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On the cognitive link between space and number: a meta-analysis of the SNARC effect

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Abstract

An association of numbers and space (SNARC effect) has been examined in an ever growing literature. In the present quantitative meta-analysis, 46 studies with a total of 106 experiments and 2,206 participants were examined. Deeper number magnitude processing determined by task, stimulus and participants characteristics was associated with a stronger SNARC effect. In magnitude classification tasks the SNARC effect assumed consistently a categorical shape. Furthermore, the SNARC effect was found to increase with age from childhood to elderly age. No specific difference in the size of the SNARC effect was observed due to the explicit use of imagery strategies that could not be explained by increased reaction times. In general, these results corroborate the predictions by the dual-route model of the SNARC effect regarding the activation of number magnitude representation and suggest that automaticity may play a role in the development of the association of numbers and space across the lifespan.

Key words: SNARC, mental number line, aging, imagery, meta-analysis

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In 1993, Dehaene, Bossini, and Giraux showed that small numbers (e.g., 0 or 1) were associated with faster left hand responses, and larger numbers (e.g., 8 or 9) with faster right hand responses (Figure 1A). This result held for single- (Experiment 1) as well as two-digit numbers (Experiment 2) and was not affected by whether participants were left-hand dominant (Experiment 5), or crossed their hands on the response buttons (Experiment 6). The effect did, however, depend on the relative magnitude of numbers in the stimulus set (Experiment 3) and was reduced in participants with right-to-left reading habits (Experiment 7). A similar spatial association was absent for letters (Experiment 4) but present when participants categorized number words (Experiments 8 and 9). Dehaene et al. (1993) concluded that numbers are systematically associated with space, and that this association reflects the orientation of a "mental number line". Specifically, the authors proposed that

> *"…the representation of number magnitude is automatically accessed during parity judgment of Arabic digits. This representation may be linked to a mental number line […], because it bears a natural and seemingly irrepressible correspondence with the natural left – right coordinates of external space." (p. 394).*

Recently, Proctor and Cho (2006) proposed an alternative explanation for the SNARC effect based on polarity correspondence that contests the necessity of assuming the existence of a mental number line. The polarity correspondence account is a general theory of compatibility effects and does not require a spatially oriented mental number line to explain the SNARC effect. Proctor and Cho (2006) argue that the polarity assigned to each stimulus and response depends on the relative saliency of their dimensions. Instead of perceptual or conceptual similarity, the polarity categorization suffices to produce the mapping of stimuli onto responses. This account is based on the activation of positive or negative polarities for different dimensions and is applicable not only to the SNARC effect but also to non-numerical experimental set-ups. When the same polarity ("+" or "-") is assigned to different dimensions of the experimental set-up (e.g., stimuli and responses), they become associated. When applied to the domain of numerical processing, both "right" and "large" have polarity "+" while both "left" and "small" have polarity "–". When the polarities of stimulus and response overlap, a link is established regardless of perceptual, spatial or conceptual overlap, improving performance.

Although the polarity correspondence account offers a parsimonious explanation for the SNARC effect in speeded binary classification tasks, some new evidence from cognitive neuropsychology lends support to the existence and relevance of a mental number line for the formation of spatial numerical associations (Zorzi et al., 2002). Zorzi et al. (2002) showed that hemineglect patients manifest a specific deficit in the representation of those number magnitudes which should be located on the left side of the mental number line. Furthermore, Zorzi et al. (2006) recently reported that this deficit is specific for the representation of number magnitudes and does not generalize to other ordinal sequences such as letters of the alphabet or months of the year.

A further theoretical account of the SNARC effect was proposed by Gevers et al. (2005a, 2006b) who developed a dual-route cognitive model of the SNARC effect. It describes how number magnitude may gain control over motor responses through different routes of information processing, namely a conditional and an unconditional route. The *conditional route* allows for controlling motor responses, e.g. by verbal instruction, in a very flexible way. The *unconditional route*, on the contrary, conveys the automatic activation of pre-existing associations between stimuli and responses. The association between number magnitudes and response codes observed in SNARC experiments, even when these associations are irrelevant for the task, is attributed by Gevers et al. (2005a, 2006b) to the automatic activation of the unconditional- in parallel to the conditional route. Both routes of information processing are activated in parallel until a threshold for the production of a response is reached and both may have an influence on response speed and accuracy. In congruent trials both conditional and unconditional routes lead to the same associations between stimulus and response. This reduces the latency of responses and contributes to an increase in response accuracy. In contrast, in incongruent trials conditional and unconditional routes activate distinct associations between stimulus and response. Since in incongruent trials the correct response is activated in the conditional route and a concurrent response in the unconditional route, response latencies become longer and accuracy decreases. The longer the time necessary to activate the conditional route, the stronger is the influence of the unconditional route on motor responses. Accordingly, when the activation of the unconditional route is strong enough to reach the response threshold, an incorrect response may be triggered.

While the dual-route model describes the general cognitive architecture of the SNARC effect, some authors have also asked for interindividual variability in the strength of the SNARC effect. Recently, Wood et al. (2006a, b) have reported that across different studies, the proportion of participants showing a negative SNARC slope varies between 65% and 75%. Accordingly, Piazza, Pinel and Dehaene (2006) showed that idiosyncratic associations between number and space may coexist with the usual SNARC effect. Finally, Cohen Kadosh and Henik, (2007) suggest that the implicit mental representation of numbers may differ across individuals and may deviate from the standard left-to-right representation typically described (Dehaene et al., 1993), what may result in higher interindividual variability in the SNARC effect.

This multiplicity of empirical findings leads to the current debate over the nature of the association between numbers and space. Reflecting an increasing scientific interest in the SNARC effect in its various forms, four qualitative reviews have appeared in the recent past (Fias and Fischer, 2005; Gevers and Lammertyn, 2005; Hubbard et al., 2005; Cohen Kadosh et al. 2008). The first two of these reviews concluded that the SNARC effect probably reflects an inherent spatial attribute of the mental representation of number magnitude, the third review focused on the neuroanatomical underpinnings of this representation whereas the latter concluded that non-numerical magnitude is also spatially coded. Neither of these previous reviews has provided a quantitative assessment of the literature or encompassed recent theoretical proposals such as polarity correspondence or the dual route model. This was the motivation for carrying on the present meta-analytic review.

1. Overview

Our review of the SNARC literature is subdivided into three parts. In section one, a set of hypotheses will be derived from the polarity correspondence account as well as the dual-route model of the SNARC effect and from the general literature. In section two, these hypotheses will be tested meta-analytically and an overview of our database will characterize the state of the field in terms of the most popular paradigms, materials, and tasks. The final section evaluates the impact of tasks, stimuli, responses, participant characteristics on the size of the SNARC effect and discusses these results in light of the current accounts of the SNARC effect.

2. Some hypotheses about the SNARC effect

The SNARC effect is commonly defined as an association between number magnitude and response codes. Therefore, the SNARC effect should become stronger when magnitude processing is activated more intensively (Gevers et al., 2006b).

2.1 Size of the SNARC effect and the strength of number magnitude activation

According to Gevers et al. (2006b), more intense number magnitude processing should be observed in slower responses because the unconditional route carrying up information on the association between number magnitude and response codes has more time to interfere with the selection of a response button. Furthermore, a differential effect of task on the strength of the SNARC effect is also plausible. The SNARC effect might be stronger in those tasks requiring deeper semantic number processing such as magnitude classification and parity judgement than in tasks requiring the analysis of superficial features of numerical stimuli such as colour- or orientation discrimination. Therefore we would expect that

(i) the size of the SNARC effect depends on response latencies and on the strength of number magnitude activation.
and (i b) the size of the SNARC effect depends on the amount of semantic number processing required in each task

2.2 The shape of the SNARC effect in magnitude classification tasks

Most of the time, the association between number magnitude and spatial coordinates is stronger for numbers in the extremes of the numerical interval tested but less strong for numbers in the intermediate positions giving origin to a continuous slope of reaction time differences on number magnitude (Figure 1A). However, there seems to be an exception for this pattern in magnitude classification tasks (i.e., “Is the number larger or smaller than 5?”). In magnitude classification tasks the shape of the SNARC effect seems to be categorical (Figure 1B, Gevers et al., 2006b, Nuerk et al., 2005a). It is known that comparing numbers against a fixed numerical standard leads to relatively slow reaction times for numbers close to the standard (i.e. 4 or 6) in comparison with numbers far from the standard (i.e. 1 or 9, Moyer and Landauer, 1967) because the magnitude of numbers close to the standard needs to be processed more intensively when discriminating their position in comparison to the standard (Gevers et al., 2006b). Since the SNARC effect should be stronger when number magnitude is processed more intensively, in magnitude classification tasks the SNARC effect should be stronger for numbers close to the standard (e.g. in the interval between 1 and 9, 4 and 6 are close to the standard 5 while 2 and 8 are far from the standard). A direct consequence is that in the magnitude classification task the SNARC effect observed in numbers in the intermediate range of the interval should be almost as large as for numbers in the extremes of the numerical interval i.e. the SNARC effect should assume a categorical shape (Gevers et al., 2006b; Nuerk et al., 2005a). This is not expected to happen in tasks such as a parity decision task because in these cases the time to judge the parity of numbers remains approximately constant across the numerical interval. Therefore we predict

(ii) in tasks of magnitude classification the SNARC effect should assume a categorical shape.

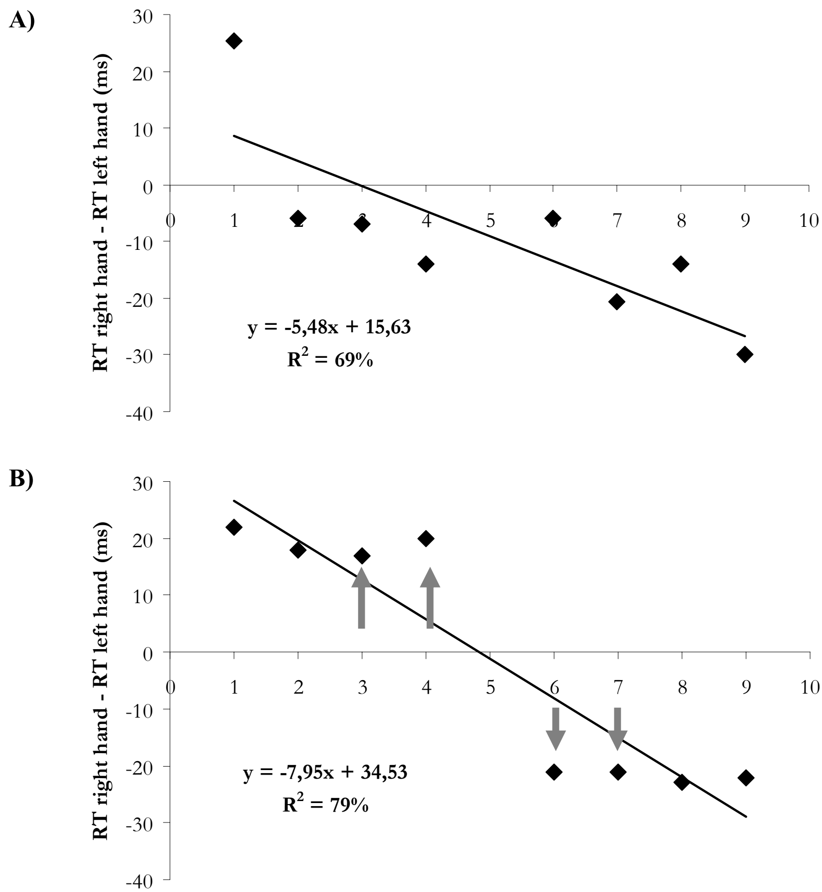

Figure 1:
A) Typical representation of the SNARC effect. The difference between the reaction times of right and left hand plotted against number magnitude produces a negative regression slope.
B) Shape of the SNARC effect in magnitude classification tasks. The magnitude numbers near the standard (i.e. near 5 in the present example) is processed more deeply than that of numbers far from standard. For this reason the SNARC effect for numbers near the numerical standard becomes comparable to the SNARC effect observed for numbers far from the standard.

2.3 The effect of imagery on the SNARC effect

Instructions underscoring the use of visual imagery have been shown to determine the orientation of the SNARC effect. Bächthold et al. (1998) told participants to judge the magnitude of numbers 1 to 5 and 7 to 11 in relation to the standard 6. In the first part of the experiment, participants were instructed to represent numbers as indicators of distances on a ruler. In the second part of the experiment, participants were instructed to represent numbers as the time displayed on a clock-face. A regular SNARC effect was found when numbers were conceived as distances on a ruler, but an inverted SNARC effect was observed when numbers were conceived as the time read on a clock-face. Therefore, the manipulation of strategies determines the relative size of the SNARC effect: while the SNARC effect is negative when participants are instructed to represent numbers on a ruler, it becomes positive when representing numbers as the time on a clock face.

Proctor and Cho (2006) attributed the results obtained by Bächthold et al. (1998) to two different types of association between number and space. On the one side, (i) categorical spatial relations are according to Proctor and Cho (2006) the main determinant of the SNARC effect and reflect the polarity correspondence between number magnitude and response codes (e.g. small-left/large-right). On the other side, according to these authors (ii) coordinate spatial relations that can modulate and even invert the SNARC effect when instructions induce the activation of mental imagery, such as in the study by Bächthold et al. (1998). Therein, Proctor and Cho (2006) attribute the activation of coordinate spatial relations to task instructions, which may more or less emphasize the use of mental imagery when solving numerical tasks. Importantly, these authors do not specify whether the activation of coordinate spatial relations should lead to a change in the absolute size of the SNARC effect or only on its direction. Interestingly, while categorical spatial relations are directly associated with the use of verbal categories which are processed primarily by the left hemisphere, coordinate spatial relations are more associated with right hemisphere functions (Laeng et al., 2003). Therefore, it is not improbable that the activation of coordinate spatial relations, which are subserved by specific brain regions in the right hemisphere, might impact on the absolute size of the SNARC effect and modulate its distribution across response time ranges. For these reasons we tentatively formulate the hypothesis that

(iii) imagery strategies might have a specific impact on the absolute size of the SNARC effect.

2.4 The SNARC effect and response discrimination

Beside bimanual responses, the SNARC effect has been reported for many other response parameters such as pointing (Fischer, 2003a), eye-movements (Fischer et al. 2004) and grasping (Andres et al. 2008). Interestingly, Fischer, (2003a) and Fischer et al. (2004) found consistently a SNARC effect in response latencies but no SNARC effect in response amplitudes. In contrast, Andres et al. (2008) found a robust SNARC effect in grasping aperture, which is a form of response amplitude. These discrepant results suggest that not all response parameters are sensitive to the SNARC effect; however, they do not answer the question about why some but not every response parameter should be sensitive to the

SNARC effect. Recently, Ansorge and Wühr (2004) proposed a response discrimination account for performance in manual choice reaction tasks. According to this account, only those response parameters allowing for an association with stimulus categories can generate spatial biases. In accord with this hypothesis, Gevers et al., (2005b) have shown that the SNARC effect can be found in different spatial aspects of the stimulus-response set when these aspects discriminate between the alternative. This can explain why in the studies by Fischer (2003a) and Fischer et al. (2004) response amplitude was not sensitive to the SNARC effect. In those studies amplitude did not discriminate responses but was held constant. In contrast, in the study by Andres et al. (2008) response amplitudes discriminated between responses. Therefore,

(iv) a SNARC effect should be found in those spatial dimensions of the experimental design which discriminate responses.

2.5 The impact of age on the size of the SNARC effect

Berch et al. (1999) have shown that in a parity decision task the SNARC effect can be found not earlier than in 9-years old children. Recently, van Galen and Reitsma (in press) found a SNARC effect in 7-years old children in a magnitude comparison task. Moreover, Vuilleumier et al. (2004), Castronovo and Seron (2006) and Priftis et al. (2006) reported a SNARC effect for participants far older than common college students. Is the SNARC effect size comparable in all age groups or is there an association between the SNARC effect size and age? In case that age has an impact on the size of the SNARC effect, there are at least two cognitive factors which may induce age-related variability in mental associations such as the SNARC effect: long-term practice (Knoch et al., 2005; Brigman and Cherry, 2002), and inhibition capacity (Hasher and Zacks, 1988). Practice effects cumulate across the life-span and may produce an age-related increase in the SNARC effect. Moreover, inhibition may be associated with an increase in the SNARC effect in children and elderly participants in comparison with young adults. Therefore, practice effects should increase the SNARC effect in function of age while inhibition should increase the SNARC effect in very young and very old groups in comparison with intermediary age groups. Therefore, we can tentatively formulate the hypothesis that

(v) age should have an impact on the size of the SNARC effect.

2.6 The interaction between stimulus format and the SNARC effect: number words

Finally, we consider effects of number formatting. Fias (2001) reported that both magnitude classification and parity judgments for written number words resulted in a SNARC effect, whereas a phoneme detection task with the same materials did not. In contrast, Arabic digits always activated the number's magnitude representation in all these tasks. A contrasting result was reported by Nuerk et al. (2005b) who found no difference in the SNARC slopes for Arabic digits, number words, auditorily presented number words and dice patterns. Fias (2001) argued that number words can be processed without access to their meaning through an non-semantic route while Arabic numbers are putatively processed through a semantic route. In light of these conflicting results it will be interesting to determine meta-analytically whether

(vi) the SNARC effect for number words should be small or absent when the task at hand can be solved without putative access to the magnitude meaning of those words.

A quantitative assessment of these six hypotheses formulated above has never been conducted with meta-analytic techniques. A meta-analytic re-analysis characterizes the strength and consistency of the empirical findings of the literature on the SNARC effect.

3. The present study

Our meta-analysis of SNARC studies has several interesting features. First, given the annually increasing output of papers (see Wood and Fischer, 2008), our report includes a substantial body of recent work that was not yet available to previous reviewers of the field. Second, our meta-analysis uses *quantitative* methods to identify and investigate patterns across studies that have remained undiscovered in previous reviews. Third, a quantitative meta-analysis of hypotheses already tested in the literature may help to evaluate the consistency of these single findings across different studies. Finally, the quantitative features of our review also allow us to test the novel predictions we have derived from recent theoretical advances and debates inference-statistically.

3.1 Inclusion and exclusion criteria for the present meta-analysis

In order to be considered for the subsequent meta-analysis, a study had to investigate the spatial representation of numbers with the SNARC effect, and had to be in press or published between 1993 and August 2006[4]. To be included, a study also had to provide a sufficiently detailed description of the stimuli and task used, as well as some participant characteristics. Most importantly, we required the study to contain a quantitative description of the association between numbers and space from which an estimate of the statistical strength of the SNARC effect could be obtained. We excluded work in which stimulus dimensions other than numbers were studied, such as days of the week or months of the year (e.g., Gevers et al., 2003; 2004) or tone height (Rusconi et al., 2005, 2006, Ishihara et al., 2008). Our review also excludes studies using the number bisection task in which participants either produce or verify the midpoint of an experimenter-defined temporal (Casaroti et al., 2007) or numerical interval (e.g. Calabria and Rosseti, 2005, Goebel et al., 2006, Nuerk et al., 2002, Zorzi et al., 2002). Although results obtained with this task are currently used to infer spatial properties of the mental number line (see for instance, Hoeckner et al., 2008), we decided to exclude

[4] We contacted several colleagues, their web sites, and electronic preview sites of journals to obtain in-press papers, including also conference posters. We wish to thank those colleagues who responded and supplied information. We also apologize if we have inadvertently neglected any relevant papers and would appreciate to receive updates from their authors for the purpose of future reviews.

them from our analysis because many different number representations become activated in the number bisection task, in addition to magnitude (see Table 1 in Nuerk et al., 2002, p. 702; see also Wood et al., 2008). The selection of a measure of number magnitude in the number bisection task is far from trivial, since there are several different ways to compute the effect of number magnitude on performance (e.g., numerical distance to the correct response, number range, numerical distance between first and second number, problem size, etc.). However, in the end, we decided that above measures are not typical SNARC-like measures. This latter decision could – of course – be further discussed, given that interval estimation tasks (de Hevia et al. 2006) and bisection tasks with flanker digits (Fischer, 2001) were included in the present analysis to better capture the range of available methods. In the end, we included 46 studies, several of which contained more than one experiment. A list of studies as well as a general description of them can be found in Appendix II. The number of experiments considered for our separate analyses as reported below may, however, differ between analyses because many experimental factors were varied in any given study.

3.2 Method for determining the size of the SNARC effect

The formula used to calculate the effect size *d* (Cohen, 1988) for each experiment was taken from Hedges and Olkin (1985). Specifically, we calculated the statistic *d* as follows:

$$d = 2t / \sqrt{df} \qquad (1)$$

where t is the value of the t-test statistic reported for the strength of the association between numbers and space, and df reflects the degrees of freedom associated with the test (usually the number of participants in the sample minus 1). Before entering a statistical analysis, any sampling bias on d was corrected according to the procedure suggested by Hedges and Olkin (1985, p. 81). Confidence intervals for the point estimates of size of the SNARC effects were obtained following the procedure described by Hedges and Olkin (1985, p. 86). For studies with multiple experiments or with multiple experimental conditions for which a SNARC effect could be estimated, separate effect sizes were calculated for each experiment or experimental condition. When only an F-value but no t-value was given in a study, the effect size d was estimated directly from the associated p-value (Fricke and Treinies, 1985, p. 94).

Often more than one estimate of the size of the SNARC effect could be obtained from a single study or even from a single experiment. For instance, Priftis et al. (2006, Experiments 2 and 3) tested hemineglect patients and young healthy controls. In this case we determined the size of the SNARC effect for each sample separately (see Appendix II). Moreover, when two non-independent estimates of the size of the SNARC effect could be subsumed into a single category, the arithmetic mean of effect size estimates was taken. For instance, the study by Wood et al. (2006a) examined the SNARC effect in four different notations (Arabic digits, visual number words, auditory number words, dice patterns) using a parity judgment task and always the same participants. To estimate the size of the SNARC effect for the factor "parity", the effect sizes obtained for these four different notations were averaged. However, to estimate the size of the SNARC effect for a specific format, only results from that format were considered.

Before reporting effect sizes as a function of experimental factors, we examined whether the effect sizes obtained in the different studies were homogeneous. The overall effect size estimate for the SNARC effect was calculated and pooled together from a total sample size of 2206 participants examined in 46 different studies. The statistic Q testing for homogeneity of effect sizes was calculated according to Hedges and Olkin (1985). This statistic for the overall size of the SNARC effect was highly significant ($\chi^2(45) = 147.0$; $p < 0.05$), pointing to significant variability in the effect sizes across the 46 studies. As a result of this heterogeneity, the impact of different experimental factors should be examined, which will be done below.

3.3 The size of the SNARC effect depends on response latencies and on the strength of number magnitude activation[5]

According to the dual route model (Gevers et al., 2006b), the size of the SNARC effect should increase together with the average RT (prediction (i), see above), since the magnitude representation has more time to interfere with response selection through the unconditional route. Average RT could be obtained from 43 independent experiments and was a significant predictor of size of the SNARC effect. A weighted least squares regression of the size of the SNARC effects on reaction times revealed a significant coefficient ($b = 0.001$, $t(42) = -2.50$, $p < 0.05$, $R^2 = 13$ %, see Hedges and Olkin 1985, p. 110, for more details on the weighting procedure). This evidence supports the view that the size of the SNARC effect increases with average RT. This result is in line with our prediction (i) as derived from the dual-route model of the SNARC effect (Gevers et al. 2006b, see also the Discussion below).

In analogy to results on the association between SNARC and RT, tasks involving semantic number processing such as parity decision or magnitude classification also were associated with a stronger SNARC effect than tasks in which semantic number processing is not required (Figure 2). Out of a total of 106 SNARC experiments that were included in this meta-analysis, just over half (number of experiments Ne = 54; 50.9 % of the total number of experiments) used a parity decision task, Ne = 18 (17 %) studied a magnitude classification task, and only Ne = 5 (4.7 %) used a magnitude comparison task (Bull et al., 2006, testing deaf and hearing participants; Fischer, 2003b; Nuerk et al. 2005a; Shaki and Petrusic, 2005[6]). The remaining Ne = 28 (27.4 %) experiments used *non-semantic tasks* which did not require any manipulation of number meaning. A large variety of tasks was subsumed in this group, such as naming or discriminating the colours of coloured numerals (Caessens et al., 2001, Keus and Schwarz, 2005, Lammertyn et al., 2002), simple detection of Arabic digits (Fischer et al., 2003), arbitrary mapping of numbers to response keys (Gevers et al. 2006b), bisection of digits strings or lines flanked by Arabic digits (Fischer, 2001), judgement about the spatial orientation of Arabic digits, arrows or geometrical figures (Caessens et al., 2004,

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[5] A large variety of response modalities has been investigated, with some studies even comparing the SNARC effect across response modalities. When this was the case we selected data only from the less common response modality for analysis. From the study by Schwarz and Keus (2004, Experiment 1), for instance, only data from saccadic latencies were used in the present analysis. For the same reason, only naming latencies from the study by Keus and Schwarz (2005, Experiment 2) and only bipedal responses from the study by Schwarz and Müller (2006, Experiment 2) were included in this analysis.

[6] In some cases, the dRT values were drawn from the figures of the published studies and should be considered as approximate values.

Fias et al., 2001, Lammertyn et al. 2002, Notebaert et al., 2006), and discrimination of visual forms (Fias et al., 2001; Zebian, 2005), as well as phoneme detection and number naming tasks (Caessens et al., 2004; Fias, 2001; Fias et al., 1996).

Table 1 shows that the size of the SNARC effect was heterogeneous in all tasks, suggesting the presence of significant variance in the size of the SNARC effects. Average effect sizes, tests for homogeneity as well as the number of participants (Np), the number of independent experiments (Ne), and average reaction times are listed in Table 1. Average effect sizes and 95 % confidence intervals are shown in Figure 2.

Table 1:
Pooled size of the SNARC effects and tests for homogeneity for different tasks

Task	*d*	χ^2	*df*	Np	Ne	RT (ms)
Parity	-0.99	197.36 **a**	53	1198	54	536
Magnitude classification (fixed standard)	-1.04	77.43 **a**	17	415	18	632
Magnitude comparison (variable standard)	-0.59	19.95 **a**	4	100	5	604
Tasks without semantic manipulation	-0.60	155.54 **a**	28	513	29	647

df: Degrees of freedom; Np: number of participants; Ne: number of experiments; *d*: pooled size of the SNARC effect; **a**: $p<0.05$

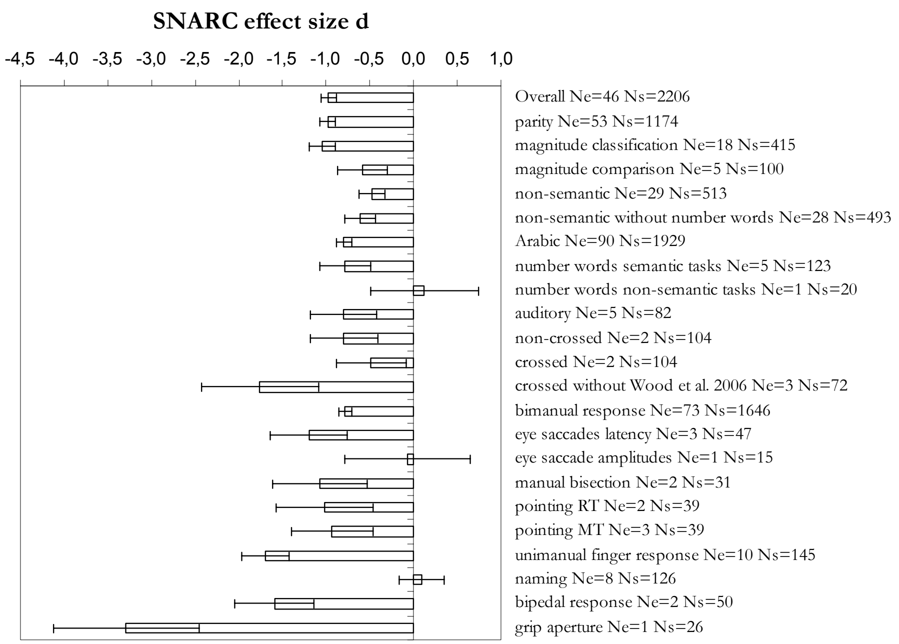

Figure 2:
Average size of the SNARC effects +/- 95% confidence intervals estimated for different experimental parameters.

The average size of the SNARC effects estimated for parity judgment tasks and magnitude classification tasks were comparable, as well as the average RTs. The effect size in the parity judgment task was slightly larger than that obtained for non-semantic tasks (Figure 2). Interestingly, the larger SNARC effect in the parity task cannot be accounted for by slower speed of responding, since in non-semantic tasks the RT was marginally slower (average m = 647 ms, standard deviation SD = 197 ms) than in the parity task (m = 573 ms, SD = 122ms).

In summary, both average RT and the nature of numerical tasks have an impact on the size of the SNARC effect. In general, the longer the time needed to reach a motor response, the stronger is the size of the SNARC effect. Furthermore, in tasks involving semantic number processing such as parity decision task, the SNARC effect tended to be larger than in non-semantic tasks.

3.4 In tasks of magnitude classification the SNARC effect should assume a categorical shape

In order to test hypothesis (ii) concerning the shape of the SNARC effect in magnitude comparison tasks, we compared the fit obtained when modelling data with categorical and linear predictors using regression models. Categorical and continuous predictors of dRT were entered stepwise in regression models calculated separately for each of the 15 studies analysed. Results are shown in Table 2.

In nine out of 15 studies (60 %) the SNARC effect could be accounted for by the categorical predictor alone. In only 1 study (7 %) the continuous predictor alone was a significant predictor of dRT (Bachot et al., 2005). In another study (Nuerk et al. 2005a[7]), both categorical and continuous predictors entered in the regression model (7 %). In the four remaining studies neither a categorical nor continuous predictors accounted for variance in the dRTs (26 %).

These results confirm prediction (ii) about the shape of the SNARC effect in magnitude comparison tasks. Gevers et al.'s (2006b) account of the categorical shape of the SNARC effect is based on the expectation of a stronger SNARC effect in slower responses. Importantly, 40% of the studies examined did not show a categorical shape. However, as will be discussed below, this may be explained by characteristics of the task, stimuli employed and participants tested.

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[7] We classified the "Eriksen flanker" task used by Nuerk et al. (2005a) as a task with variable standard because, although targets should be compared against the fixed standard 5, they were flanked by other Arabic numbers.

Table 2:
Stepwise regression models of the SNARC effect. Continuous and categorical predictors were contrasted.

Study	**Predictor remaining in the model**	***R²* (adjusted)**	***F*-test (*df*1, *df*2)**	**Increment§**
Shaki and Petrusic (2005) intermixed	continuous	.45	10.1 **a** (1, 10)	<1%
Shaki and Petrusic (2005) negative blocked	continuous	.94	75.3 **a** (1, 4)	4%
Shaki and Petrusic (2005) positive blocked	continuous	.94	85.4 **a** (1, 4)	4%
Shaki et al. (2006)	categorical	.92	92.5 **a** (1, 6)	13%
Bachot et al. (2005) control children	continuous	.42	6.2 **a** (1, 6)	20%
Bachot et al. (2005) VSD children†	(continuous)	.24	2.1 (2, 5)	15%
Gevers et al. (2006b)	categorical	.82	32.9 **a** (1, 6)	7%
Castronovo & Seron (2006) blind participants	categorical	.92	84.4 **a** (1, 6)	16%
Castronovo & Seron (2006) sighted participants	categorical	.93	91.6 **a** (1, 6)	23%
Nuerk et al. (2005)	categorical continuous	.96	7.0 **a** (1, 5)	7%
Fischer and Rottmann (2005) whole interval	categorical	.69	40.2 **a** (1, 16)	10%
Fischer and Rottmann (2005) negative interval†	(categorical)	0.01	.24 (2, 5)	<1%
Fischer and Rottmann (2005) positive interval†	(categorical continuous)	.52	4.9 (2, 5)	14%
Bull et al. (2005) deaf participants	categorical	.94	126.4 **a** (1, 6)	21%
Bull et al. (2005) hearing participants	categorical	.60	11.6 **a** (1, 6)	2%
Ito and Hatta (2004) †	(categorical continuous)	.16	.52 (2, 5)	2%
Bächthold et al. (1998) ruler task	categorical	.96	221.1 **a** (1, 8)	22%
Bächthold et al. (1998) clock-face task	categorical	.97	292.9 **a** (1, 8)	22%

df: Degrees of freedom; **a:** $p<0.05$; § The increment refers to the extra proportion of variance accounted by the predictor kept in the model. † Both predictors were excluded from the stepwise model. Numerical values shown refer to a regression model computed using the enter method.

3.5 Imagery strategies might have a specific impact on the size of the SNARC effect

In section 2.3 above, we have tentatively postulated that the absolute size of the SNARC effect may vary in function of imagery instructions. In order to test this hypothesis, we compared the slopes of size of the SNARC effect on RT obtained separately in experiments explicitly requiring the use of mental imagery (i.e., Bächthold et al., 1998; Vuilleumier et al., 2004) and experiments with instructions neutral about mental imagery. If imagery instructions lead to the activation of coordinate spatial relations, possibly the association between size of the SNARC effect and response latencies may be stronger than when only categorical spatial relations are activated. To test that we regressed separately the size of the SNARC effects on average RT for tasks requiring the use of mental imagery and those tasks with neutral instructions. For the interpretation of eventual differences in intercepts and slopes between the two types of tasks we employed the rationale presented by Verhaegen and Cerella (2002). Verhaegen and Cerella (2002) distinguish between additive and multiplicative processes interfering with the size of behavioural effects. Additive processes impact only on the intercept but not on the regression slopes, and are believed to be effective upon one single stage of cognitive processing. In contrast, multiplicative processes produce steeper slopes in the more complex conditions (i.e. in the present case the imagery condition) and are believed to interfere with two or more different stages of cognitive processing.

When instructed to use mental imagery to guide magnitude classification, participants were significantly slower (m = 832 ms; SD = 212 ms) than when the instructions were neutral (m = 548 ms; SD = 126 ms; $t(15) = 2.60$; $p < 0.05$). A weighted least squares regression analysis revealed for tasks requiring the use of mental imagery the following intercepts and slopes of the size of the SNARC effects on RT (*intercept* = -0.770, standard error SE = 1.64; b = -0.002, SE = 0.002). For tasks with neutral instructions, the following intercepts and slopes were obtained: *intercept* = -0.474, SE = 0.913; b = -0.002, SE = 0.002. Interestingly, neither the intercept ($t(15) = -0.55$, $p>0.05$) nor the slope of the size of the SNARC effect on RT ($t(15) = 0$) differed between conditions. These results suggest that although mental imagery has an impact on the average time necessary to solve SNARC tasks, the function describing the association between the size of the SNARC effect and RT remains constant. Therefore, no evidence for additive or multiplicative increase in task complexity was evident in the present analysis. These results will be further discussed in section 4.3, below.

3.6 A SNARC effect should only be found in those spatial dimensions of the experimental design which discriminate responses

The SNARC effect is often interpreted as a response bias resulting from spontaneous magnitude processing. Therefore it is of theoretical importance to determine the generality of this bias across different response modalities. Information from 105 independent experiments was classified into the following categories: Bimanual responses (Ne = 73, 70 %), saccadic latencies (Ne = 3, 2.9 %; Fischer et al., 2004; Schwarz and Keus, 2004), saccade amplitudes (Ne = 1, 1 %; Fischer et al., 2004), motor bias in number string bisection (Ne = 2, 1.9 %; Fischer, 2001), pointing latencies (Ne = 2, 1.9 %; Fischer, 2003a), movement times in pointing (Ne = 3, 2.9 % Fischer, 2003a), unimanual finger responses (Ne = 10, 10 %; e.g. Priftis et al., 2006), naming latencies (Ne = 8, 7.6 %; e.g., Keus and Schwarz, 2005), foot responses (Ne = 2, 1.9 %; Müller and Schwarz, 2006), and grip apertures (Ne = 1, 1 %; Andres et al., 2004). With the exception of saccadic amplitudes and naming latencies all response modalities showed a large SNARC effect thus speaking for the ubiquity of the effect and its importance for studies of human cognition more generally.

The size of the SNARC effects for bimanual responses, saccadic latencies, manual bisection, reaction time (RT) and movement time (MT) from pointing, as well as unimanual finger responses and bipedal responses were all comparable although average RT in the different tasks differed between response modalities (Figure 2, Table 3). The null effect for naming tasks is mainly due to the results of Zebian (2005), who found no SNARC effect for Arabic speaking participants. For this reason the present results may be interpreted with caution. For saccadic amplitudes (Fischer et al., 2004) a null effect was found as well. Finally, a very strong size of the SNARC effect was found for grip apertures.

Importantly, a SNARC effect was not observed in saccade amplitudes and in naming tasks. The lack of a SNARC effect in saccade amplitudes can be explained by the experimental setup adopted by Fischer et al. (2004), in which saccades from a fixation point to eccentric and equidistant squares should be carried on. In that experiment, the amplitudes of saccadic movements did not discriminate between responses. Interestingly, in the same experiment the *direction* of saccades was associated with a reliable SNARC effect. These results are in line with the account proposed by Gevers et al. (2005b) based on the response discrimination. The direction of saccades was highly discriminative of responses while amplitudes did not distinguish between responses. The null effect observed in naming tasks may be due to many different factors and cannot be easily interpreted. The populations tested by Zebian (2005), as well as the task used and the response modality may be responsible for the null effect. For this reason we refrain from interpreting this result in more detail.

In summary, the SNARC effect can be observed in many different motor responses. Crucially, the dimensions of response which discriminated between different responses were associated with the SNARC effect. These results corroborate the role of response discrimination in the association between number magnitudes and response codes.

Table 3:
Pooled size of the SNARC effects and tests for homogeneity for response modality.

Response	*d*	χ^2	*df*	Np	Ne	RT
bimanual response	-0.79	320.44 **a**	72	1646	73	561
eye saccades latency	-1.20	0.30	2	47	3	450
eye saccade amplitudes	-0.07	-	-	15	1	-
manual bisection	-1.08	4.54 **a**	1	31	2	-
pointing RT	-1.02	1.93 **a**	1	39	2	497
pointing MT	-0.94	0.87	2	39	3	404
unimanual finger response	-1.69	20.13 **a**	9	145	10	660
naming	0.09	0.00	7	126	8	724
foot response	-1.59	0.32	1	50	2	592
grip aperture	-3.29	-	-	26	1	492

df: degrees of freedom; Np: number of participants; Ne: number of experiments; *d*: pooled size of the SNARC effect; **a**: $p<0.05$

3.7 Age should have an impact on the SNARC effect

From Ne=106 independent experiments included, information about the age of participants was available only for 95 samples (89 %). The average age of participants in those studies was 25.56 years (*SD* = 12.45, *range* = 9 to 66 years). In order to investigate the impact of age on the size of the SNARC effect we selected only those studies reporting average RT and average age of participants and entered both variables as predictors of the size of the SNARC effect in a weighted least squares regression model. Seventeen studies met the selection criteria for this analysis. The weighted least squares regression model including age and RT as predictors of the size of the SNARC effects explained (adjusted) R^2 = 65% of variance. The higher the mean age of participants the stronger was the effect size. While age was a highly significant predictor of the size of the SNARC effect (b = -0.036; SE = 0.007; $t(14)$ = -5.29; $p < 0.05$), response speed was only marginally significant (b = -0.001; SE = 0.001; $t(14)$ = -2.04; p = 0.06, but see Footnote[8]). Figure 3 shows the association between size of the SNARC effects and age estimated after partialling out the effect of RT.

Our results strongly suggest that the size of the SNARC effect increases with age. Moreover, they suggest that the SNARC effect may not be found easily in children much younger than 10 years old. Inspection of the confidence intervals on the estimated regression slope of size of the SNARC effect on age shows that the SNARC does not differ from 0 unless children are approximately 9.5 years old (lower 95% confidence interval *CI* = -0.050, upper 95% *CI* = -0.021). This conclusion converges with empirical results obtained by Berch et al., (1999) who assessed the SNARC effect in children aged 7.8, 9.2, 9.8, 11.7, and 13.6 years old on average: Only from age 9.2 onwards was the SNARC effect reliably present (Bachot et al., 2005, but see van Galen & Reitsma, in press).

3.8 The SNARC effect for number words should be small or absent when the task at hand can be solved without putative access to the magnitude meaning of those words

Numerical information can be conveyed in several different formats. In addition to the ubiquitous Arabic digit format, we frequently encounter visual and auditory number words, fingers (Bull et al., 2006), dot patterns (Nuerk et al., 2005b; Wood et al., 2006a) and tally marks. Most studies of the SNARC effect used Arabic numbers as stimuli (Ne = 90, 79 %). Both visual and auditory number words were each employed in 4.4 % of the studies (both Ne = 5; these were Dehaene et al., 1993; Fias, 2001; Nuerk et al., 2004; Nuerk et al., 2005b; and Wood et al., 2006a, for visual number words; and Castronovo and Seron, 2006; Fischer and Hill, 2004; Nuerk et al., 2005b and Wood et al., 2006a, for auditory number words). Other stimulus formats, such as fingers (Atmaca et al., 2006; Bull et al., 2006), dot patterns (Nuerk et al., 2005b; Wood et al., 2006a), East Arabic numbers (Dehaene et al., 1993), and arrows (Caessens et al., 2004) were used in the remaining 12.3 % of experiments.

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[8] To examine the effect of age on the size of the SNARC effects we have averaged the RT for each of the seventeen studies, because the average age of participants almost did not vary within studies. Note that for the analysis of the association between RT and size of the SNARC effects we examined the 43 independent experiments separately, because RT did vary considerably between different samples.

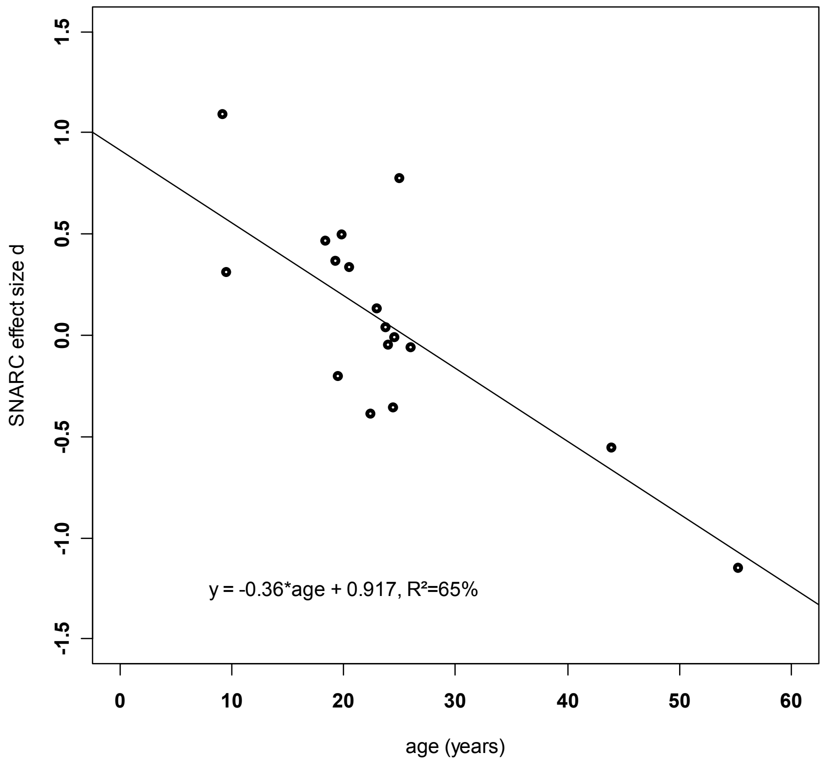

Figure 3:

The size of the SNARC effect plotted against the average age of participants. The bold line describes a negative slope of the size of the SNARC effect on age, reflecting the increase in the size of the SNARC effect due to the increase in age.

Table 4:

Pooled size of the SNARC effects and tests for homogeneity for different stimuli.

Format	***d***	χ^2	***df***	**Np**	**Ne**
Arabic	-0.83	395.81 **a**	89	1929	90
Number words with semantic	-0.82	20.00 **a**	6	153	7
Number words without semantic	0.12	-	-	20	1
Auditory number words	-0.98	16.29 **a**	4	82	5

df: degrees of freedom; Np: number of participants; Ne: number of experiments; *d*: pooled size of the SNARC effect; **a**: $p<0.05$

Concentrating on Arabic digits, auditory and visual number words, we present size of the SNARC effects and 95 % confidence intervals in Figure 2. The size of the SNARC effect was highly heterogeneous for all types of stimuli. Statistical tests for homogeneity, the number of studies and of participants are summarized in Table 4.

Note that the effect sizes for number words were split into two categories: number words in semantic tasks (Dehaene et al., 1993; Fias, 2001, Experiment 1; Nuerk et al, 2004; Nuerk et al, 2005b and Wood et al., 2006a) and number words in non-semantic tasks (Fias, 2001, Experiment 2). As predicted by Fias (2001), the size of the SNARC effect for number words in non-semantic tasks did not differ from zero (i.e. the confidence interval contains zero, see Figure 2), suggesting that magnitude information was not activated. Furthermore, as can be seen in Figure 2, the size of the SNARC effect for number words in non-semantic tasks differed from the size of the SNARC effect for Arabic digits and auditory number words, since the 95% confidence intervals for the average effect in these two conditions did not overlap. Critically, the small overlap between the confidence intervals obtained for number words in semantic and non-semantic tasks was due to the null effect reported by Wood et al. (2006a). When excluding this study from the sample, the overlap disappears (Figure 2). These data corroborates the findings originally reported and shows that these results are robust and not specific for experimental conditions of the original study by Fias (2001). In summary, comparable size of the SNARC effects were obtained for Arabic numbers, auditory and written number word. This corroborates an amodal association between number and space, as proposed by Nuerk et al. (2005b). Furthermore, a typical size of the SNARC effect can be obtained for number words in semantic tasks but not in non-semantic ones. Therefore, the association between number and space seems to be mediated by the specific materials used to test it.

4. General Discussion

The size of the SNARC effect is modulated by a broad scope of experimental factors including type of task, stimuli, motor response and participant-related factors. In general, predictions derived from the literature and from the dual-route model were confirmed by the different analyses presented above: the SNARC effect depends heavily on the strength of number magnitude activation (hypothesis i). In tasks of magnitude classification (e.g., "Is the number larger or smaller than 5?"), the SNARC effect clearly assumed a categorical shape (Gevers et al. 2006b, hypothesis ii). However, evidence does not seem to corroborate hypothesis (iii) on the impact of imaging strategies on the absolute size of the SNARC effect. Furthermore, a SNARC effect was found in spatial dimensions of the experimental design whenever they discriminated responses (prediction iv) as well as an effect of age on the size of the SNARC effect (hypothesis v). Finally, data lent further support to the view that the SNARC effect for number words is absent when the task at hand can be solved without putative access to the magnitude meaning of those words (vi). In the following, the most relevant of these results will be discussed.

4.1 The strength of number magnitude activation

Very robust evidence that the strength of number magnitude activation determined the size of the SNARC effect has been provided in the literature. The impact of number magnitude activation could be observed in response latencies and in the nature of the experimental task and task demands. In general, the longer the time needed to reach a motor response the stronger was the size of the SNARC effect. The association between response latencies and the SNARC effect was depicted as a significant regression slope which was estimated from a broad variety of studies differing in many aspects such as task, population, stimulus modality and stimulus format, as well as response modality. Therefore, since a significant regression slope was obtained, which can explain about 13 % of the variance across all SNARC experiments, one may conclude that response latencies are one determinant of the SNARC effect. An increase in the SNARC effect due to increased *response latencies* is predicted by the dual-route model (Gevers et al. 2006a): the longer the time to select a response, the stronger is the impact of number magnitude on responses and stronger is the SNARC effect. Although the present meta-analytical finding is not new, it illustrates the generality of the impact of response latencies on the SNARC effect. Moreover, it is necessary to distinguish the influence of response latencies from other determinants of the SNARC effect, such as task demands. The SNARC effect was larger in *tasks involving semantic number processing* such as the parity decision task than in non-semantic tasks such as colour discrimination. Importantly, this effect was independent from response latencies, since in non-semantic tasks RTs were even slower than in the parity task. Therefore, response latencies alone cannot explain the effect task on the size of the SNARC effect.

To our knowledge this is the first evidence for dissociation between the effects of response latency and task demands on the size of the SNARC effect. The effect of task demands can be interpreted as a consequence of deeper number magnitude processing induced by specific task characteristics or demands. In line with the polarity correspondence account (Proctor and Cho, 2006), this effect can be seen as an increase in the saliency of magnitude in semantic tasks. Different causes for this increase in the saliency of number magnitude can be enumerated: first, task instructions can induce the processing style of stimuli to be deeper or more superficial. In the case of semantic tasks, deeper number processing is necessary due to abstract properties of stimuli such as parity of magnitude. In non-semantic tasks peripheral features of stimuli should be processed such as phoneme detection, colour or even arbitrary criteria (see Gevers et al. 2005b) which are quite independent from semantic properties of numbers.

Not only task demands seem to determine the SNARC effect but also stimulus materials. In the special case of number words, the size of the SNARC effect obtained in tasks without semantic manipulation even did not differ from 0, but differed from the SNARC slopes obtained for written number words in semantic tasks. These results are a meta-analytical corroboration of the empirical study by Fias (2001). In the case of number words, different routes can be activated, one of which is a semantic route and leads to the activation of number magnitude while the other one converts a pre-semantic input directly in an output format. In semantic tasks involving the comparison of two or more numbers (e.g. Nuerk et al. 2005a) size of the SNARC effects was smaller than in other semantic tasks. A possible explanation for this fact is the interference between the different stimuli presented in each trial. While in a magnitude classification task or in a parity task only one association between number magnitude and response codes is activated in each trial, in magnitude comparison tasks as many spatio-numerical associations are potentially activated as there are numbers being presented. Since these responses and their spatial associations may differ depending on the magnitude of numbers being presented, they can counteract each other and lead to a smaller effect size.

In summary, the present results corroborate the dual route model by Gevers et al. (2006b) that the strength of magnitude activation is a pervasive determinant of the SNARC effect. Magnitude activation influences the SNARC effect through the response latencies specific for different experimental designs as well as through task demands which may require more or less magnitude activation.

4.2 Categorical vs. continuous SNARC slopes

In 60 % of the experiments examined for the shape of the SNARC effect, a categorical shape was observed. However, in 40 % of the experiments a more complex pattern of results arose. In only one experiment the SNARC effect was clearly continuous (Bachot et al., 2005, Table 2). In three experiments neither a categorical nor a continuous predictor explained the results, while in a last experiment both continuous and categorical predictors explained a significant proportion of variance. According to the dual route model of the SNARC effect (Gevers et al., 2006a), the categorical shape of the SNARC effect is due to the stronger activation of the magnitude representation typically associated with longer response latencies to numbers near the numerical standard. Accordingly, in those studies in which the SNARC effect presents a continuous shape, the number magnitude representation should have been activated to a lesser extent than in usual SNARC experiments. As discussed below, it seems to be the case at least in part of these studies. In the only study reporting a continuous slope participants were children in the age range of 7 to 12 years. As will be discussed in more detail in Section 4.5 below, at this age participants may still not activate number magnitude to the same extent as adults. Furthermore, the mapping of numbers onto space also may be less automatic at this age (Wood et al. submitted). Consequently, the impact of the distance effect on the shape of the SNARC effect may be reduced in children in comparison with adults, and the shape of the SNARC effect may resemble more a continuous slope, even in magnitude classification tasks.

Altogether, the impact of magnitude classification on the shape of the SNARC effect may depend on the exact nature of stimuli and characteristics of participants in the studies. More importantly, the present results confirm predictions (i) and (ii) of the dual-route model (Gevers et al. 2006b) that the strength of magnitude representation determines the amount of SNARC effect observed and that in magnitude classification tasks the SNARC effect may assume a categorical shape whenever the magnitude representation gets activated in a more precise and automatic fashion.

4.3 The impact of imaging

The manipulation of strategies has an important effect on the relative size of the SNARC effect: the SNARC effect is negative when participants are instructed to represent numbers on a ruler and becomes positive when representing numbers as the time on a clock face (Bächthold et al., 1998). Here we have investigated whether the effect of instructing participants to use imagery might also impact on the association between the size of the SNARC effect and RT. The findings of the present review revealed that experiments requiring the explicit use of imagery strategies produced much slower RT than experiments which did not require the use of imagery. Interestingly, both intercepts and slopes of size of the SNARC effects on RT were similar when participants were instructed to use imagery strategies and when they were not. Therefore, the stronger SNARC effect found in experiments involving the explicit use of imagery strategies can be parsimoniously attributed to the slower reaction times required to implement the strategy of using a mental image according to the given instructions. These results suggest that the use of imagery demands more effort and takes longer to be processed but they do not indicate a qualitative change in the association between the SNARC effect and response latencies. Regardless of the preferred interpretation of the effect of mental imagery on the size of the SNARC effect, one may conclude that the impact of these instructions is restricted to slowing down the response latencies and has no impact on the association between the SNARC effect and response latencies. These results can be interpreted in two ways: the first one implies that coordinate spatial relations are activated in tasks explicitly requiring the use of imagery strategies as well as in neutral tasks. In this case, participants may have used mental imagery resources in an implicit way even in those experiments not requiring this explicitly. Moreover, it is also possible that both coordinate and categorical spatial relations are associated to number magnitude to the same extent. In this case the slope of size of the SNARC effect on RT should not differ between tasks depending on imagery instructions. Unfortunately we cannot decide between these two explanations based on our meta-analytical data alone. Further empirical studies addressing this point are necessary for disclosing the role of categorical and coordinate spatial relations on the association between numbers and space. Finally, due to the small number of studies examined in this analysis, the negative results obtained should be interpreted with some caution.

4.4 Response discrimination

A robust SNARC effect was found for almost all response modalities which discriminate responses (Gevers et al., 2005b). The only dimensions which were not associated with the SNARC effect were naming latencies and saccadic amplitudes. The results from naming experiments are difficult to interpret because of massive differences in the stimulus, populations and tasks employed. For this reason one may refrain to discuss them. In contrary, the null effect observed for saccade amplitudes can be accounted by response discrimination (Ansorge and Wühr, 2004).

4.5 Age

For the first time we have disclosed a robust association between size of SNARC and age. Recently an empirical study confirmed the present finding in a large sample of individuals with ages between 9 and 79 years (Wood, et al., submitted). The SNARC effect was present in every age group, but was stronger in older participants. The association of larger (smaller) numbers and the right (left) hemi-space seems to be a habit acquired in and reinforced by the cultural environment and the linguistic background (Dehaene et al., 1993, Hung et al., 2007; Zebian, 2005). Although 9 years old children already show a significant SNARC effect, it is plausible that the amount of practice accumulated until they become adult increases. Interestingly, the SNARC effect further increases in adulthood and is largest in elderly. Therefore, it is possible that the habit of associating numbers and space becomes stronger along the whole life span. In line with this view, Velanova et al., (2006) report that older participants perform cognitive tasks in a less flexible fashion than younger participants and that their performance may depend more on well-learned habits. Therefore, it is possible that the habit of associating numbers and space consolidate along the life span. This can explain the data observed in this review.

An increase in the SNARC effect could still occur since older adults are less efficient in suppressing task-irrelevant information, thus leading to more interference of the automatic association on performance than younger adults. Supporting evidence for this claim comes from studies reporting a decrease in inhibitory control in elderly in comparison with younger adults (Hasher and Zacks, 1988; Lustig et al., in press; Martin et al., 2006) and from priming studies showing that the performance of elderly but not of younger participants is facilitated by irrelevant priming information (Kim et al., in press).

Therefore, the present empirical evidence lends stronger support to the lifelong development of the habit of associating numbers with specific regions of space and possibly also to a reduction of inhibitory capacity as the cause of the increase in the size of the SNARC effect. In summary, although the association between age and the SNARC effect reported here was highly dependent on the few studies including older participants, the results reported by Wood et al. (submitted) allow us the conclusion that an effect of age on the SNARC effect is robust.

4.6 The dual-route model of the SNARC effect

The dual-route model is a powerful cognitive framework which can account for a large diversity of features of the SNARC effect, such as the association between response speed and accuracy and the size of the SNARC effect and its shape in magnitude comparison tasks, as well as the association between the Simon and the SNARC effect (Gevers et al. 2005a). The Simon effect describes an automatic trend to respond in the direction of stimuli (Simon, 1969), and was shown to interact with the SNARC effect (Gevers et al. 2005a, Keus and Schwarz, 2005). In the present section we will discuss some challenging aspects of present meta-analysis of the SNARC effect which may lead to constraints helpful for further developments of the dual-route model by Gevers et al. (2006b).

One of the most interesting new developments is the finding that the SNARC effect is associated with the different spatial dimensions of the task that discriminate between the different responses (Gevers et al. 2005b). Another important development are studies showing that the SNARC effect may be associated with hand-based and space-based frames of reference (Müller and Schwarz, 2006; Wood et al. 2006a, b; but see also Fischer, 2006). Together, these pieces of evidence suggest that saliency of stimuli and responses, as well as strategic components may be important determinants of the SNARC effect.

Solid evidence has been presented supporting the view that the SNARC effect appears at the stage of response selection (Daar and Pratt, 2008, Keus, Jenks and Schwarz, 2005, Keus and Schwarz, 2005). Nonetheless, a few studies now suggest that this may not be the whole story about the association between numbers and space. Fischer et al. (2003) found a SNARC effect in a detection task not involving response selection at all (Salillas et al., 2008). This result suggests that the computation of congruity between spatial and numerical features characteristic of the SNARC effect may not be restricted to the stage of response selection – as typically the case with the SNARC effect – but may extend to earlier cognitive processing stages.

In summary, the present version of the dual-route model captures the most important features of the SNARC effect with regard to spatial response selection. However, in our view, the existing data indicate that potentially a component should be added to the model to account for SNARC effect at cognitive stages earlier than the response selection stage. Furthermore, the saliency of different spatial features of experimental setups and for the strategic use of space to discriminate magnitudes (Wood et al., submitted) should be considered.

4.7 The polarity correspondence account of the SNARC effect vs. the mental number line

In our view, the data suggest that currently there is no need for a decision between the polarity correspondence account and the mental number line account; rather the contribution of both of them to the SNARC effect should be identified. To distinguish between the contributions of coordinated and categorical spatial relations for the SNARC effect is difficult and still an under explored terrain. Therefore, it is in our view premature to reject the number line account at this point as contributions of coordinated as well as categorical spatial relations have been repeatedly presented in the literature. While in most tasks involving speedy binary classification the polarity correspondence framework can account for more data than the mental number line, in the context of neuropsychological research very clear evidence for the use of a mental image is available (Hoeckner et al., 2008; Vuilleumier et al., 2004; Zorzi et al., 2002, 2006). The results from these studies suggest that both coordinated and categorical spatial relations may be important for the SNARC effect, in particular, and for the association between numbers and space, in general.

5. Conclusions

Overall, it is clear that the strength of magnitude activation is a pervasive determinant of the SNARC effect. Magnitude activation influences the SNARC effect through the response latencies specific for different experimental designs as well as through task demands which may require more or less magnitude activation. The impact of imagery instructions is restricted to slowing down response latencies and seems to have no impact on the quality of spatial representations recruited. Moreover, an important effect of age on the SNARC effect was found. Two possible, not mutually exclusive origins for this effect are the development of the habit of associating numbers with specific regions of space and, especially in elderly, the capacity to inhibit it. The association of number magnitude and space has been shown to be very flexible and reflects the activation of a more abstract magnitude representation. Recent studies present evidence that counting habits are relevant for the SNARC effect (Fischer, 2008, see also Sato and Lalain, 2008). Future research must explore whether the polarity account might suffice to explain the occurrence of the SNARC effect or whether the number line account is still needed as suggested by recent neuropsychological (neglect) studies.

In sum, this meta-analysis has suggested some determinants of the SNARC effect which have previously been not systematically investigated in one controlled study, such as the effect of lifetime development on the SNARC effect. We hope that some of the questions and hypotheses raised by the present meta-analysis will be experimentally addressed in the future.

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Appendix I

The following letters were used to characterize the studies included in each one of the different analyses conducted in the present meta-analysis.

A: Overall SNARC slope
B: Parity decision task
C: Magnitude classification task
D: Magnitude comparison task
E: Non-semantic tasks
F: Non-semantic tasks without number words
G: Arabic numbers
H: Number words in semantic tasks
I: Number words in non-semantic tasks
J: Auditorily presented number words
K: Hands in non-crossed position
L: Hands in crossed position
M: Hands in crossed position without the study by Wood et al., 2006
N: Bimanual response
O: Eye saccade latencies
P: Eye saccade amplitudes
R: Manual bisection
S: Pointing RT
T: Pointing MT
U: Unimanual finger response
V: Naming
W: Bipedal response
X: Grip aperture
Shape: categorical vs. continuous shape of the SNARC effect
Size: Sample size
Age: Effect of age
RT: average RT
Errors: average error rates
Hand: Effect of the proportion of right-handed participants
Gender: Effect of gender
Language: Effect of language

Appendix II: Primary data description

Study	Group composition§	Experiment	Task Description	Participants	Response	Stimuli	N	Females	Right-handedness	mean Age (years)	range Age (years)	mean RT (ms.)	d †
Tlauka, 2002	a	Experiment 1	number categorization	English speaking students	bimanual	Arabic	50	*	*	19	18-22	458	-0.98
Tlauka, 2002	b	Experiment 2	number categorization	English speaking students	bimanual	Arabic	50	*	*	20	19-32	482	-1.20
Lammertyn et al., 2002	a	Experiment1a	color discrimination	Flemish speaking students	bimanual	Arabic	20	17	*	*	*	566	-0.06
Lammertyn et al., 2002	a	Experiment1b	orientation discrimination	Flemish speaking students	bimanual	Arabic	20	17	*	*	*	576	-1.02
Fias et al., 1996	a	Experiment 1a	parity judgment	Flemish speaking adults	bimanual	Arabic	24	16	*	23.4	*	494	-1.27
Fias et al., 1996	a	Experiment 1b	parity judgment	Flemish speaking adults	bimanual	Arabic	24	16	*	23.4	*	471	-1.20
Fias et al., 1996	b	Experiment 2	phoneme /e/ detection	Flemish speaking adults	bimanual	Arabic	23	12	*	25.7	*	591	-1.24
Fias et al., 1996	c	Experiment 3a	phoneme /e/ detection	Flemish speaking adults	bimanual	Arabic	26	17	*	20.8	*	552	-1.06
Fias et al., 1996	c	Experiment 3b	phoneme /e/ detection	Flemish speaking adults	bimanual	Arabic	26	17	*	20.8	*	552	-1.54
Fias et al., 1996	c	Experiment 3c	phoneme /e/ detection	Flemish speaking adults	bimanual	Arabic	26	17	*	20.8	*	552	-1.79
Mapelli et al., 2003	a	Experiment 1	parity judgment	Italian speaking students	bimanual	Arabic	24	*	24/24	*	*	507	-0.84
Mapelli et al., 2003	a	Experiment 2	parity judgment	Italian speaking students	bimanual	Arabic	24	*	24/24	*	*	535	-0.80
Reynvoet & Brysbaert, 1999	a	Experiment 2a	parity judgment	Flemish speaking students	bimanual	Arabic	12	*	*	*	*	428	-0.32
Reynvoet & Brysbaert, 1999	a	Experiment 2b	parity judgment	Flemish speaking students	bimanual	Arabic	12	*	*	*	*	388	-0.82
Fias et al., 2001	a	Experiment 1a	triangle orientation discrimination	Flemish speaking students	bimanual	Arabic	24	7	20/24	19.3		458	-1.12
Fias et al., 2001	a	Experiment 1b	triangle orientation discrimination	Flemish speaking students	bimanual	Arabic	24	7	20/24	19.3		458	-0.78
Fias et al., 2001	a	Experiment 2a	color discrimination	Flemish speaking students	bimanual	Arabic	24	7	20/24	19.3		383	0.17
Fias et al., 2001	a	Experiment 2b	color discrimination	Flemish speaking students	bimanual	Arabic	24	7	20/24	19.3		382	0.23
Fias et al., 2001	b	Experiment 3a	light/dark color discrimination	Flemish speaking students	bimanual	Arabic	24	4	20/24	18.3		495	0.58
Fias et al., 2001	b	Experiment 3b	Light/dark color discrimination	Flemish speaking students	bimanual	Arabic	24	4	20/24	18.3		495	0.61
Fias et al., 2001	b	Experiment 4a	line orientation discrimination	Flemish speaking students	bimanual	Arabic	23	4	20/23	18.3		479	-1.41
Fias et al., 2001	b	Experiment 4b	line orientation discrimination	Flemish speaking students	bimanual	Arabic	23	4	20/23	18.3		480	-1.44
Fias et al., 2001	c	Experiment 5	geometrical figure discrimination	Flemish speaking students	bimanual	Arabic	18	11	16/18	24.2		462	-0.13
Dehaene et al., 1993	a, b	Experiment 1	parity judgment	French speaking students	bimanual	Arabic	20	*	20\20	21.7	20-27	468	-1.43
Dehaene et al., 1993	a	Experiment 1a	parity judgment	French speaking literature students	bimanual	Arabic	10	*	10\10	22.3	20-27	468	*
Dehaene et al., 1993	b	Experiment 1b	parity judgment	French speaking science students	bimanual	Arabic	10	*	10\10	21	20-23	468	-1.30
Dehaene et al., 1993	c	Experiment 3a	parity judgment	French speaking students	bimanual	Arabic	12	*	*	23.8	19-31	472	-1.83
Dehaene et al., 1993	c	Experiment 3b	parity judgment	French speaking students	bimanual	Arabic	12	*	*	23.8	19-31	465	-1.62
Dehaene et al., 1993	d	Experiment 4a	letter classification	French speaking adults	bimanual	letters	10	*	*	30.03	18-53	510	0.44
Dehaene et al., 1993	e	Experiment 4b	consonant-vowel classification	French speaking adults	bimanual	letters	10	*	*	30.03	18-53	461	0.83

Study	Group composition§	Experiment	Task Description	Participants	Response	Stimuli	N	Females	Right-handedness	mean Age (years)	range Age (years)	mean RT (ms.)	d †
Dehaene et al., 1993	f	Experiment 5	parity judgment	French speaking left-handed adults	bimanual	Arabic	10	*	00\10	31	19-44	490	-1.93
Dehaene et al., 1993	g	Experiment 6	parity judgment	French speaking adults	crossed bimanual	Arabic	8	*	08\08	25.5	19-33	475	-2.44
Dehaene et al., 1993	h	Experiment 7a	parity judgment	Iranian (and French) speaking adults	bimanual	East Arabic	20	*	20\20	22	18-29	502	-0.84
Dehaene et al., 1993	h	Experiment 7b	parity judgment	Iranian (and French) speaking adults	bimanual	Arabic	20	*	20\20	22	18-29	540	-0.50
Dehaene et al., 1993	i	Experiment 8a	parity judgment	French students	bimanual	number words	24	*	24\24	23.3	21-33	505	-0.96
Dehaene et al., 1993	i	Experiment 8b	parity judgment	French students	bimanual	mirrored number words	24	*	24\24	23.3	21-33	550	-0.96
Dehaene et al., 1993	j	Experiment 9a	parity judgment	French students	bimanual	Arabic	24	*	24\24	23	21-28	482	-0.79
Dehaene et al., 1993	j	Experiment 9b	parity judgment	French students	bimanual	number words	24	*	24\24	23	21-28	545	-0.39
Dehaene et al., 1993	j	Experiment 9c	parity judgment	French students	bimanual	Arabic	24	*	24\24	23	21-28	482	-1.14
Dehaene et al., 1993	j	Experiment 9d	parity judgment	French students	bimanual	number words	24	*	24\24	23	21-28	545	-0.38
Fias, 2001	a	Experiment 1a	parity judgment	Flemish speaking students	bimanual	number words	20	18	18\20	18.6	*	571	-1.13
Fias, 2001	b	Experiment 2	phoneme /e/ detection	Flemish speaking students	bimanual	number words	20	13	17\20	18.3	*	519	0.12
Bächthold et al., 1998	a	Experiment 1a	magnitude classification (imagined ruler)	German speaking students	bimanual	Arabic	32	0	32\32	23.8	16-38	642	-1.36
Bächthold et al., 1998	a	Experiment 1b	magnitude classification (imagined ruler)	German speaking students	bimanual	Arabic	32	0	32\32	23.8	16-38	664	-1.02
Bächthold et al., 1998	b	Experiment 2a	magnitude classification (imagined clock)	German speaking students	bimanual	Arabic	32	0	32\32	23.8	16-38	877	-0.98
Bächthold et al., 1998	b	Experiment 2b	magnitude classification (imagined clock)	German speaking students	bimanual	Arabic	32	0	32\32	23.8	16-38	882	-1.29
Berch et al., 1999	a	Experiment 1	parity judgment	English speaking 2th grade Children	bimanual	Arabic	28	17	*	7.75	6y4m-8y5m	*	*
Berch et al., 1999	b	Experiment 2	parity judgment	English speaking 3th grade Children	bimanual	Arabic	19	10	*	9.16	8y4m-10y1m	1079	-1.36
Berch et al., 1999	c	Experiment 3	parity judgment	English speaking 4th grade Children	bimanual	Arabic	50	29	*	9.84	9y2m-10y8m	871	-0.85
Berch et al., 1999	d	Experiment 4	parity judgment	English speaking 6th grade Children	bimanual	Arabic	41	17	*	11.67	8y2m-12y7m	679	*
Berch et al., 1999	e	Experiment 5	parity judgment	English speaking 8th grade Children	bimanual	Arabic	27	15	*	13.58	10y1m-14y8m	598	*
Fischer, 2003a	a	Experiment 1a	parity judgment	German speaking students	pointing	Arabic	8	5	*	25	21-38	440	-0.44

Study	Group composition§	Experiment	Task Description	Participants	Response	Stimuli	N	Females	Right-handedness	mean Age (years)	range Age (years)	mean RT (ms.)	d †
Fischer, 2003a	a	Experiment 1b	parity judgment	German speaking students	pointing	Arabic	8	5	*	25	21-38	354	-1.11
Fischer, 2003a	a	Experiment 1c	parity judgment	German speaking students	pointing	Arabic	8	5	*	25	21-38	*	*
Fischer, 2003a	b	Experiment 2a	vowel distance judgment	German speaking students	pointing	letters	11	7	*	24	20-42	531	*
Fischer, 2003a	b	Experiment 2b	vowel distance judgment	German speaking students	pointing	letters	11	7	*	24	20-42	435	-0.60
Fischer, 2003a	b	Experiment 2c	vowel distance judgment	German speaking students	pointing	letters	11	7	*	24	20-42	*	*
Fischer, 2003a	c	Experiment 3a	parity judgment	German speaking students	pointing	Arabic	20	15	*	23	17-42	520	-1.29
Fischer, 2003a	c	Experiment 3b	parity judgment	German speaking students	pointing	Arabic	20	15	*	23	17-42	424	-1.07
Fischer, 2003a	c	Experiment 3c	parity judgment	German speaking students	pointing	Arabic	20	15	*	23	17-42	*	*
Fischer, 2001	a	Experiment 1	bisection of digit strings	English speaking adults	unimanual bisecting	Arabic	16	*	15\16	26	20-38		-1.73
Fischer, 2001	b	Experiment 2a	line bisection (flanked by digits)	English speaking adults	unimanual bisecting	Arabic	15	13	14\15	30	20-66	*	0.05
Fischer, 2001	b	Experiment 2b	line bisection (flanked by digits)	English speaking adults	unimanual bisecting	Arabic	15	13	14\15	30	20-66	*	-0.89
Fischer, 2001	b	Experiment 2c	line bisection (flanked by digits)	English speaking adults	unimanual bisecting	Arabic	15	13	14\15	30	20-66	*	-0.80
Fischer, 2003b	a	Experiment 1a	magnitude comparison A+N+	English speaking adults	bimanual	Arabic	14	9	13\14	*	20-38	649	-2.40
Fischer, 2003b	a	Experiment 1b	magnitude comparison A-N+	English speaking adults	bimanual	Arabic	14	9	13\14	*	20-38	649	*
Fischer, 2003b	a	Experiment 1c	magnitude comparison A+N-	English speaking adults	bimanual	Arabic	14	9	13\14	*	20-38	649	*
Fischer, 2003b	a	Experiment 1d	magnitude comparison A-N-	English speaking adults	bimanual	Arabic	14	9	13\14	*	20-38	649	*
Nuerk et al., 2004	a	Experiment 1a	parity judgment	German speaking students	bimanual	Arabic	23	11	31\32	26	23-30	509	-0.91
Nuerk et al., 2004	a	Experiment 1b	parity judgment	German speaking students	bimanual	Arabic	23	11	31\32	26	23-31	518	-0.88
Nuerk et al., 2004	a	Experiment 1c	parity judgment	German speaking students	bimanual	number words	23	11	31\32	26	23-32	551	-1.24
Iversen et al., 2004	a	Experiment 1	parity judgment	German sign language speaking pre-lingually deaf participants	bimanual	Arabic	20	8	19\20	31	23-47	*	-1.53
Fischer et al., 2004	a	Experiment 1a	parity judgment	western adults	eye-saccades	Arabic	15	7	13\15	19.27	17-24	540	-1.13
Fischer et al., 2004	a	Experiment 1b	parity judgment	western adults	eye-saccades	Arabic	15	7	13\15	19.27	17-24	*	-0.07
Fischer et al., 2003	a	Experiment 1	simple visual detection	Adults	unimanual	Arabic	15	*	15\15	*	*	384	-1.45
Fischer et al., 2003	b	Experiment 2	simple visual detection	Adults	unimanual	Arabic	10	*	*	*	*	365	-1.25
Schwarz & Keus, 2004	a	Experiment 1a	parity judgment	Dutch speaking students	bimanual	Arabic	16	13	16\16	*	18-26	449	-2.04
Schwarz & Keus, 2004	a	Experiment 1b	parity judgment	Dutch speaking students	eye-saccades	Arabic	16	13	16\16	*	18-27	403	-1.10
Schwarz & Keus, 2004	b	Experiment 2	parity judgment	Dutch speaking students	eye-saccades	Arabic	16	12	16\16	*	18-42	409	-1.37
Keus & Schwarz, 2005	a	Experiment 1	parity judgment	Dutch speaking students	naming	Arabic	16	11	*	*	19-27	550	0.06

Study	Group composition§	Experiment	Task Description	Participants	Response	Stimuli	N	Females	Right-handedness	mean Age (years)	range Age (years)	mean RT (ms.)	d †
Keus & Schwarz, 2005	b	Experiment 2a	parity judgment	Dutch speaking students	naming	Arabic	16	15	16\16	*	19-27	565	*
Keus & Schwarz, 2005	b	Experiment 2b	parity judgment	Dutch speaking students	naming	Arabic	16	15	16\16	*	19-27	461	0.67
Keus & Schwarz, 2005	b	Experiment 2c	parity judgment	Dutch speaking students	bimanual	Arabic	16	15	16\16	*	19-27	514	-2.02
Keus & Schwarz, 2005	b	Experiment 2d	parity judgment	Dutch speaking students	bimanual	Arabic	16	15	16\16	*	19-27	514	-0.90
Keus & Schwarz, 2005	c	Experiment 3a	color discrimination	Dutch speaking students	bimanual compatible	Arabic	16	15	16\16	*	18-26	514	-0.17
Keus & Schwarz, 2005	c	Experiment 3b	color discrimination	Dutch speaking students	Bimanual incompatible	Arabic	16	15	16\16	*	18-26	406	-1.14
Ito & Hatta, 2004	a	Experiment 1	parity judgment	Japanese speaking students	bimanual	Arabic	30	15	*	20.6	*	477	-0.66
Ito & Hatta, 2004	b	Experiment 2A	parity judgment	Japanese speaking students	bimanual	Arabic	28	13	*	20.6	*	458	-0.71
Ito & Hatta, 2004	c	Experiment 2B	parity judgment	Japanese speaking students	bimanual	Arabic	28	23	*	20.4	*	435	-0.75
Ito & Hatta, 2004	d	Experiment 3	magnitude classification	Japanese speaking students	bimanual	Arabic	28	15	*	20.6	*	410	0.03
Caessens et al., 2004	a	Experiment 1	arrow orientation + number word naming	German speaking students	bimanual + naming	arrows + colors	20	16	*	*	19-29	908	-1.03
Caessens et al., 2004	b	Experiment 2	arrow orientation + number word naming	German speaking students	bimanual + naming	arrows + colors	16	8	*	*	18-34	681	-1.20
Caessens et al., 2004	c	Experiment 3	letter judgment + number word naming	German speaking students	bimanual + naming	arrows + colors	16	8	*	*	22-31	901	-1.37
Bull et al., 2005	a	Experiment 1	magnitude classification	American deaf language speaking deaf students	bimanual	Arabic	14	6	*	*	18-28	659	-1.95
Bull et al., 2005	b	Experiment 1	magnitude classification	English speaking students	bimanual	Arabic	17	9	*	*	18-28	592	-1.41
Andres et al., 2004	a	Experiment 1	parity judgment	French-speaking students	grip aperture	Arabic	26	16	26\26	*	18-26	492	-3.29
Nuerk et al., 2005b	a	Experiment 1	parity judgment	German speaking students	bimanual	Arabic	32	16	32\32	25	18-37	487	-1.00
Nuerk et al., 2005b	a	Experiment 1	parity judgment	German speaking students	bimanual	number words	32	16	32\32	25	18-37	574	-0.61
Nuerk et al., 2005b	a	Experiment 1	parity judgment	German speaking students	bimanual	auditory number words	32	16	32\32	25	18-37	909	-0.82
Nuerk et al., 2005b	a	Experiment 1	parity judgment	German speaking students	bimanual	dot patterns	32	16	32\32	25	18-37	538	-0.67
Wood et al., 2006a	a	Experiment 1	parity judgment	German speaking students	crossed bimanual	Arabic	32	16	32\32	25	18-37	500	-0.34
Wood et al., 2006a	a	Experiment 1	parity judgment	German speaking students	crossed bimanual	number words	32	16	32\32	25	18-37	559	0.42
Wood et al., 2006a	a	Experiment 1	parity judgment	German speaking students	crossed bimanual	auditory number words	32	16	32\32	25	18-37	925	0.32

Study	Group composition§	Experiment	Task Description	Participants	Response	Stimuli	N	Females	Right-handedness	mean Age (years)	range Age (years)	mean RT (ms.)	d †
Wood et al., 2006a	a	Experiment 1	parity judgment	German speaking students	crossed bimanual	dot patterns	32	16	32\32	25	18-37	528	0.42
Nuerk et al., 2005a	a	Experiment 1	magnitude classification	German speaking students	bimanual	Arabic	24	10	*	23	*	461	-0.75
Gevers et al., 2005a	a	Experiment 1	parity judgment	Flemish speaking students	bimanual	Arabic	20	7	*	*	18-28	487	-1.44
Gevers et al., 2005a	a	Experiment 1, compatible	parity judgment	Flemish speaking students	bimanual	Arabic	20	7	*	*	18-28	482	-0.74
Gevers et al., 2005a	a	Experiment 1, incompatible	parity judgment	Flemish speaking students	bimanual	Arabic	20	7	*	*	18-28	491	-1.67
Gevers et al., 2005a	b	Experiment 2	magnitude classification	Flemish speaking students	bimanual	Arabic	20	14	*	*	18-23	451	-1.05
Fischer & Rottmann, 2005	a	Experiment 1a	parity judgment	Students/math & psychology	bimanual	Arabic	20	*	01\20	21	18-31	559	-1.36
Fischer & Rottmann, 2005	a	Experiment 1b	parity judgment	Students/math & psychology	bimanual	Arabic	20	*	01\20	21	18-31	549	0.90
Fischer & Rottmann, 2005	a	Experiment 1c	parity judgment	Students/math & psychology	bimanual	Arabic	20	*	01\20	21	18-31	546	-0.73
Fischer & Rottmann, 2005	a	Experiment 1d	parity judgment	Students/math & psychology	bimanual	Arabic	20	*	01\20	21	18-31	546	0.91
Fischer & Rottmann, 2005	a	Experiment 1e	parity judgment	Students/math & psychology	bimanual	Arabic	20	*	01\20	21	18-31	546	-1.40
Fischer & Rottmann, 2005	b	Experiment 2	magnitude classification	Students/math & psychology	bimanual	Arabic	14	9	01\20	23.5	20-38	477	-0.65
Keus et al., 2005	a	Experiment 1	parity judgment	Flemish speaking students	bimanual	Arabic	22	20	02\22	*	18-30	513	-1.89
Schwarz & Müller, 2006	a	Experiment 1	parity judgment	German speaking students	bipedal	Arabic	27	21	03\27	*	19-29	609	-1.48
Schwarz & Müller, 2006	b	Experiment 2a	parity judgment	German speaking students	bimanual	Arabic	23	17	02\23	*	19-27	493	-1.66
Schwarz & Müller, 2006	b	Experiment 2b	parity judgment	German speaking students	bipedal	Arabic	23	17	02\23	*	19-27	574	-1.74
Zebian, 2005	a	Experiment 1a	numerical similarity	Arabic speaking monoliterate adults	naming	Arabic	19	10	*	*	27-45	799	-0.96
Zebian, 2005	b	Experiment 1a	numerical similarity	Arabic and English speaking biliterate adults	naming	Arabic	17	13	*	*	15-59	748	0.66
Zebian, 2005	c	Experiment 1a	numerical similarity	English speaking monolitarates	naming	Arabic	19	12	*	*	18-43	770	-0.52
Zebian, 2005	d	Experiment 1b	numerical similarity	Arabic speaking adult illiterates	naming	Arabic	11	11	*	*	25-62	934	0.50
Zebian, 2005	e	Experiment 1c	numerical similarity	Biliterate Arabic and English speaking children	naming	Arabic	8	*	*	*	8-12	1106	1.16
Zebian, 2005	f	Experiment 1d	numerical similarity	English speaking monoliterates	bimanual	Arabic	20	*	*	*	*	*	-0.70
Zebian, 2005	g	Experiment 1e	numerical similarity	English speaking monoliterates	naming	Arabic	20	*	*	*	*	583	-0.99
Gevers et al., 2006a	a	Experiment 1	parity judgment	Flemish speaking adults	bimanual	Arabic	13	0	00\13	*	19-32	471	-1.76
Gevers et al., 2005b	a	Experiment 1a	parity judgment	Flemish speaking adults	unimanual	Arabic	16	*	00\16	*	19-25	604	-1.30
Gevers et al., 2005b	a	Experiment 1b	parity judgment	Flemish speaking adults	unimanual	Arabic	16	*	00\16	*	19-25	604	-1.69
Gevers et al., 2005b	b	Experiment 2	parity judgment	Flemish speaking adults	unimanual	Arabic	16	*	00\16	*	19-25	584	-1.55
Shaki & Petrusic, 2005	a	Experiment 1 a	magnitude comparison	students	bimanual	Arabic	22	*	*	*	*	829	-1.55
Shaki & Petrusic, 2005	a	Experiment 1 b	magnitude comparison	students	bimanual	Arabic	22	*	*	*	*	643	-2.73

Study	Group composition§	Experiment	Task Description	Participants	Response	Stimuli	N	Females	Right-handedness	mean Age (years)	range Age (years)	mean RT (ms.)	d †
Shaki & Petrusic, 2005	a	Experiment 1 c	magnitude comparison	students	bimanual	Arabic	22	*	*	*	*	643	2.03
Vuilleumier et al., 2004	a	Experiment 4a	magnitude classification (imagined clock)	elderly healthy participants	unimanual with the dominant hand	Arabic	40	20	40\40	55.5	*	597	-1.22
Vuilleumier et al., 2004	b	Experiment 4b	magnitude classification (imagined clock)	left hemisphere damaged patients	unimanual with the dominant hand	Arabic	8	2	08\08	55.6	*	706	-2.87
Vuilleumier et al., 2004	c	Experiment 4c	magnitude classification (imagined clock)	right hemisphere damaged patients without neglect	unimanual with the dominant hand	Arabic	8	1	08\08	56.2	*	985	-2.87
Vuilleumier et al., 2004	d	Experiment 4d	magnitude classification (imagined clock)	right hemisphere damaged patients with neglect	unimanual with the dominant hand	Arabic	10	4	10\10	53.8	*	1115	-2.77
Castronovo & Seron, 2006	a	Experiment 1a	magnitude classification	French speaking blind participants	bimanual	auditory number words	15	4	15\15	44	18-67	612	-1.95
Castronovo & Seron, 2006	b	Experiment 1a	magnitude classification	French speaking participants	bimanual	auditory number words	15	4	13\15	44	18-67	580	-2.12
Castronovo & Seron, 2006	a	Experiment 1b	parity decision	French speaking blind participants	bimanual	auditory number words	15	4	15\15	44	18-67	*	-1.42
Castronovo & Seron, 2006	b	Experiment 1b	parity decision	French speaking participants	bimanual	auditory number words	15	4	13\15	44	18-67	*	-0.82
Bull et al., 2006	a	Experiment 1	physical magnitude judgment	deaf students	bimanual	Arabic	20	9	*	*	18-27	470	-0.21
Bull et al., 2006	a	Experiment 1	numerical magnitude judgment	deaf students	bimanual	Arabic	20	9	*	*	18-27	666	-0.46
Bull et al., 2006	a	Experiment 1	numerical magnitude judgment	deaf students	bimanual	Arabic	20	9	*	*	18-27	*	0.01
Bull et al., 2006	a	Experiment 1	physical magnitude judgment	deaf students	bimanual	Fingers	20	9	*	*	18-27	465	0.25
Bull et al., 2006	a	Experiment 1	numerical magnitude judgment	deaf students	bimanual	Fingers	20	9	*	*	18-27	830	-0.60
Bull et al., 2006	a	Experiment 1	numerical magnitude judgment	deaf students	bimanual	Fingers	20	9	*	*	18-27	*	0.49
Bull et al., 2006	b	Experiment 1	physical magnitude judgment	students	bimanual	Arabic	20	8	*	*	18-27	470	-0.15
Bull et al., 2006	b	Experiment 1	numerical magnitude judgment	students	bimanual	Arabic	20	8	*	*	18-27	621	-0.30
Bull et al., 2006	b	Experiment 1	numerical magnitude judgment	students	bimanual	Arabic	20	8	*	*	18-27	*	0.36
Bull et al., 2006	b	Experiment 1	physical magnitude judgment	students	bimanual	Fingers	20	8	*	*	18-27	465	-0.46

Study	Group composition§	Experiment	Task Description	Participants	Response	Stimuli	N	Females	Right-handedness	mean Age (years)	range Age (years)	mean RT (ms.)	d †
Bull et al., 2006	b	Experiment 1	numerical magnitude judgment	students	bimanual	Fingers	20	8	*	*	18-27	836	0.19
Bull et al., 2006	b	Experiment 1	numerical magnitude judgment	students	bimanual	Fingers	20	8	*	*	18-27	*	0.37
Atmaca et al., 2005	a	Experiment 1	parity judgment go-no-go	students	bimanual	Arabic	30	*	*	*	*	*	-0.91
Atmaca et al., 2005	b	Experiment 1	parity judgment go-no-go	students	bimanual	Arabic	30	*	*	*	*	*	0.18
Atmaca et al., 2005	c	Experiment 2	parity judgment go-no-go	students	bimanual	Fingers	30	*	*	*	*	*	-2.82
Atmaca et al., 2005	d	Experiment 2	parity judgment go-no-go	students	bimanual	Fingers	30	*	*	*	*	*	0.20
Gevers et al., 2006b	a	Experiment 1a	parity judgment	Flemish speaking adults	bimanual	Arabic	40	*	06\40	24.4	*	443	-1.02
Gevers et al., 2006b	a	Experiment 1b	magnitude classification	Flemish speaking adults	bimanual	Arabic	40	*	06\40	24.4	*	393	-0.70
Gevers et al., 2006b	b	Experiment 2	arbitrary mapping	Flemish speaking adults	bimanual	Arabic	16	*	*	*	*	522	-1.97
Priftis et al., 2006	a	Experiment 2	parity judgment	Italian speaking students	right index and middle finger	Arabic	16	8	14\16	25.1	21-35	*	-2.79
Priftis et al., 2006	b	Experiment 3	parity judgment	Neglect patients	right index and middle finger	Arabic	6	4	06\06	66	60-70	*	-2.65
Bachot et al., 2005	a	Experiment 1	magnitude classification	Healthy Flemish speaking children	bimanual	Arabic	16	*	*	9.29	7-12	825	-0.95
Bachot et al., 2005	b	Experiment 1	magnitude classification	Flemish speaking children with visuo-spatial disability	bimanual	Arabic	16	*	*	9.24	7-13	*	0.61
Bull & Benson, 2006	a, b, c, d	Experiment 1	parity judgment	adults	bimanual	Arabic	75	38	*	22.87	18-52	*	-0.65
Bull & Benson, 2006	a, c	Experiment 1	parity judgment	all participants with high left hand 2d4d asymmetry	bimanual	Arabic	38	20	*	22.82	18-53	*	-0.55
Bull & Benson, 2006	b, d	Experiment 1	parity judgment	all participants with low left hand 2d4d asymmetry	bimanual	Arabic	36	18	*	22.89	18-54	*	-0.73
Bull & Benson, 2006	a	Experiment 1	parity judgment	male participants with high left hand 2d4d asymmetry	bimanual	Arabic	18	0	*	24.03	18-55	*	-0.58
Bull & Benson, 2006	b	Experiment 1	parity judgment	male participants with low left hand 2d4d asymmetry	bimanual	Arabic	18	0	*	24.03	18-56	*	-0.47
Bull & Benson, 2006	c	Experiment 1	parity judgment	female participants with high left hand 2d4d asymmetry	bimanual	Arabic	20	20	*	21.74	18-57	*	-0.49
Bull & Benson, 2006	d	Experiment 1	parity judgment	female participants with low left hand 2d4d asymmetry	bimanual	Arabic	18	18	*	21.74	18-58	*	-0.91
Bull & Benson, 2006	e, g	Experiment 1	parity judgment	all participants with high right hand 2d4d asymmetry	bimanual	Arabic	37	19	*	22.85	18-59	*	-0.42
Bull & Benson, 2006	f, h	Experiment 1	parity judgment	all participants with low right hand 2d4d asymmetry	bimanual	Arabic	37	19	*	22.85	18-60	*	-0.89
Bull & Benson, 2006	e	Experiment 1	parity judgment	male participants with high right hand 2d4d asymmetry	bimanual	Arabic	18	0	*	24.03	18-61	*	-0.20

Study	Group composition§	Experiment	Task Description	Participants	Response	Stimuli	N	Females	Right-handedness	mean Age (years)	range Age (years)	mean RT (ms.)	d †
Bull & Benson, 2006	f	Experiment 1	parity judgment	male participants with low right hand 2d4d asymmetry	bimanual	Arabic	18	0	*	24.03	18-62	*	-0.94
Bull & Benson, 2006	g	Experiment 1	parity judgment	female participants with high right hand 2d4d asymmetry	bimanual	Arabic	19	19	*	21.74	18-63	*	-0.61
Bull & Benson, 2006	h	Experiment 1	parity judgment	female participants with low right hand 2d4d asymmetry	bimanual	Arabic	19	19	*	21.74	18-64	*	-0.84
Fischer & Hill, 2004	a	Experiment 1a	parity judgment	English speaking students	bimanual	auditory number words	12	*	*	*	*	643	-1.41
Fischer & Hill, 2004	a	Experiment 1b	parity judgment	English speaking students	crossed bimanual	auditory number words	12	*	*	*	*	679	-1.41
Fischer & Hill, 2004	b	Experiment 2	parity judgment with blindfolded participants	English speaking students	crossed bimanual	auditory number words	8	*	*	*	*	638	-1.98
Shaki et al., 2005	a	Experiment 1	physical magnitude comparison	students	bimanual	Arabic	22	*	*	*	*	640	-1.30
Müller & Schwarz, 2006	a	Experiment 1a	parity judgment	German speaking students	bimanual	Arabic	36	*	*	*	18-44	565	-0.84
Müller & Schwarz, 2006	a	Experiment 1b	parity judgment	German speaking students	bimanual	Arabic	36	*	*	*	18-44	565	0.42
Müller & Schwarz, 2006	b	Experiment 2a	parity judgment	German speaking students	bimanual	Arabic	24	*	*	*	18-44	520	-0.85
Müller & Schwarz, 2006	b	Experiment 2b	parity judgment	German speaking students	bimanual	Arabic	24	*	*	*	18-44	520	0.42
Müller & Schwarz, 2006	c	Experiment 3a	parity judgment	German speaking students	bimanual	Arabic	24	*	*	*	18-44	527	-0.82
Müller & Schwarz, 2006	c	Experiment 3b	parity judgment	German speaking students	crossed bimanual	Arabic	24	*	*	*	18-44	527	-1.76
Notebaert et al., 2006	a	Experiment 1a	orientation discrimination, compatible magnitude mapping	Flemish speaking students	bimanual	Arabic	20	*	*	*	18-23	*	-1.96
Notebaert et al., 2006	b	Experiment 1b	orientation discrimination, incompatible magnitude mapping	Flemish speaking students	bimanual	Arabic	20	*	*	*	18-23	*	0.87
Notebaert et al., 2006	c	Experiment 2a	orientation discrimination, compatible location of response	Flemish speaking students	bimanual	Arabic	20	*	*	*	18-25	*	-1.09
Notebaert et al., 2006	d	Experiment 2b	orientation discrimination, incompatible location of manual response	Flemish speaking students	bimanual	Arabic	20	*	*	*	18-25	*	0.93
Notebaert et al., 2006	e	Experiment 4a	orientation discrimination hands, compatible location of pedal response	Flemish speaking students	bimanual	Arabic	13	9	*	*	18-30	*	-1.57

§ Within a study groups or conditions designated by same letter are not independent and only can be assessed separately; † Cohen's effect size d estimated from t-tests and corrected for sample size (Hedges & Olkin, 1985)