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Title: A universal left-to-right bias in number-space mapping across ages and cultures

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Abstract:

Number and space are inherently related. For decades, authors have collected evidence showing that numbers are aligned to a so-called “mental number line”, which is malleable and affected by cultural factors. However, preverbal human and non-human animals also map numerosities into space, in a consistent left to right direction. These contrasting pieces of evidence raise the question of whether Space Number Associations (SNA) are culturally or biologically determined. Here, we investigated Italian adults, Italian preschoolers and Himba adults to determine whether cultural influences are necessary for SNA to emerge. We found that, when explicitly asked to order numerosities, only Italian adults showed a consistent left to right preference, while preschoolers and Himba adults did not have a consistent preference for one direction or the other. On the other hand, in a numerosity comparison task, all groups performed better when small numerosities were presented in the left hemispace. These results suggest that SNA is not a unique phenomenon, but rather is dissociable in two components: a universal one, biologically predisposed and left-to-right oriented, and an acquired one, culturally dependent and not fixed in orientation.

One-Sentence Summary:

A universal biological predisposed left-to-right space-number association is found across culture and age

Main Text:

Number and space are utterly related in everyday life in cultures with formal education systems. From calendars to measuring instruments we are used to seeing numbers mapped onto space. Since Galton's initial systematic description of individuals reporting vivid associations between numbers and space (1), subsequent studies have consistently demonstrated that a majority of Western educated adults exhibit a robust tendency to associate small numbers with the left side and larger numbers with the right side of space. The strength and the direction of this number-to-space association (known as SNARC, for *Spatial-Numerical Association of Response Codes*, by Dehaene and colleagues in 1993 (2)), however, has been shown to be malleable to reading habits and contexts: while left-to-right readers systematically show a left-to-right SNARC (e.g. 3–6), subjects raised in cultures with writing systems that are organized from right-to-left or from top-to-bottom tend to show no, inverted, or top-to-bottom SNARC (7–10). Moreover, the SNARC depends on the context: when put in the context of judging time, with reference to the traditional clock, the SNARC is inverted (11), and a short session of finger counting in an opposite direction can influence SNARC effects (12). Another piece of evidence in favor of an important influence from cultural practices like reading and counting on the direction of the number-to-space mapping comes from the study of illiterate or pre-literate populations. In a recent study conducted by Pitt et al. (2021), a group of adult Tsimanes, an indigenous culture with an oral tradition from Bolivia, and of U.S. preschoolers, were examined in terms of their directional bias when organizing cards depicting 1 to 5 dots based on their numerical value. Both populations exhibited a lack of consistent directional preference, with individuals equally likely to arrange the cards in either a left-to-right or a right-to-left order. These outcomes suggest that the direction of the number-to-space mapping is largely determined by cultural inputs, and that in the absence of cultural influence, mental mappings are "direction-agnostic," as concluded by the authors (13).

Space Number Associations in the absence of cultural biases

This conclusion, however, stands in stark contrast with an independent growing body of evidence from both human infant and non-human animal studies indicating an early culture-independent strong directional specific (left-to-right) bias in associating number to space. Starting from birth, humans preferentially orient towards the left when experiencing a decrease and towards the right when experiencing an increase in numerosity (14, 15). Similarly, in their first year of life, infants prefer increasing sequences of dots moving from left to right (7-months old) (14) and orient their attention to the left after being cued with a small numerosity and to the right after a large one (8-months old) (15). Studies with non-human animals (for example, Clark's nutcrackers (*Nucifraga Columbiana*) (16), domestic chicks (*Gallus*) (16–18), and honey bees (*Apis mellifera*) (17)) also indicate an association between small quantities to the left side of space and large quantities to the right. Taken together, these studies suggest a universal biologically determined, possibly innate mechanism that predisposes for a left-to-right direction of the SNA. How can we reconcile these findings with the previously reported absence of specific directional SNA in preschool children and in populations with no reading-writing systems?

Multiple Space Number Associations

One possibility is that, in humans, two dissociable kinds of SNAs co-exist: one that is biologically determined, universal, and has a left-to-right directional bias, and another that is acquired and the direction of which is determined by cultural/contextual input. According to this hypothesis, the culturally-determined SNA only emerges in the presence of strong and well-integrated cultural practices such as reading/writing. On the contrary, the biologically determined SNA manifests very early in life and persists throughout the lifespan, independent of both maturation and cultural influences. However, it is possible that the cultural SNAs have a stronger impact on overt behaviour and thus can overshadow the presence of the biologically determined SNA. In this case, the behavioural paradigms and tasks used to test directional biases of the SNAs might be key in differentiating among SNAs. Animal and infant studies rely on implicit procedures, as it is impossible to instruct the participants to explicitly report their association between number and space. On the contrary, studies on children and adults typically (but not always) require explicit numerical judgments. This is the case, for example, for the studies where western preschool children and illiterate adults were instructed to position numbers (in the form of dot patterns) on a line (13).

To verify that the different kinds of SNAs simultaneously exist and have different developmental trajectories (meaning that they are differentially modulated by age and culture), we tested space-number mapping, using both explicit and implicit tasks, in three different populations: Italian adults, Italian preschoolers, and Himba adults, a native population with an oral culture from Northern Namibia, with limited mathematical knowledge and no formal schooling, whom we tested in two separate field trips, one carried out in 2021 and the other in 2022 (Supplementary Materials - Material and Methods). While Italian and Himba adults are equivalent in overall level of maturation (unlike the Italian kindergarteners), Italian kindergarteners and Himba adults are equivalent in terms of their lack of, or extremely reduced, formal education and literacy.

According to our hypothesis, while with implicit tasks a left-to-right SNA should be observed irrespective of age and culture, with explicit tasks only the literate group should show the culturally-determined left-to-right bias.

Experiment 1. Explicit Space Number Associations

To investigate how number and space are associated using an explicit task, we asked participants to manually order 10 cards depicting 1 to 10 dots on the table in front of them, with the only constraint that they should arrange the cards so that they were “well ordered” (fig 1A). In all three groups, the majority of subjects spontaneously chose a horizontal linear spatial arrangement (74.1 % of the Himba adults tested in 2021, 84.3% of the Himba adults tested in 2022; 65.1% of the Italian kindergarteners, and 80,8% of the Italian adults). The other spatial layouts chosen were non-horizontal linear arrangements (diagonal or vertical) (3.7% Himba 2021; 7.2% Himba 2022; 2.3% Italian kindergarteners, and 2.1% Italian adults), 2-D geometric

configurations (grids or circles) (3.7 % Himba 2021, 13.9% Italian kindergarteners, and 17.0% Italian adults) and no geometric shape (random arrangements) (18% Himba 2021; 8.4% Himba 2022; 18.6% Italian kindergarteners) (fig. S2). We then focussed on the data from those participants who organized the cards on horizontal lines: while for all groups the distribution of their mapping differed from chance, indicating that participants in all groups well understood the task and did not arrange the cards randomly (fig. 2A), only the Italian adults systematically organized numerosities monotonically from left to right. By contrast, neither Himba' adults nor Italian preschoolers showed such a systematic rightward bias, in that they were equally likely to order numbers from right to left and from left to right (fig. 2A). This result nicely replicates the one reported by Pitt et al. and confirms that, for this explicit mapping task, in the absence of strong cultural bias, the mapping between number and space is arbitrary and inconsistent across individuals.

Experiment 2. Implicit Space Number Associations

To investigate implicit number to space mapping we employed a computerized numerosity comparison task using a go-no-go paradigm. After the presentation of a first set of dots (reference stimulus), participants were required to press a central button when a second set (test stimulus) was smaller (“decreasing task”) or larger (“increasing task”), in different blocks. Critically, while the reference stimulus was presented in the centre, the test stimulus was presented either on the left or the right side of the screen. We defined targets as *Congruent* or *Incongruent* based on their quantitative relation with the reference and their spatial location: targets that were smaller than the reference and appeared on the left, as well targets that were larger and appeared to the right, were defined as “congruent”, whereas smaller right targets and larger left targets were defined as “incongruent”. Congruency was thus defined with respect to the canonical left-to-right orientation (fig. 2B). Contrary to what was found in the explicit task, where Himbas and preschoolers behave differently from Italian adults, here for all three groups we found the very same pattern of results: a consistent congruency effect (better performance when smaller numerosities were presented on the left vs. right side of the screen) for the decreasing task instructions, and no congruency effect for the increasing instructions (fig. 2B).

Explicit and Implicit tasks are not correlated

To explore whether implicit and explicit behaviors are actually dissociable and to demonstrate the independence of one component from the other, we analyzed whether the performance of Himbas and preschoolers in one task predicted the performance in the other task. We correlated the explicit mapping scores with the implicit congruency effect for each Task instruction for each participant (fig. 3). No correlation was found between the two measures, suggesting that the explicit and implicit scores might be the results of two separate SNA components.

Discussion

It is not yet clear how and to what extent formal education is crucial for the emergence of SNA phenomena. For example, some studies report that before starting primary school children do not show oriented space-number mapping or SNARC-like effects (22–24), while other studies reveal that small adjustments in the task paradigm allow a left-to-right mapping to emerge as soon as kindergarten years (25, 26). Our results seem to shed light on these contradictory findings: the nature of the tasks themselves might induce different components of SNA to emerge.

In our study, we conducted two different experiments, one with explicit measures and one with implicit ones, to investigate the influence of cultural exposure and conscious behavior on SNA. The results indicate that explicit requests for mapping numerosities into space elicit different responses depending on cultural influences, whereas implicit measures reveal a consistent pattern across populations regardless of cultural factors. Indeed, illiterate Himba participants and preschoolers both mapped numerosities into space when explicitly asked, but without a systematic directional bias at the group level. As suggested by other researchers, this could mean that SNA requires specific cultural practices or experiences to emerge (27), but this is true only when the request is explicit and participants need to take conscious decisions on the mapping. Accordingly and coherently with our hypothesis, when we investigated automatic behaviors using implicit measures, we found evidence for a consistent left-to-right SNA, even in populations that are not biased by reading/writing habits (preschoolers and adult Himbas).

The biological predisposition for a left-to-right oriented SNA could originate in the lateralized organization of the bilaterian nervous system with the left side of the brain attending to stimuli with positive valence and the right side to stimuli with negative valence (28). It has been argued that changes in numerosities towards larger or smaller numbers are in appetitive contexts associated with differential hemispheric activation and consequently with contralateral hemispace biased attention (to the left for a change from large to small numbers and to the right for a change from small to large numbers) (26, see figure 7 therein).

The left/right lateralization of the brain and the developmental trajectory of the number sense in the parietal cortex also provide additional insights into the observed effects. It has been demonstrated that the neural basis of the so-called “*number sense*” develops first in the right parietal cortex of the human brain (30–33) and only later in life it also extends to the left parietal cortex (34–36). This later bi-parietal activation might be related to the acquisition of language: the initial perception of numerosities per se, right hemisphere based, is then accompanied by the semantic knowledge of numbers, left hemisphere based. It is likely that in the task used in this study, which focuses on numerosities rather than explicit numbers, the right hemisphere plays a more prominent role, resulting in a facilitation effect over the left hemisphere. Note, however, that the stronger right hemisphere activation cannot solely account for the observed findings, as no preference for the incongruent condition (i.e. left hemispace) was found in the increasing task. The most plausible explanation for this finding is that, in our task, both right hemisphere stronger activation and left-to-right SNA are present and interact with one another.

In conclusion, this study provides valuable insights into the emergence of SNA and their relationship with formal education and cultural influences. The findings highlight the

importance of task instructions in differentiating different components of SNA. Moreover, the observed left-to-right orientation of SNA aligns with the lateralized organization of the brain, suggesting a connection between cognitive biases and the processing of positive and negative valence stimuli. Further research is needed to explore the intricate interplay between cultural practices, brain lateralization, and the development of SNA, shedding more light on this intriguing phenomenon.

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Conceptualization: GV, MP

Methodology: GV, MP, SC

Software: EE, MJ

Resources: GV, SC

Investigation: EE, MJ, SC

Formal analysis: EE, MB, MJ, MP

Visualization: EE, MJ, MP

Funding acquisition: GV, SC

Supervision: GV, MP, SC

Writing – original draft: EE, MP

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Data and materials availability: All data, code, and materials used in the analysis are available through Zenodo <https://zenodo.org/badge/latestdoi/655714958>.

Supplementary Materials

Materials and Methods

Supplementary Text

Figs. S1 to S4

Tables S1 to S4

References (*15, 37–41*)

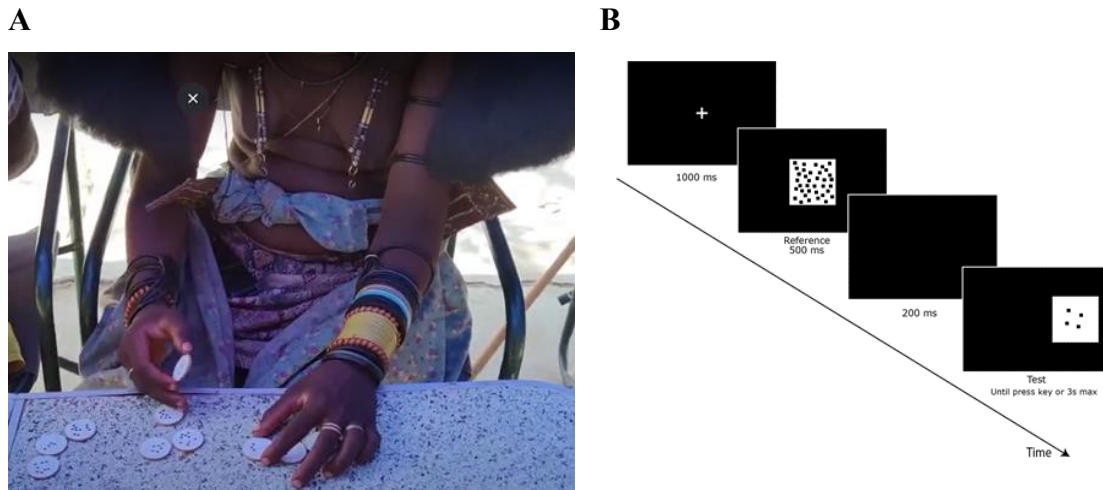


Fig. 1 Ordering Card Task and Numerosity Comparison Task

Panel **A**. A picture taken on the field of one Himba participant during the Ordering Card Task. In this task, participants were asked to order 10 cards, depicting 1 to 10 dots, on the table in front of them, such that they would look “in order”. No other instruction was given.

Panel **B**. A schematic representation of one exemplar trial in the Numerosity Comparison Task. In this trial, the test numerosity is smaller and appears on the right side of the screen, corresponding to an “incongruent” condition. In the “Decreasing Task Instruction”, participants were instructed to press a central key as fast as possible (using their dominant hand) only when the test numerosity was smaller than the prime numerosity. In the “Increasing Task Instruction”, instructions were reversed. All subjects but the Himba tested in 2021 performed both tasks, in counterbalanced order. In the group of Himba tested in 2021, half the subjects performed the task with the Increasing Instructions and the other half with the Decreasing Instructions. See also Material and Methods in Supplementary Materials.

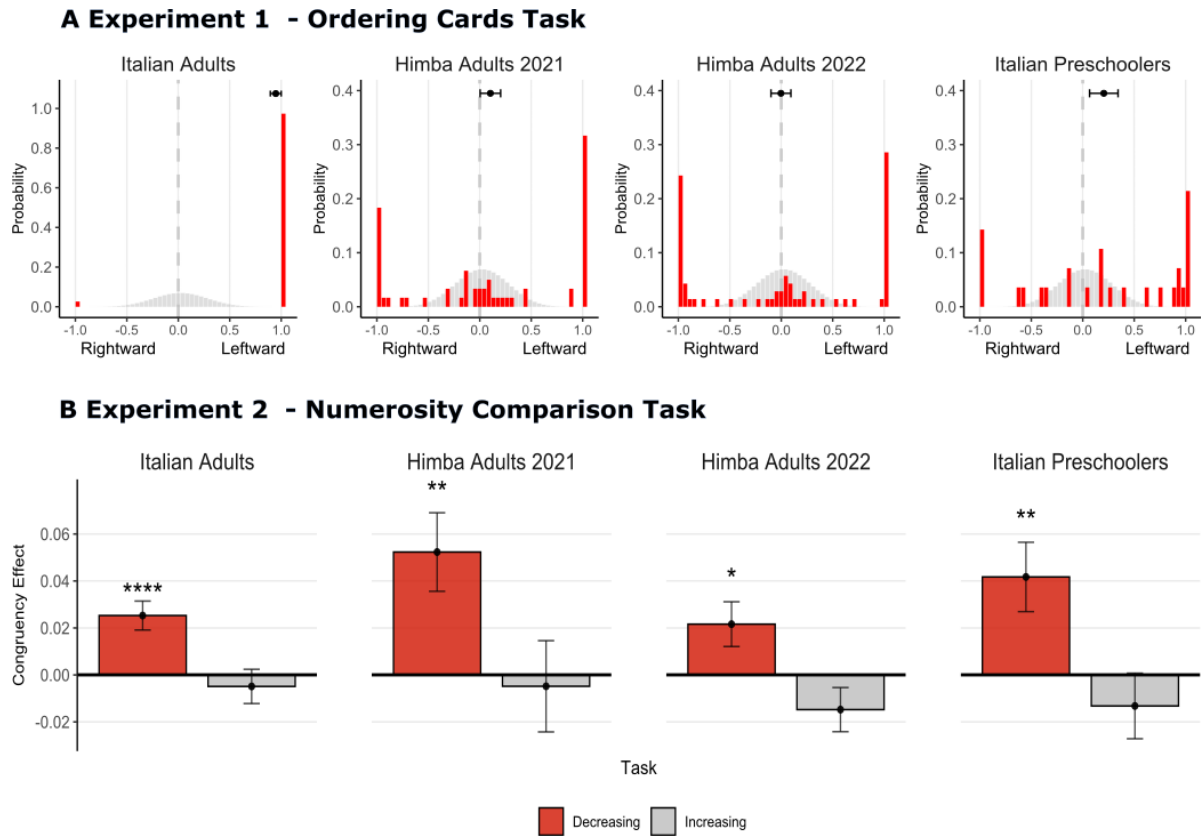


Fig. 2 Results of the Ordering Cards and Numerosity Comparison tasks in the four groups

In the explicit task (A) participants ordered 10 cards depicting 1 to 10 dots according to their relative numerosity: for all group the mapping distributions (red) is different from chance distribution (grey) (Two sample Kolmogorov-Smirnov goodness-of-fit hypothesis test; Italian adults: $N = 38$, $D = 0.957$, $p_{\text{value}} < .0001$, Himba 2021: $N = 60$, $D = 0.913$, $p_{\text{value}} < .0001$, Himba 2022: $N = 70$, $D = 0.913$, $p_{\text{value}} < .0001$, Italian Preschooler: $N = 28$, $D = 0.957$, $p_{\text{value}} < .0001$). Black dots and whiskers show mean mapping scores and the standard error of the mean. Only Italian Adults showed a Left-to-Right direction, while other groups' mean was not significantly different from zero. (One-sample Wilcoxon signed rank test ($\mu = 0$); Italian Adults: $N = 38$, $V = 721.5$, $p_{\text{value}} < .0001$, Himba 2021: $N = 60$, $V = 1067$, $p_{\text{value}} = .257$, Himba 2022: $N = 70$, $V = 1284.5$, $p_{\text{value}} = .805$, Italian Preschooler: $N = 28$, $V = 261$, $p_{\text{value}} = .188$).

In the implicit task (B) we measured participants' performance in terms of a combined measure of speed and accuracy (Inverse Efficiency Score, see SM - Method session). A 2x2 mixed ANOVA (*Groups x Task Instruction*) revealed only a significant main effect of *Task Instruction* on the Congruency Effect ($F_{(1,160)} = 21.164$, $p_{\text{value}} < .001$; Himba tested in the 2021 were excluded from the model as they did not perform the Task in a within design fashion). In all groups, the Congruency Effect was significantly greater than zero only for the Decreasing Instruction Task (One-sample T-test ($\mu = 0$); Himba 2021: $N = 33$, $t_{(32)} = 3.13$, $p_{\text{value}} = .0037$, Himba 2022: $N = 76$, $t_{(77)} = 2.27.5$, $p_{\text{value}} = .026$, Italian Preschooler: $N = 38$, $t_{(37)} = 2.82$, $p_{\text{value}} = .0076$; One-sample Wilcoxon signed rank test ($\mu = 0$); Italian Adults: $N = 47$, $V = 918$, p_{value}

<.0001), while the Congruency Effect for the Increasing Instruction Task was at chance level in all the groups. In the graph mean value, standard error of the mean and significant p-values are reported for each population and Task Instruction (* = p-value <.05, ** = p-value <.01, **** = p-value <.0001).

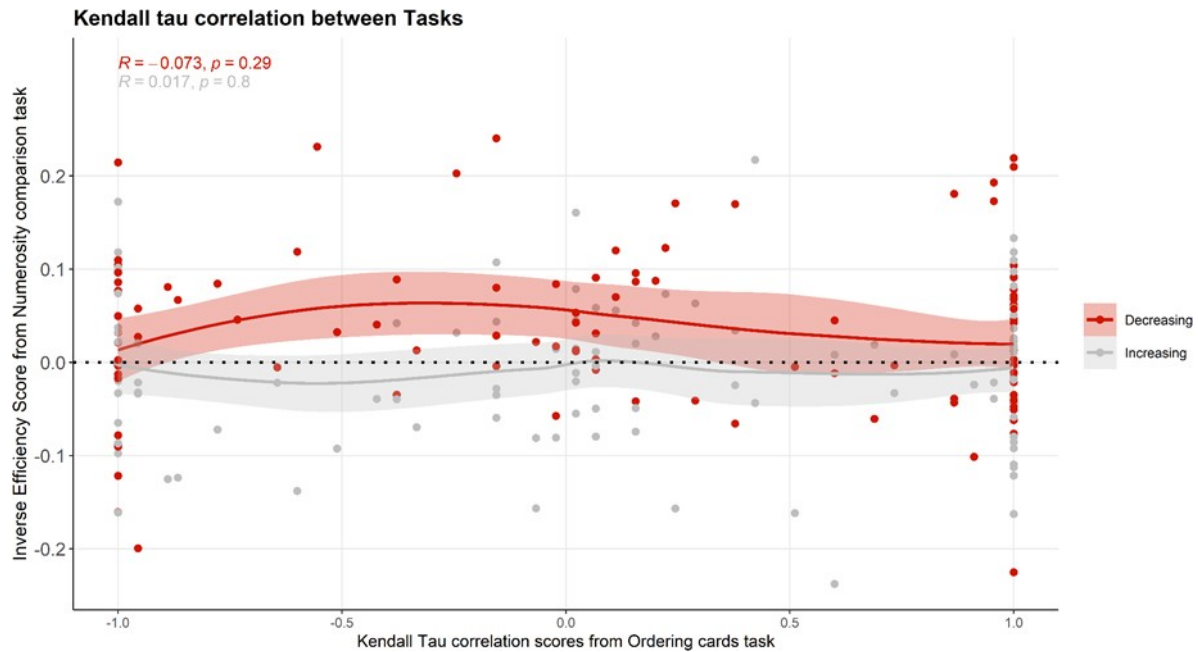


Fig. 3 Correlation between task measures

The correlation between Inverse Efficiency Score and Mapping score is not significant for neither the two Task Instructions (Kendall Tau correlation; Decreasing task instructions, N = 110, $\tau = -.073$, $p_{\text{value}} = .285$; Increasing task instructions, N = 110, $\tau = .017$, $p_{\text{value}} = .799$). This analysis included only the participants for which it was possible to calculate the Kendall tau scores (i.e. those who ordered the cards on a horizontal line), moreover Italian adults were excluded from the analysis due to the skewness in their data (98% of the scores were perfectly equal to 1).

Supplementary Materials for

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The PDF file includes:

Materials and Methods

Supplementary Text

Figs. S1 to S4

Tabs S1 to S3

References (15, 37-41)

Materials and Methods:

The study has been conducted following the Declaration of Helsinki and has been approved by local University of Trento Research Ethics Committee (for Italian children and adults' study) and the ethics committee of Inserm. (for Himba studies; opinion number 21-855). The Italian adults gave their written consent after being informed about the study's purpose and procedures. The Himba participants, who were unable to read or write, provided oral consent in accordance with ethical guidelines. For the Italian children, we obtained informed consent from their legal guardian. Italian adults received a small monetary reimbursement for their participation, while Himba participants were given a set of four gift items including maize meal, sugar, vaseline, and soap (the approximate value of the items was equivalent to 5 euros).

Subjects

- 191 Himba adults, an indigenous group with an oral culture from northern Namibia, with little or no formal education, were recruited in small villages. All were monolingual native speakers of Otjihimba, a dialect of the Otjiherero language. Data has been collected in two different missions, one in October/November 2021 (90 Himba people tested in 4 villages) and the other one year later November 2022 (101 Himba people tested in 2 other villages). Here, we will refer to the first group as Himba 2021

and to the second one as Himba 2022. Among these, we report data for 130 participants (60 from the first, 44 females, mean age = 33 ± 16 years, mean grade in school = 0.5 ± 1.3 ; 70 from the second mission, 37 females, mean age = 33 ± 11 years, mean grade = 0.1 ± 0.3 years) who self-reported as being unable to read/write (note that a few participants have attended one or two years of school but were still unable to read/write). The same translator and experimenter conducted the two missions, and experimental conditions were relatively similar. To our knowledge, none of the participants had prior experience with experimental research. It is important to mention that there is some uncertainty regarding the age of some participants, as it is culturally rare to track count of age. When necessary, we relied on the translator to provide an estimated assessment of the participants' ages. All experiments were conducted on an outdoor table, in a shaded area.

- 45 Italian preschoolers, recruited in kindergartens in the area of Rovereto (TN), took part in the study. Among them 2 were discarded as they did not complete all three tasks. 43 children (21 females; mean age = 5.1 ± 0.3 years) were included in the final sample, and they were all reported by their parents as being unable to read/write.
- 47 young adults (36 female; mean age = 21.7 ± 2.3 years), recruited through the social media group of the University of Trento, took part in the study.

Stimuli

- Ordering Card Task: Stimuli were ten white cards (4 x 4 cm). On each card black dots from 1 to 10 were printed. The dots were 0.5 cm diameter in size, and they were displayed in a random order.
- Numerosity comparison task: For this computerized task, the stimuli were visual arrays of 4, 12, or 36 black squares (1.3 x 1.3 degree of visual angle each, distance from the screen was approximately 50 cm) presented on a white background (17 x 17 degree) (stimuli from (15), fig S1).

Experimental protocols

The three populations ran the exact same three experiments, albeit in slightly different settings: Italian adults were tested in a semi-dark room of the University laboratory, pre-schoolers in a quiet room in their kindergarten, and Himba participants were tested outside, sitting at a shaded table located nearby their local villages. While all participants received oral instructions by the experimenter (helped by a translator in the case of Himba people), Italian adults also read the instructions on the computer screen (for the computerized experiment) or on a paper sheet (for the ordering card experiments). The order of the experiments was maintained fixed for all participants, and was Free Ordering Task, Numerosity comparison Task, and Line Ordering Task. Before the experimental tasks, we interviewed both Himba and Italian adults on their literacy (i.e. their ability to read and write) and their schooling level. The same information about reading/writing ability was collected from preschoolers' parents through a written questionnaire.

- *Ordering card tasks*

For the Ordering card task, subjects were asked to manually order 10 cards depicting 1 to 10 dots on the table in front of them, with the only constraint that they would be considered to be

“in order”. No other instruction was given. Subjects were presented with the 10 cards piled up in a random order and head down on the table in front of them

- *Numerosity comparison task*

Stimuli were presented on a laptop computer screen and participants sat at approximately 50 cm from it. Trials started with a fixation cross at the centre of the screen that lasted for 1 s, followed by a set of dots presented centrally for 500 ms. Then, a black screen appeared for 200 ms, and was followed by a second set of dots (hereafter “test stimulus”), which was presented on the left or on the right side of the screen. The test stimulus remained on the screen until the subject pressed the response-key or for a maximum of 3 s. Participants were instructed to press a central key as fast as possible (with their dominant hand) only when the test stimulus was less numerous compared to the previous stimulus (hereafter “decreasing condition”), or only when the test stimulus was more numerous (hereafter “increasing condition”). Feedback was always provided (a green happy smiley for correct responses and a red sad smiley for incorrect responses were presented for 1 s after the subjects’ response).

The experiments started with 18 trials to familiarize the participants with the task, followed by 48 experimental trials. Of those, 30 were targets (i.e. trials that required a response; 15 presented on the left and 15 on the right) and 18 were distractors ((i.e. trials that did not require a response: 9 presented on the left and 9 on the right). We analyzed the responses to the target trials only. All the experimental groups did the task in both conditions (with the order counterbalanced across subjects), with the exception of Himba 2021 who performed the task in a between-subject design.

Both stimuli presentation and data collection were performed with Psychopy software (37).

Supplementary Text

Data analysis and plot generation have been performed with R software, R version 4.1.3 (2022-03-10) (38) in RStudio environment (39). For all statistical analyses alpha = .05 significance level was chosen

Data Analysis Description

- *Ordering cards task*

For the Free Ordering task, we started by performing a qualitative analysis, which consisted in reporting the frequency with which each type of spatial configuration (horizontal line, vertical line, square, curvilinear shape, random shape) was chosen by the subjects in each group (fig S2). Then, for those subjects who used a linear horizontal configuration, and for all subjects in the Line Ordering task, we performed the quantitative analysis, which, following Pitt et al., proceeded in two steps.

First, we tested the *systematicity* of the horizontal line mapping. To do so, for each participant we correlated the chosen order to that of the ideal left-to-right ideal order using Kendall’s Tau, yielding a score between -1 and 1. The absolute value of the score indexes the systematicity of the mapping (i.e. how orderly: a score of +/-1 corresponds to a mapping where numerosity increases monotonically in one direction across all ten positions). Intermediate scores reflect imperfectly ordered mappings (fig. S3). To determine whether subjects performed the task ordering the cards with a certain systematicity, we compared the distribution of mapping scores

they produced to the distribution of mapping scores that would be expected by chance (i.e. as a result of random arrangements of the 10 stimuli on the line) using the Two sample Kolmogorov-Smirnov goodness-of-fit test.

Second, we tested the *direction* of the mapping. The sign of the Kendall's Tau correlation indexes the direction of the mapping: positive scores indicate generally rightward mappings, while negative scores indicate a leftward one. To determine whether a preferential direction of mapping emerged at population level we tested whether the group average score differed significantly from 0, using a non-parametric Wilcoxon signed-rank test to account for the non-normal distribution of the scores.

- *Numerosity comparison task*

We started the analysis by excluding participants that responded at or below chance (62.5% accuracy), resulting in the removal of 5 Himba 2021, 6 Himba 2022 and 5 pre-schoolers. In order to condense speed and accuracy in a single measure, for each subject and condition we computed the inverse efficiency score (IES), defined as $\frac{RT^{mean}}{Accuracy}$ (i.e. lower scores means a better performance) (40).

Shapiro-Wilk test was performed to test for normal distribution of data, and data resulted not normally distributed. However due to the necessity of testing for both repeated measure factors and interaction effects, we decided to perform an ANOVA test as it has been demonstrated to be robust against Type 1 Error also in case of violation of normality assumption (41). Because the two task instructions were presented to all subjects (as in a repeated measure design) in all groups except from the Himba 2021, we performed a Three-way mixed ANOVA, with Group (Himba 2022 vs Italian Adults vs Preschooler) as a between subjects variable, Congruence (Congruent vs Incongruent), and Task Instruction (Decreasing vs Increasing) as within subjects variable (Table S1). We analysed the Himba 2021 separately with a Two-way mixed ANOVA with Congruence as a within subjects variable and Task Instruction as a between subjects variable (Table S2). Planned t-test were performed to compare differences between congruent and incongruent condition for each Task for each Group (Table S3). T-test comparisons were performed one-sided, as for priori defined hypothesis of congruent condition being lower than incongruent condition.

To account for the average difference in the inverse efficiency across groups (see Table S1) mostly due to the fact that children were slower and Italian adults were more accurate compared with the other groups, for each subject and Task Instruction we also computed a “congruency effect” by normalising the difference in IE for incongruent and congruent conditions by their sum: $\frac{IEC_{incongruent} - IEC_{congruent}}{IEC_{incongruent} + IEC_{congruent}}$ (fig. S4). Then, to investigate whether this congruency effect was significant we tested it using a two-sided one sample t-test against zero (alternative hypothesis $\mu \neq 0$) for normally distributed data and a two-sided Wilcoxon signed-rank test against 0 (alternative hypothesis $\mu \neq 0$) for not normally distributed data (fig. 2B in main text). Shapiro-Wilk test was performed to test for normal distribution of data (Tables S4).

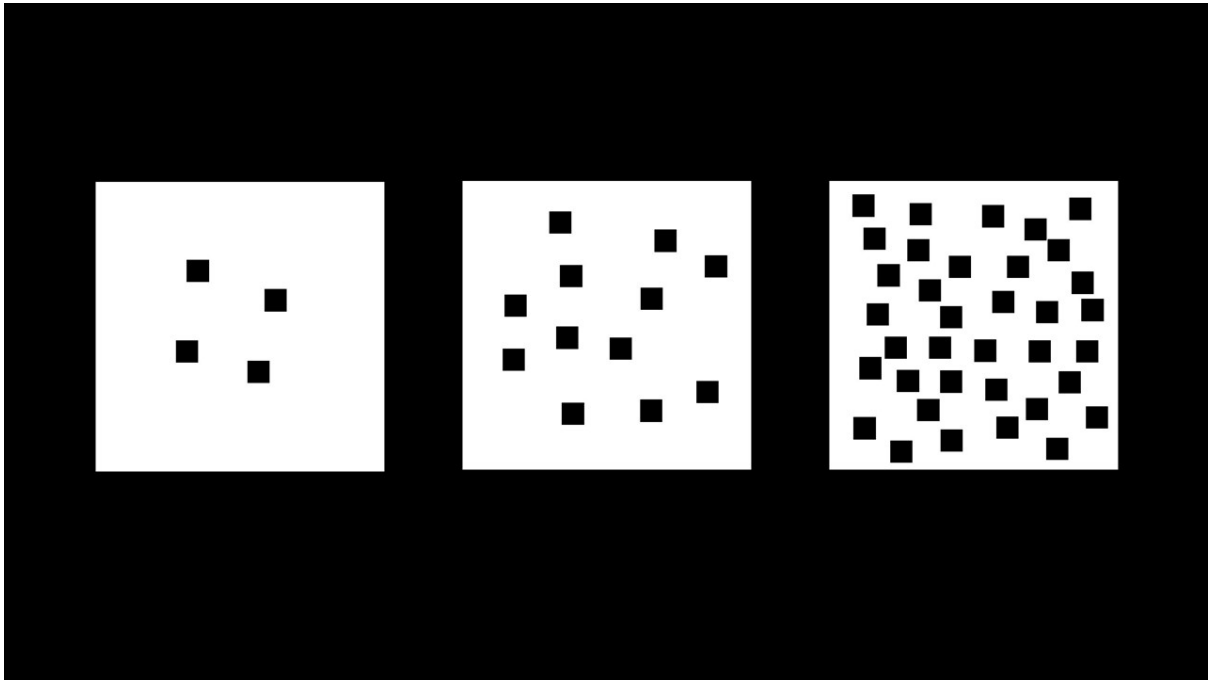


Fig. S1 Stimuli used for the Numerosity comparison Task

Stimuli are replicated and used with authors permission from Di Giorgio et al., 2019 (15)

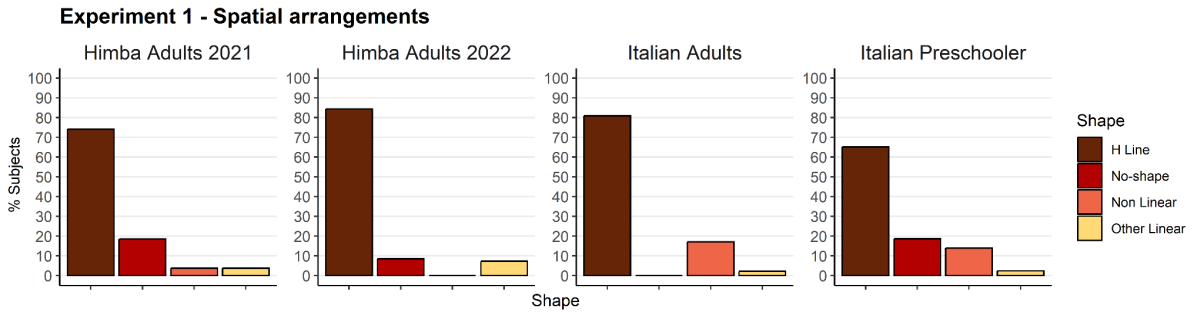


Fig. S2 Cards spatial arrangements in the four groups

Percental of shape choice for each group are shown in the figure. Example of “Non-linear” shapes were circle, arch, or grid arrangements; example of “Other Linear” shapes were vertical line, diagonal line or L-shaped line; “No shape” arrangements were random scatter disposition of the cards.

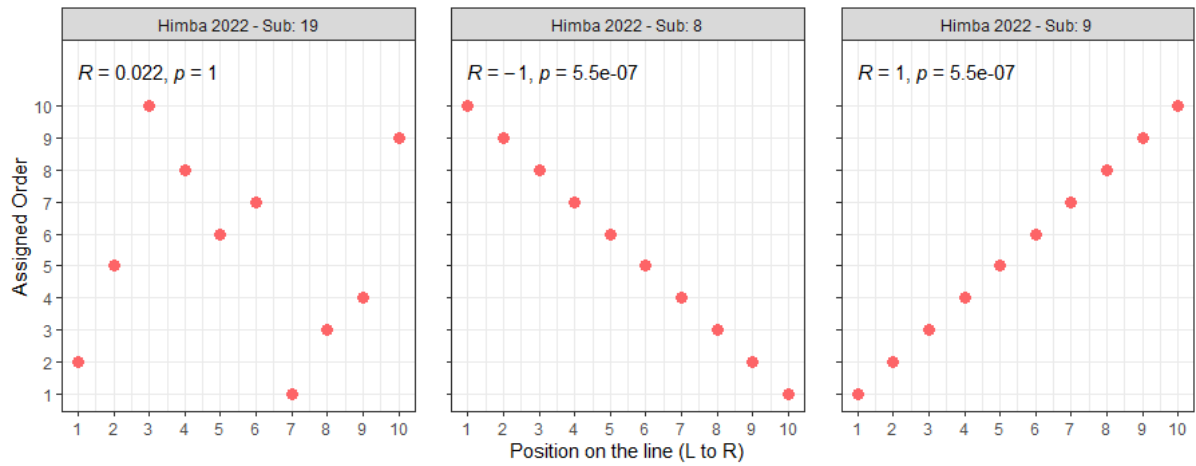


Fig. S3 Examples of correlation plots between Cards order assigned by participants and 1 to 10 left-to-right order

For this task we calculated the Kendall Tau correlation between the cards ordinal position (y axis), and the supposed left-to-right order of the numerosities (x axis). In the figure an example of random disposition (left graph), perfect right to left disposition (central graph) and perfect left to right disposition (right graph).

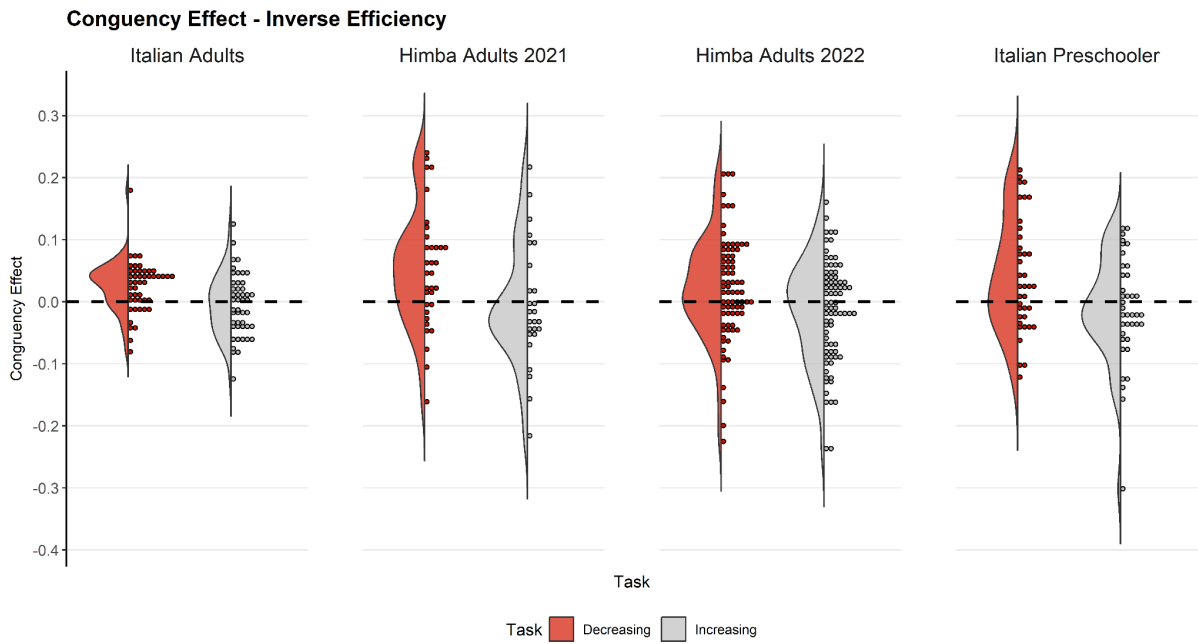


Fig. S4 Distributions of Congruency Effect groups per task instructions

Dashed line represents the 0-chance level (i.e. no effect of the congruent condition on the performance)

Table S1

Three-Way Analysis of Variance of Inverse Efficiency Scores in Population by Task Instruction and Congruency Condition

<i>Source</i>	<i>DF_n</i>	<i>DF_d</i>	<i>SS_n</i>	<i>SS_d</i>	<i>F</i>	<i>P</i>	<i>η²_{partial}</i>
Population	2	160	100.674	59.699	134.9	<.0001	0.892
Task Instruction	1	160	0.353	15.355	3.674	.057	-
Congruency Condition	1	160	0.024	2.089	1.379	.2420	-
Population x Task Instruction	2	160	0.233	15.355	1.216	.299	-
Population x Congruency Condition	2	160	0.005	2.809	0.129	.879	-
Task Instruction x Congruency Condition	1	160	0.222	3.112	11.397	.0009	0.066
Population x Task Instruction x Congruency Condition	2	160	0.120	3.112	3.074	.048	0.037

In **bold** p_{value} significant for alpha value = .05

Table S2

Two-Way Analysis of Variance of Inverse Efficiency Scores in Himba 2021 by Task Instruction and Congruency Condition

<i>Source</i>	<i>DF_n</i>	<i>DF_d</i>	<i>SS_n</i>	<i>SS_d</i>	<i>F</i>	<i>p</i>	<i>η²_{partial}</i>
Task Instruction	1	57	0.746	32.518	1.308	.258	-
Congruency Condition	1	57	0.185	2.274	3.520	.066	-
Task Instruction x Congruency Condition	1	57	0.196	2.274	4.901	.031	0.006

In **bold p**value significant for alpha value = .05

Table S3

Planned comparison for differences between Congruency Condition for Task Instruction for each population

<i>Population</i>	<i>Task</i>	<i>Condition 1</i>	<i>Condition 2</i>	<i>df</i>	<i>t-.statistic</i>	<i>pvalue</i>	<i>Effect Size</i>
Italian Adults	Decreasing	Congruent	Incongruent	46	-3.66	.003	0.216
Italian Adults	Increasing	Congruent	Incongruent	46	0.676	.749	-
Himba Adults 2021	Decreasing	Congruent	Incongruent	32	-2.762	.005	0.232
Himba Adults 2021	Increasing	Congruent	Incongruent	25	0.272	.606	-
Himba Adults 2022	Decreasing	Congruent	Incongruent	77	-1.58	<u>.06</u>	0.113
Himba Adults 2022	Increasing	Congruent	Incongruent	77	0.772	.779	-
Italian Preschooler	Decreasing	Congruent	Incongruent	37	-2.32	.013	0.186
Italian Preschooler	Increasing	Congruent	Incongruent	37	0.967	.83	-

In **bold p_{value}** significant for alpha value = .05, underscored values show a tendency towards significance. Effect size measured as Cohen's D absolute value

Table S4

Shapiro-Will test for Normality on Congruency Effect for each Population and Task Instructions

<i>Population</i>	<i>Task</i>	<i>n</i>	<i>statistic</i>	<i>pvalue</i>
Italian Adults	Decreasing	47	0.923	.004
Italian Adults	Increasing	47	0.992	.985
Himba Adults 2021	Decreasing	33	0.974	.606
Himba Adults 2021	Increasing	26	0.968	.578
Himba Adults 2022	Decreasing	78	0.979	.222
Himba Adults 2022	Increasing	78	0.980	.245
Italian Preschoolers	Decreasing	38	0.957	.148
Italian Preschoolers	Increasing	38	0.938	.035

In **bold values** significant for alpha value = .05 meaning that data distribution departed significantly from normality, thus non-parametric test has been performed on these groups.