davare, Andres, & Fadiga, 2007). In fact, using functional MRI, Simon, Mangin, Cohen, Le Bihan, and Dehaene (2002) concluded that number processing and grasping are supported by adjacent parietal areas, and they postulated that the parietal lobe expanded with the development of human calculation abilities.

4.2. Nature of the number line

As previously mentioned, the set-up of the current task allowed us to explore whether the mental number line is exclusive to one-digit numbers or whether it can also be found for two-digit numbers. Importantly, the vast majority of studies investigating the SNARC effect have exclusively used one-digit numbers. Studies that have looked at the effects of numerical magnitude in two-digit numbers have reported contradictory findings (Zhou et al., 2008; Tan & Dixon, 2011). In the present study, we conceived the possibility of an all-inclusive mental number line from 0 to 19 where numbers 0–9 are deemed as lower than numbers 10–19; a single-digit line from 0 to 9, in which 0–4 are lower than 5–9; and a double-digit line from 10 to 19, in which 10–14 are lower than 15–19. Analyses of hand use showed a different number line depending on age. Post-secondary age adults were affected by the one-digit line only (0–4 as low, 5–9 as high), corroborating the results of the original SNARC publication. (Dehaene et al., 1993, p. 380) failed to find a SNARC effect in reaction time when participants responded to the parity of double digit numbers, calling it a “weaker, if not absent” effect in comparison to that found for single digits. Surprisingly however, Primary age children displayed a SNARC hand bias that reflected an all-inclusive number line (with 0–9 as low and 10–19 as high). The reason for this age-based difference is not immediately clear, but it is possible that children distinguish low magnitudes from high magnitudes based on the number of digits (one or two). Thus, any number with two digits would be considered greater than any number with only one digit. In the only study that has examined the SNARC effect on free-choice hand selection (for key-presses, Daar & Pratt, 2008), only one digit numbers were used. Hence, the present results provide the first insight into hand preference when responding to two-digit numbers.

With regard to space, the groups that displayed a space SNARC effect (Secondary and Post-secondary) were both influenced by the one-digit line only. Thus, consistent with Dehaene et al. (1993) observation, it appears that double-digit numbers are not automatically associated with left or right space. One speculation is that individuals interact with single digits on a more frequent basis than composite numbers, and frequent processing could translate into a more effortless linkage between magnitude and space.

4.3. Developmental trajectory

Results demonstrated the SNARC effect for hand preference in Post-secondary age participants, and the SNARC effect for space preference in Post-secondary and Secondary age participants. These results indicate that by Secondary school age (12 years), numerical processing may automatically shift an individual's attention towards parts of space. Additionally, the findings suggest that the influence of numerical magnitude on space preference is stronger and/or appears at an earlier developmental age than its influence on hand preference. A possible explanation for the later and less pronounced emergence of the hand effect is the intrinsic bias to use the right hand during grasping. Numerous studies have demonstrated the robustness of the right hand preference for visually-guided grasping (Bryden & Roy, 2006; Gonzalez & Goodale, 2009; Stone, Bryant, & Gonzalez, 2013). It may be that this underlying and pre-existing hand bias for the reach-to-grasp movement “over-rides” the impact of a mental number line on hand selection, until adulthood. Intriguingly however, the current study indicates that reported handedness does not influence the SNARC effect as hand/space use did not correlate with reports of the EWHI. Further research could aim at exploring why hand use is less susceptible than space use to the SNARC effect.

A number of studies have considered the developmental trajectory of number-space mapping. Some have found evidence for number-space mapping in pre-verbal infants; they appear predisposed to associate both object size (Lourenco & Longo, 2010) and object length (de Hevia & Spelke, 2010; de Hevia, Vanderslice, & Spelke, 2012) with numerosity. Such findings suggest that, from a very early age, the brain uses a general magnitude system to represent spatial and numerical information. With respect to the development of the SNARC effect specifically, the results are mixed. In terms of the age at which the effect emerges, Berch et al. (1999) found that third-graders (~9.2 years) exhibit the SNARC effect, while second-graders (~7.8 years) do not. However, another study detected the effect much earlier—in kindergarteners (~5.8 years; Yang et al., 2014). In addition to examining the age of emergence, both studies explored how the SNARC effect subsequently changes over time. Berch et al. (1999) argued that the effect diminishes with increasing age (after grade four), while Yang and authors found that the size of the effect did not change from kindergarten through grade six and still did not differ in adulthood. In a meta-analysis examining 17 separate SNARC studies, that included participants ranging in age from 9 years to mid-fifties, Wood, Willmes, Nuerk and Fischer (2008) found that the size of the effect reliably increased with age. The results of the present study corroborate the conclusion of Wood's meta-analysis. Correlation and regression analyses were conducted on the strength of the SNARC effect and participant's age (in years). Both types of analyses demonstrated a predictive relationship between the strength of the SNARC effect in both hand and space use and the participant's age. The older the individual, the greater the influence of the mental number line—at least for hand and space use during grasping.

We identified two non-mutually exclusive factors that may, in part, explain these age-related changes: mathematical experience and visual experience. However, since we did not test participants in either domain, we may only speculate the involvement of these factors. Given that all children were (at the time of testing) enrolled in school, one can assume that the older children and the adults would have received more years of mathematical instruction than the younger children. Hence, the relationship between the SNARC effect and age might be mediated by the accumulation of this experience. The original SNARC study did not support this hypothesis (Dehaene et al., 1993), although the authors based “experience” on students’ area of study, rather than developmental age. A second possible explanation for age-related increases in the SNARC effect is visual experience. Many researchers have contemplated the association between numerical processing and visual system integrity. It has been shown that children with visuospatial disabilities (VSDs) do not display a SNARC effect, while the effect is robust in matched healthy controls (Bachot, Gevers, Fias, & Roeyers, 2005). Notably, individuals with VSDs also displayed impairments in arithmetic (Bachot et al., 2005). Patients with hemispatial neglect systematically neglect both the left side of space (e.g. when bisecting a physical line) and the left side of the mental number line (e.g. when stating the midpoint of a numerical interval; Zorzi, Priftis, & Umilta, 2002). Further evidence for the connection between visual processing and number-space association is underscored in Gerstmann Syndrome, which can produce both left-right space confusion and calculation deficits in affected individuals (Gerstmann, 1940). Important to our speculation, visuospatial functions mature protractedly during childhood and some abilities do not fully mature until late adolescence (for a review see Stiles, Akshoomoff, & Haist, 2013). If visuospatial functions develop slowly throughout childhood and adolescence, and these functions contribute to numerical processing, this could partly explain why the SNARC effect strengthens with age.

4.4. Conclusion

The present study is the first to investigate free choice hand and space selection in a natural grasping task. The results demonstrate that the reach-to-grasp movement is indeed susceptible to spatial biases induced by magnitude processing. Notably, it was found that developmental age plays a significant and predictive role in modulating this effect. The SNARC effect on hand and space use was found to be progressively strengthened with age (and associated years of schooling). The findings support the notion that the mental number line is an acquired cognitive mechanism, and that age and educational experience are salient factors contributing to the SNARC effect.

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