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The mental representation of non-numerical quantifiers: The Spatial-Linguistic Association of Response Codes (SLARC) effect.

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Abstract

How quantifiers are represented in the human mind is still a topic of intense debate. Seminal studies have addressed the issue of how a subclass of quantifiers, i.e. number words, is spatially coded displaying the SNARC (Spatial-numerical Association of Response Codes) effect; yet, none of these studies have explored the spatial representation of non-numerical quantifiers such as “some” or “many”. The aim of the present study is to investigate whether non-numerical quantifiers are spatially coded in the human mind. We administered two typical comparison tasks to 52 participants: the first task involved non-numerical quantifiers; the second task involved number words. Results showed a response-side compatibility effect for both number words and non-numerical quantifiers, suggesting that both types of quantifiers are encoded in a spatial format; quantifiers referring to “small” quantities are responded to faster with the left hand and quantifiers referring to “large” quantities are responded to faster with the right hand. We labeled this effect for non-numerical quantifiers as the SLARC (Spatial-Linguistic Association of Response Codes) effect. Notably, we found that the SNARC and the SLARC effects were strictly related to each other, namely more a participant was sensitive to the SNARC effect in the number word task, the more a SLARC effect was detectable in the non-numerical quantifier task. These findings add evidence to the tendency of humans to align magnitude information on a mental line that is coded from left to right.

(236 words)

Keywords: *Quantifiers, SNARC, Spatial representation, Number words*

Introduction

Expressions such as “many students”, “three days”, “few hours”, “some cats are grey”, are widely used in natural language. Differently from other determiners (such as “my cat” or “the red car”), these expressions do not directly refer to objects or entities, but they quantify over members of a set (e.g., a certain amount of hours or students) or they establish a relation between different sets (Bairwise & Cooper, 1981; Keenan, 2012). For instance, in the expression “some cats are grey” the quantifier “some” establishes a relation (of intersection, in this case) between the set of *cats* and the set of *things that are grey*. In uttering this expression, we refer to the set resulting from this operation, whose size (namely, the number of individuals that are included in the set) might vary according to the expression used in the sentence. Following the same example, the set that is identified by the sentence “Two cats are grey” will include two members, both complying with the property of being a cat and being grey; on the other end of the continuum, the sentence “All cats are grey”, instead, will result in a relation of inclusion in which the set of cats is a subset of the set of grey things. These operations between sets are defined in terms of quantities, amounts or degrees, and this is the reason why these expressions are labelled as “quantifiers”. Quantifiers can be classified as numerical (“two”, “three”) or non-numerical (“many”, “some”), depending on whether they contain number words or not (Keenan & Stavi, 1986). By virtue of their intrinsic link with quantities, and thus with the numerosity of a set, understanding the mental process subserving the use of these expressions is of great interest to different cognitive scientific communities.

A large number of studies indicate that the mental representation of numerical quantifiers (i.e., number words) is systematically associated with space (Dehaene, Bossini, & Giraux, 1993; Nuerk, Iversen, & Willmes, 2004; Winter, Matlock, Shaki, & Fischer, 2015).

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The most prominent experimental fact for such a tight link comes from the so-called Spatial-Numerical Association of Response Codes (SNARC) effect, which refers to the empirical phenomenon that responses involving small numbers are faster when produced through the left hand and responses involving large numbers are faster when produced through the right hand (Dehaene, Bossini, & Giraux, 1993). The SNARC effect suggests that numbers are represented along a “mental number line”, on which small numbers are spatially represented on the left and large numbers on the right (de Hevia, Vallar, Girelli, 2008).

Whereas there has been a great deal of interest in the representation of numerical quantifiers over the last three decades, research addressing the class of non-numerical quantifiers is relatively limited. There is some evidence based on explicit ratings indicating that the representation of non-numerical quantifiers is internally ordered on a mental scale, based on the magnitude of the set they denote (Holyoak & Glass, 1978; Moxey & Sanford, 1993; Yildirim, Degen, Tanenhaus, & Jaeger, 2013; Pezzelle, Bernardi, & Piazza, 2018). Moreover, other studies concerning numerical quantifiers have reported a strict relationship between non-symbolic numerical estimation and semantic processing in a sentence-picture verification task (Heim et al. 2012; Deschamps, Agmon, Loewenstein, & Grodzinsky, 2015). Some studies suggest that non-numerical quantifiers such as “many” and “few” require both numerical processing, such as magnitude estimation, and semantic processing, namely a process related to linguistic meaning (Shikhare et al 2015; but see Troiani et al., 2009; Cheng et al., 2013), in line with neuroimaging evidence showing that both types of information recruit the right inferior parietal cortex, a key area in number processing (McMillan et al., 2005).

Yet, it is not clear if the mental representation of non-numerical quantifiers shows some analogies with the spatial representation of number words. To address this question, we

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investigated whether a SNARC-like effect can be observed during the processing of non-numerical quantifiers. By administering a typical comparison task in two different versions to the same participants (i.e., one with non-numerical and one with numerical quantifiers) we also aimed at investigating the extent to which these effects (and, hence, their underlying representations) relate to each other.

Method

Participants

Fifty-two students from University Milano-Bicocca (42 females; mean age: 22 years; range: 19-28), native speakers of Italian, participated in the study for course credits. The number of participants was determined a priori following the guidelines proposed in Brysbaert & Stevens (2018) in order to design a properly powered reaction time experiment with repeated measures and mixed-effects analysis.

None of the participants self-reported previous linguistic or arithmetical disorders. The protocol of the study was approved by the Local Ethics Committee (CRIP, University of Milano-Bicocca; protocol RM-2019-183).

Materials

The present experiment consists of two comparison tasks in which participants were asked to compare two words with respect to their magnitude, presented simultaneously on a computer screen. The former involved number words, the latter involved non-numerical quantifiers. In the number-word comparison task, participants were presented with pairs of number words. Ten number words were employed, divided into two categories: Low-Magnitude (LM) number words and High-Magnitude (HM) number words. LM number

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words ranged from “zero” to “four” (Italian number words: “zero”, “uno”, “due”, “tre”, “quattro”), HM number words ranged from “five” to “nine” (Italian number words: “cinque”, “sei”, “sette”, “otto”, “nove”). The inclusion of the number word “zero” was motivated by the fact that we involved in the experiment non-numerical quantifiers like “nobody” and “nothing”, that refer to an empty set.

In the non-numerical-quantifier comparison task, participants were presented with pairs of non-numerical quantifiers. Non-numerical quantifiers were divided into Low-Magnitude (LM) quantifiers and High-Magnitude (HM) quantifiers based on the size of the set they denote (Newstead & Coventry, 2000; Pezzelle, Bernardi, & Piazza, 2018). LM quantifiers indicated “small” (down to empty) subsets with respect to the whole: *nessuno* (“none”), *niente* (“nothing”), *pochi* (“few”), *alcuni* (“some”), *qualche* (“some”). HM quantifiers referred to “large” subsets: *molti* (“many”), *tanti* (“many”), *parecchi* (“several”), *ogni* (“each/every”), *tutti* (“all”).

Apparatus

The experiment was conducted in a dimly-lit sound-attenuated room. Participants were sitting at approximately 50 cm from the screen. Stimuli were presented on a CRT monitor with a resolution of 1920×1080 pixels. Participants responded by using a USB-connected standard keyboard. The experimental procedure was created with the software OpenSesame (Mathôt et al., 2012). Stimuli were displayed in Bahnschrift white font with a 55-point size on a black background. Each trial began with the presentation of a fixation cross (58-point size) in the center of the screen for 300 milliseconds. Then, the word-pairs appeared, with their center respectively at -300 px and +300 px from the mid-sagittal plane of

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the screen. The experiment was administered using the same monitor and the same keyboard for all participants.

Procedure

Participants were asked to compare two words presented simultaneously on a computer screen by pressing a button on the keyboard. The allowed buttons were A (on the left-side of the keyboard) to select the stimulus on the left and L (on the right-side of the keyboard) to select the stimulus on the right. Each experimental pair contained a word from the LM group and a word from the HM group. The experimental pairs were created by matching the 5 low-magnitude quantifiers with the 5 high-magnitude quantifiers both in the order LM-HM and in the order HM-LM. Each experimental pair was repeated twice per block, for a total of 100 experimental pairs per block. Words appeared in two conditions depending on the magnitude of the quantifiers and their position on the screen (Figure 1): in the Congruent condition, a LM quantifier appeared on the left and a HM quantifier appeared on the right side of the screen; in the Incongruent condition, a LM quantifier appeared on the right and a HM quantifier appeared on the left side of the screen.

Figure 1. *Representation of the Congruent and Incongruent conditions for number words (top; the word pair “three-seven” represents the Congruent condition, while the word pair “seven-three” represents the Incongruent condition) and non-numerical quantifiers (bottom; “few-many” represents the Congruent condition, while “many-few” represents the Incongruent condition).*

Participants first completed the non-numerical quantifier comparison task and, subsequently, the number-word comparison task, in order to avoid that the activation of a compatibility effect in the number-word task could influence the performance of the participants on the non-numerical-quantifier task. All participants completed both tasks in a unique session.

Each task included two experimental blocks. In the first block, participants were instructed to choose which of the two words represented the larger amount; in the second experimental block participants were instructed to choose which of the two words represented the smaller amount. The order in which the blocks were performed was counterbalanced between participants. Each block contained 100 experimental pairs and 40 filler stimuli. These latter were pairs of quantifiers belonging to the same magnitude group¹. The experimental pairs and fillers were repeated across the two blocks. Word pairs were presented in random order.

Before the experiment, an instruction page describing the task was displayed. A training session was implemented before each block to help the participant familiarize with the task (nine trials). Participants were asked to be as accurate and fast as possible. Response times (RTs) and accuracy on each trial were recorded.

¹ Only filler-pairs from the HM group were displayed (e.g., “tutti – ogni”, “sette-nove”) and not filler-pairs from the LM group (e.g., “pochi-alcuni”, “due-quattro”), as a result of an omission in the script.

Results

All the participants completed the study. We established a priori a cut-off at 60% of accuracy; below such cut-off we deemed the performance to be low enough to be considered random, and we wanted to be sure that participants did not respond randomly and that they understood and attended to the task. On this basis, six participants were excluded from the analyses. The lowest accuracy score of the remaining participants was 80.7%.

Data were analyzed with R (R Core Team, 2018) using the lme4 package (Bates, Maechler & Bolker, 2012) to perform linear mixed effects analyses. P-values were obtained using the lmerTest package (Kuznetsova et al., 2017).

Number-word comparison task

Once we excluded participants with accuracy lower than the minimum threshold and filler trials, 9200 datapoints were analyzed. Trials in which the participants responded very fast (less than 150 milliseconds) or very slow (more than 1500 milliseconds) were further excluded from the analysis (equal to 6.8% of the total). Trials in which participants failed at recognizing the correct response were excluded from the RTs analysis only (1.8% of the total). We ran a linear mixed effects model with log-transformed response times as the dependent variable, condition (congruent vs. incongruent) as the independent variable, subjects as random intercepts and random slopes, and item pairs as random intercepts. Results (Figure 2, left panel) showed significantly faster response times in the Congruent condition than in the Incongruent condition ($t(43.85) = 5.5$, $p < .0001$), namely participants responded faster when LM number words appeared on the left and HM appeared on the right of the screen. In order to probe the robustness of the observed effect, we further evaluated it

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by running a mixed-effects analysis with no outliers removal and a median-based t-test. In both cases, the congruency effect holds (mixed-effects analysis: $t(45.07)=3.3$, $p=.001$; median-based analysis: $t(45)=-2.8$, $p=.008$).

Figure 2. Mean response times in the congruent and incongruent condition for Number words (left) and Non-numerical quantifiers (right). Error bars indicate the standard error of the mean (SEM).

We then tested the presence of the distance effect, a typical effect found for numerical information (Moyer & Landauer, 1967), by running a linear mixed-effects model with log-transformed response times as the dependent variable, the distance between the number words as independent variable, subjects as random intercepts and random slopes and word-

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pairs as random intercepts. As expected, we found a typical distance effect, namely that the larger the distance between number words, the faster the RTs ($t(22.95) = -7.2$, $p < .0001$).

A generalized linear mixed model (GLMM) with accuracy as dependent variable, condition as predictor variable, subjects as random intercepts and random slopes and item-pairs as random intercepts was used to analyze accuracy (Jaeger, 2008 on the analysis of categorical variables). The results showed no significant effect of condition on accuracy.

Non-numerical quantifier comparison task

Once we excluded participants with accuracy lower than the minimum threshold and filler trials, 9200 datapoints were included in the analysis. Trials in which the participants responded very fast (less than 150 ms) or very slow (more than 1500 ms) were further excluded from the analysis (equal to 6.9% of the total). Trials in which participants committed errors were excluded from the RTs analysis (2.78% of the total). As for the number-word task, RT data were analyzed using a linear mixed-effects model, with log-transformed response times as dependent variable, condition as independent variable, subjects as random intercepts and random slopes, and item pairs as random intercepts. Also in this case, results (Figure 2, right panel) showed that response times were significantly faster in the Congruent than in the Incongruent condition ($t(44.73) = 5.9$, $p < .0001$). To probe the robustness of the observed effect, we further evaluated it by running a mixed-effects analysis with no outliers removal and a median-based t-test. In both cases, the congruency effect holds (mixed-effects analysis: $t(44.61) = 4.2$, $p = .0001$; median-based analysis: $t(45) = -4.3$, $p < .0001$).

A GLMM model was used to analyze accuracy, with the condition as independent variable, subjects as random intercepts and random slopes and item-pairs as random

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intercepts. Results showed a significant effect of the condition on the accuracy ($z = -1.9$, $p = 0.046$), indicating that participants were more accurate in the Congruent than in the Incongruent condition, in analogy with RTs data.

Dissecting the congruency effect: magnitude by response side

In the previous analyses, the experimental variable “condition” variable encoded the congruency between the magnitude of the presented quantifiers and their spatial position. To further probe that the congruency effect reflects an interaction between magnitude and spatial position (i.e., left-right), we performed a control analysis explicitly testing the interaction between stimulus magnitude and spatial position. First, we examined the response times for both number words and non-numerical quantifiers as a function of magnitude of the stimuli and their spatial position (Table 1).

Table 1

Mean Values of the Response Times (in Milliseconds) Based on Magnitude (Low-Magnitude, High-Magnitude) and Spatial Position of the Stimulus (Left, Right).

Stimulus type	Left	Right
LM number words	874.4 ms	905.4 ms
HM number words	873.2 ms	861.3 ms
LM non-num. quantifiers	973.7 ms	1009.3 ms
HM non-num. quantifiers	970.4 ms	948.8 ms

For number words, we ran a linear mixed-effects model with log-transformed response times as the dependent variable, magnitude, spatial position, and their interaction as

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predictors, and subjects and item pairs as random intercepts. Results showed a significant interaction between magnitude and spatial position ($t= 5.6$, $p<.0001$). A parallel analysis on non-numerical quantifiers showed an analogous significant interaction between magnitude and spatial position ($t=4.8$, $p<.0001$). These results confirm that the congruency effect is due to the interaction between the magnitude and the spatial position of the stimuli; namely, they confirm that low-magnitude quantifiers are responded to significantly faster when presented on the left of the screen (as compared to when they are presented on the right), while high-magnitude quantifiers are responded to faster when presented on the right of the screen (as compared to when they are presented on the left).

Association between the processing of number words and non-numerical quantifiers

Having established that our participants showed a SNARC-like effect for both number words and non-numerical quantifiers, we tested to what extent the by-participants performance in the two tasks were actually related. First, we tested whether the congruency effect was modulated by the type of stimuli presented when considering all the collected data in a single analysis. We ran a model with log-transformed response times as the dependent variable, condition (congruent/incongruent), type of stimuli (number words/non-numerical quantifiers) and their interaction as predictors, and subject and word-pairs as random intercepts. Results showed that the fixed-effects for both condition and type of stimuli were significant [condition ($t=7.7$, $p<.00001$); type of stimuli ($t=3.8$, $p<.001$)], while we did not find a significant interaction between condition and types of stimuli ($t=-1.731$, $p=0.08$). This result suggests that both number words and non-numerical quantifiers show a comparable

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spatial-congruity effect, providing a first piece of evidence supporting a relation between these two processes.

To directly test this hypothesis, we then extracted the conditional modes of the random effects estimated for each subject in the mixed effects models for response times from each task, namely the individual-level random slopes. Extracting the individual-level slopes for subjects allows us to observe the inter-participant variability in the sensitivity to the congruency effect. As shown in Figure 3, the individual random-slope parameters from the number words task and the non-numerical quantifiers task were found to be significantly correlated ($r=.57$, $p<.0001$): the more participants show a SNARC effect in comparing number words, the more they show a similar effect also in comparing non-numerical quantifiers (Figure 3). In Figure 3, the axes represent the values of adjustment, for each participant, with respect to the fixed effect (which is $-.026$, in the number-word task, while it is $-.037$ in the non-numerical quantifier task). The midpoint of the axes is zero, which represents the values with no adjustment with respect to the mean, while the negative values represent participants with negative adjustment (i.e., smaller slopes compared to the mean) and the positive values represent participants with positive adjustment (i.e., larger slopes compared to the mean). Higher slopes indicate a stronger congruency effect with respect to the mean of the participants, while lower slopes indicate that the congruency-effect is weaker compared to the mean of the participants.

Figure 3. Correlation between individual random-slope parameters in the analysis on Number words vis-à-vis the analysis on Non-numerical quantifiers.

To further investigate this aspect and test to what extent the sensitivity to the number-word SNARC could predict the sensitivity to the parallel effect for non-numerical quantifiers, we included the by-subject random-slope parameters extracted from the analysis of the number-word task as predictor in the RT analysis in the non-numerical quantifier task. Since this predictor captures the sensitivity of each individual participant to the SNARC effect in the number-word task, we labelled it *SNARC sensitivity*. Hence, the SNARC sensitivity was captured through the individual adjustment to the congruency effect in the number-word task, and it amounts to the estimated by-subject random-slope parameters. We hence ran a linear mixed effects model with log-transformed RTs in the non-numerical quantifier task as the dependent variable, the congruency of the condition and SNARC sensitivity, as well as their

mutual interaction, as predictor variables, and subjects and item-pairs as random intercepts. Results showed a significant interaction between SNARC sensitivity and condition ($t(45.38) = 2.53$, $p = .014$, see Table 2). These results indicate that the higher the degree of SNARC sensitivity shown by the participants, the larger the RT difference between the Congruent condition and the Incongruent condition for non-numerical quantifiers. Note that the congruency effect for quantifiers is larger in the case of higher SNARC sensitivity. As the value of the SNARC sensitivity decreases, the effect of the condition in the prediction of the RTs of the non-numerical quantifiers task is reduced. In other words, the more a participant is sensitive to the SNARC effect, the more the same participant is sensitive to the SNARC-like effect for non-numerical quantifiers.

Table 2

Results of the Analysis in the Non-Numerical Quantifier Task Including SNARC Sensitivity as Predictor. The Degrees of Freedom are Estimated via the Satterthwaite's Approximation, so the Denominator Degrees of Freedom is Different for Each Dependent Variable.

Predictor	Estimate	Std. Err.	df	t-value	p-value
Condition	0.037	0.006	43.635	6.285	<.001
SNARC sensitivity	-12.751	2.847	44.024	-4.478	<.001
Condition:SNARC sensitivity	1.777	0.701	45.383	2.535	.0147

Discussion

In the present paper, we aimed at investigating whether the mental representation of non-numerical quantifiers shared analogies with the spatial representation of number words. In order to explore this hypothesis, we administered two comparison tasks, one involving

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numerical quantifiers (i.e., number words) and one with non-numerical quantifiers. We found a response-side compatibility effect for both number words and non-numerical quantifiers, thus suggesting that both these types of information are encoded in a spatial format. This effect, that could be labeled as SLARC (Spatial-Linguistic Association of Response Codes) effect, adds evidence that SNARC-like effects can be observed within a range of different types of stimuli (Macnamara et al., 2018). The SLARC effect consists in the fact that LM (Low-Magnitude) quantifiers, such as *pochi* (“few”) or *alcuni* (“some”), are responded to faster with the left hand and HM (High-Magnitude) non-numerical quantifiers, such as *molte* (“many”) or *parecchi* (“several”), are responded to faster with the right hand.

It is noteworthy that previous SNARC-like effects have been reported in the linguistic domain with series of items that are characterized by a precise sequencing, such as the letters of the alphabet and the months of the year (Gevers, Reynvoet, & Fias, 2003). However, the ordinal relationship between the items on these kinds of scales is arbitrary. For non-numerical quantifiers, instead, the order in which the items might be represented on the scale is not arbitrary, being a byproduct of the entailment relationships that link scalar quantifiers.

Despite these entailment relations, an ordinal sequencing is nevertheless not so easily identified in the case of non-numerical quantifiers, since they cannot be ordered within an arbitrary sequence, as it is the case for the other linguistic elements mentioned above, nor to a functional algorithm, as it is the case for numbers, for which the ordinal sequencing is given by applying +1 to the preceding number word. This suggests that the SNARC-like effect described for non-numerical quantifiers is likely due to absolute cardinal relationships, such as the quantitative representation of the numerosity of the set denoted by each quantifier, and not to fixed ordinal relationships between different quantifiers. In addition, the possibility that the effect showed in the present work is due to cardinal relationships is supported by the

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robust association that we found between the participants' performances in the two tasks. Considering that number words display both ordinal (i.e., the algorithmic sequence of numbers: N , $N+1$) and cardinal (i.e., the relative magnitude) properties but non-numerical quantifiers display only cardinal properties, namely the magnitude of the set denoted, the tight relationship between the two tasks may rely on the common, cardinal property of the two types of quantifiers involved. Hence, we suggest that both effects are dependent on the mental representation of the magnitude of both types of quantifiers. Our results did not simply indicate that the spatial representations of number words and non-numerical quantifiers are vaguely similar, but rather our data speak in favor of a strong relationship between these two spatial formats. Indeed, at the individual level, we found that the more a participant displayed a SNARC effect, the more the same participant was likely to display a SLARC effect for non-numerical quantifiers. Even more convincingly, we found that the way each participant performed with the number word task predicted the way the same participant performed with the non-numerical quantifiers: the higher the sensitivity to the SNARC-like effect in the number word task, the more a SLARC effect was detectable in the non-numerical quantifier task. Such an interconnection is remarkable, given the very distinct types of information that these two classes of quantifiers express: one expressing precise numerical information about the numerosity of a set, the other referring to relations between sets. This experimental phenomenon implies that the processes underlying the mental representation of exact ("four") and non-precise ("some") numerical information have robust connections, or even rely on the same spatial underpinnings. One possible interpretation of these results could be framed into the "A Theory of Magnitude" (ATOM) framework (Walsh, 2003), according to which stimuli expressing magnitude information are represented using a common abstract magnitude code. However, it is interesting to notice that within the ATOM framework the

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stimuli that are taken into consideration have an exact magnitude that can be experimentally manipulated, while such an attribute does not characterize non-numerical quantifiers. For instance, when considering physical size (e.g., dots with different diameters) or conceptual size (e.g., words referring to objects of different size, such as “bean” and “apple”) (Ren et al., 2011), the intrinsic magnitude is *per se* something measurable and objective; on the contrary, the magnitude expressed by non-numerical quantifiers in isolation remains undetermined and not directly or objectively measurable.

Our study increases the knowledge on the spatial representation of non-binary and non-sequential classes of words, such as that of quantifiers. Indeed, a variety of stimuli (such as luminance, numbers and non-numerical quantifiers) have been shown to be spatially coded (Shaki et al., 2012; Ishihara et al., 2008; Holmes & Lourenco, 2011; Helmreich et al., 2011), suggesting that there might be a generally shared mechanism that underlie the representation of such conceptually different stimuli. Whether these mechanisms first originated to support the representation of symbolic magnitudes and then they were adopted to represent other types of magnitudes, such as that associated to non-numerical quantifiers, is still unclear. These spatial coding mechanisms could also originate earlier in life and then employed to similarly represent a variety of elements, from magnitude to time representation. For instance, a propensity for infants to map magnitudes on a left-to-right spatial continuum has been documented (de Hevia et al., 2017). Yet, whether the early predisposition to map non-symbolic numerosity onto space can be taken as a precursor of the spatial representation of symbolic information is still unknown.

More generally, our findings add knowledge to the existing evidence (Macnamara et al., 2018; Shaki et al., 2012; Ishihara et al., 2008; Holmes & Lourenco, 2011; Helmreich et al., 2011) documenting a tendency of humans to align magnitude information (and not only

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numbers) on a spatial continuum, a phenomenon that is of great interest for psychological research since it provides evidence of deep connections between (apparently) different cognitive domains.

Data availability

All the data generated during this study are available at
https://osf.io/q3fgb/?view_only=1fd99b0b38fd49a7969a2796ba0c8d4f

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