Distance in depth: A comparison of explicit and implicit numerical distances in the horizontal and radial dimensions

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Variants of the DE

The classical comparison DE was first discovered in a magnitude comparison task that consists of responding to the smaller or larger between two target numbers (Moyer & Landauer, 1967; review in Leth-Steensen & Marley, 2000; meta-analysis in Wood et al., 2008). An alternative version of this task involves the classification of single-target numbers as smaller or larger with respect to a SUHYLRXVO\ DJUHHG VWDQGDUG RU UHIHUHQFH QXPEHU I magnitude classification task). While performance signatures are similar for magnitude comparison and magnitude classification, the direction of the DE depends on task requirements. Holyoak (1978) was the first to reveal a DE different from the canonical one in a distance comparison task requiring participants to respond to either the closer or the farther between two numbers with respect to a third number that represented the reference. Overall, a critical role of the instructions emerged: Selection of the farther number triggered a comparison DE, with monotonic decrease of RTs as a function of the numerical distance; in contrast, selection of the closer number speeded up the processing of stimuli numerically close to the reference. This task has been widely employed in spatial cognition (e.g., judgment of geographic proximity: Holyoak & Mah, 1982; Sadalla et al., 1980) but not in numerical cognition.

Additional variants of the DE result from the administration of other paradigms. For instance, number-priming experiments elicit a priming distance effect: When the numerical distance between the target number (relevant for the task) and a preceding prime number (not relevant for the task) decreases, performance is faster and more accurate (Dehaene et al., 1998; Gilmore et al., 2018). Van Opstal and colleagues (2008) documented dissociations between comparison and priming distance effects, revealing that the comparison DE originates with various kinds of material (e.g., letters and numbers, Van Opstal et al., 2008) but only in comparison tasks, while the priming DE appears only with numerical stimuli but in different tasks (e.g., naming and readings tasks; Heyer & Briand, 1986; Brysbaert, 1995).

comparison task[1]). Critical evidence comes from magnitude comparison studies where some numerical values were omitted (numbers 4,5,6 from the 1-9 numerical range) to manipulate the numerical distance (numerical distance from 3 to 7 = 1). Interestingly, the comparison DE was determined not by the numerical value (numerical distance from 3 to 7 = 4) but by the properties of the session (evidence with artificial notation in Krajcsi & Kojouharova, 2017; evidence with Indo-Arabic digits in Kojouharova & Krajcsi, 2019).

The predictions of the classical ANS account and of the novel DSS account have systematically been tested by Krajcsi and colleagues in a series of experiments (review in Krajcsi et al., 2022). Three findings support the higher explanatory power of the DSS in symbolic numerical cognition: First, the distance and magnitude effects are not two measures of the distributional overlap of number representations as they are independent and dissociable (Kojouharova & Krajcsi, 2019; 2020; Krajcsi et al., 2016; Krajcsi & Kojouharova, 2017); secondly, the symbolic distance effect is rooted in the associations between the numbers and the response nodes (Kojouharova & Krajcsi, 2020; Krajcsi & Kojouharova, 2017); thirdly, the symbolic distance effect is not rigid but highly flexible to the characteristics of the stimuli (Kojouharova & Krajcsi, 2020).

The Present Study

All the above studies have assessed distance effects in an implicit way: The relevant property to solve the task was either the numerical magnitude or the numerical order, but never the numerical distance between stimuli. An exception is represented by \RDN¶V VWXG\ LQ FRPSDUDWLYH MXGJPHQWV EDVHG RQ WKH QXPHULFDO GLV manipulations on task instructions (closer vs. farther) and reference points (all numbers in the range between 1 and 9) do not allow to directly compare the implicit and explicit assessment of the DE. This represents a critical theoretical and methodological gap in the literature, since the other major

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[1] The extensive formulation of the model is called Hybrid ANS-DSS account (Krajcsi et al., 2022).

signatures of numerical cognition (magnitude effect, SNARC) have been investigated both implicitly and explicitly, revealing performance dissociations based on the type of assessment.

Considering the variants of the DE and their functional link to subsequent mathematical abilities, it seems important to assess this effect both implicitly and explicitly. To do so, we introduce here the novel distance classification task. It requires participants to classify numbers as numerically close to RU IDU IURP WKH UHIHUHQFH ‡ · WKXV PDNLQJ WKH QXPHU task. In the present study, both the well-established magnitude classification task and the novel distance classification task were administered to directly compare the numerical distance effects emerging from implicit and explicit assessment. The use of symbolic material was motivated by two reasons: 1) The implicit and explicit assessment of the magnitude-related signatures of numerical cognition (e.g., SNARC) have been extensively compared with Arabic digits, 2) the DSS model applies to the symbolic distance effect.

The typical horizontal (left–right) arrangement of response buttons was applied. In analogy to what was observed for the magnitude and the SNARC effects, we hypothesized to find two qualitatively different numerical distance effects: A canonical comparison DE (we refer to it as implicit-DE), resulting from implicit distance assessment with the magnitude classification task; and a novel explicit-DE, resulting from explicit distance assessment with the distance classification task. In particular, we predicted an advantage for numbers farther (1,9) as well as for numbers closer (4,6) WR WKH UHIHUHQFH ‡ · 2XU K\SRWKHVHV ZHUH GHULYHG theorized in the DSS model (Krajcsi et al., 2022), according to which distance effects emerge from the strength of the association between numbers and response-related properties (small/large properties in the magnitude classification task vs. close/far properties in the distance classification task). These predictions are supported by previous findings of facilitation for close numbers during distance comparison tasks when instructions focused on close numbers (Holoyak, 1978). In the distance classification task, it is noteworthy that also pre-existing associations from counting (i.e., the neighbor advantage) would further facilitate number classification based on distance.

Experiment 1: Implicit and Explicit Numerical Distance Effects in the Horizontal Dimension

In Experiment 1, we compared the DE in the well-established magnitude classification task (implicit-DE) with the DE in the novel distance classification task (explicit-DE). We expected to find a main effect of numerical distance, reflecting significant differences in RTs as the numerical distance between the target and the reference number changes. Importantly, in light of the impact of the task on the DE (Gilmore et al., 2018; Holyoak, 1978; Turconi et al., 2006; Van Opstal et al., 2008) and of the type of assessment (implicit vs. explicit) on other basic numerical effects (e.g., Ranzini et al., 2015; Shaki & Fischer, 2018), we predicted a significant modulation of the DE as a function of task. In particular, we expected to find a classical comparison DE in the magnitude classification task, with increasing RTs as the numerical distance decreased; and a novel, explicit-DE in the distance classification task, with an RT advantage for numbers close to the reference. Moreover, in line with the literature, we expected to find an overall SNARC effect independently of the task, indicated by faster RTs when responding to small/large numbers with the left/right response button, respectively.

Method

In order to limit the risk of COVID-19 infection, the present study was administered online. It was conducted in accordance with the ethical standards stated in the Declaration of Helsinki. Prior to the experiment, all participants gave their informed consent and completed a sociodemographic questionnaire. The sociodemographic questionnaire included questions on native language, gender, age, country of residence, and diagnosis of dyscalculia/dyslexia. It is publicly available at: https://osf.io/vs6rw/?view_only=a5464f8f55b54d33a735899385ffe9bf

Transparency and Openness

We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study. The raw data for Experiment 1 are available in an OSF archive at https://osf.io/vs6rw/?view_only=a5464f8f55b54d33a735899385ffe9bf. Mean individual RTs were analyzed using SPSS Statistics, Version 27.0 (IBM SPSS Statistics for Windows, Version 27.0. Armonk, NY: IBM Corp). The results were obtained using Greenhouse-Geisser corrected analyses of variance and Bonferroni corrected t-tests. This study's design and its analysis were not pre-registered.

Participants

Forty-four healthy human adults (13 males, 31 females; mean age = 24.48, SD = 8.9) enrolled at the University of Potsdam (Germany) completed the experiment either for course credit or without any compensation. The sample size was determined prior to the start of data collection, based on previous web-based experiments that found DEs with a minimum of twenty-three participants Kochari Considering the similarities between collect data of at least twenty-three participants. Seven participants were left-handed (scores below -50 in the Edinburgh Handedness Inventory, short version; Veale 2014). The average handedness score of our total sample indicated 67.42. All participants reported not to have received a diagnosis of dyscalculia and/or dyslexia.

In light of the influence of counting direction habits on the SNARC effect (Fischer & Shaki, 2016; 2017; Shaki & Fischer, 2021) a dot counting task was administered (Fischer & Shaki, 2017; Shaki et al., 2012) after the two number classification tasks. It requires participants to sequentially count the number of four black dots, horizontally displayed, by clicking on each of them with their computer mouse. The Dot counting task is informative about the counting direction habit (from left to right or from right to left). The order of counting was recorded. Among all considered participants, 38 completed the dot counting task. All participants counted the array of dots sequentially from left to right, except for 5 participants who reported a random counting order.

Experimental Setup

The study was conducted online via Gorilla Experiment Builder, a dedicated experiment web platform, allowing researchers to build and host psychological and behavioral experiments (Anwyl-Irvine et al., 2019; https://gorilla.sc/). Thus, participants performed the computer-based tasks on their own computer from home. Gorilla Experiment Builder is extensively used across different research fields, leading to high-quality, peer-reviewed, and published research that has replicated many well-known psychological effects, including RT based signatures of cognition (Anwyl-Irvine et al., 2021; Poort & Rodd, 2019; Ward, 2022; a comprehensive list of publications can be found here https://gorilla.sc/success/publications/). In order to maximize the quality of the data and to standardize the setting, before each task, we adopted several precautions. In particular, we invited participants to 1) Select a quiet and dimly lit room to perform the experiment; 2) arrange not to be disturbed during the experiment; 3) remove numerical cues around their working space (e.g., wristwatches and phones); 4) align both the screen and the keyboard with their body midline; 5) close all irrelevant browser tabs and windows; 6) go into the full-screen mode. We checked their compliance through a checklist where participants were asked to tick the suggestions they had followed.

Materials and Procedure

In the first part of the experiment, the participants performed two number classification tasks: the magnitude classification and the distance classification tasks. In the second part of the experiment, they were invited to complete two additional tasks: the dot counting task (Fischer & Shaki, 2017; Shaki et al., 2012) and the Brief Mathematical Assessment-3 (BMA-3; Steiner & Ashcraft, 2012). The former informs about the counting direction habits, a variable that has been shown to influence the number representation (Fischer & Shaki, 2016; 2017; Shaki & Fischer, 2021); the latter gives an index of general mathematical abilities, useful to assess correlations with performance on the number classification tasks. At the end of the experiment, the short form of the Edinburgh Handedness

Inventory involving only four items (write, throw, use a toothbrush, use a spoon; Veale, 2014), was administered. The instructions were displayed on the screen in English. The entire experiment lasted approximately 30 minutes.

Magnitude and Distance Classification Tasks

The participants were invited to perform two numerical tasks. The well-established magnitude classification task (Dehaene et al., 1990; review in Lethensen & Marley, 2000; meta-analysis in Wood et al., 2008) and the novel distance classification task. The numerical tasks were identical in all aspects (stimuli and timeline), except for the instructions (see Figure 1, panel A).

Each trial consisted of the following sequence of events: (1) a fixation cross (size: 40 pixels, font Courier) for 300 ms; (2) a blank screen for 200 ms; (3) a digit (size: 80 pixels, font Courier) lasting until the response or at maximum 3000 ms; (4) a blank screen for 500 ms. All stimuli were black and centrally presented over a gray background.

In the magnitude classification task, the participants were instructed to classify the numerical magnitude RI WKH YLVXDO GLJLWV DV VPDOOHU RU ODUJHU WK response buttons, horizontally aligned on the keyboard (see Figure 1, panel B1). Response keys were labeled with the letters on the keyboard and no reference to the left or right side were made. In one EORFN VPDOOHU QXPEHUV L H ZHUH DVVRFLDWH 6, 7, 8, 9) ZLWK WKH ‡.· EXWWRQ LQ WKH RWKHU EORFN WKH response association was reversed.

Instead, in the novel distance classification task, the participants were instructed to classify the numerical distance RI WKH YLVXDO GLJLWV DV FORVH WR RU IDU IUR WZR UHVSRQVH EXWWRQV ,Q RQH EORFN QXPEHUV FORVH ‡'· EXWWRQ DQG QXPEHUV IDU IURP button; in the other block, the ZL stimulus-response association was reversed.

In both tasks, participants were instructed about the numbers to assign to each category: In the magnitude classification task, they were told that numbers EHORQJHG WR WKH ‡VP group, whereas numbers 6 EHORQJHG WR WKH ‡ODUJH QXPEHUV· JUR WDVN WKH\ ZHUH WROG WKDW QXPEHUV EHORQJHG EHORQJHG WR WKH ‡IDU QXPEHUV· JURXS %HIRUH During the task, the participants were asked WR VKLIW WKH PRXVH FXUVRU DZD\ IURP WKH VFUHHQ DQG buttons of the keyboard. A press on the space bar initialized each block. Participants were encouraged to respond as fast as possible without making errors.

Design

A 2 Tasks (magnitude classification vs. distance classification) X 8 Target numbers (1-9, excluding 5) X 2 Response sides (left button vs. right button) within-subject design was used. Each condition was repeated 10 times, resulting in overall 320 experimental trials. Each task included two blocks with different stimulus-response associations. Each of the two experimental blocks was preceded by a practice block involving 8 trials. Positive and negative feedback was provided for 200 ms, only in the practice blocks.

Both the order of the tasks and the order of the blocks were counterbalanced across participants. Thus, overall, the experiment consisted of four blocks, defined by the starting condition: magnitude classification with small-left and large-right associations, magnitude classification with large-left and small-right associations, distance classification with close-left and far-right associations, distance classification with far-left and close-right associations.

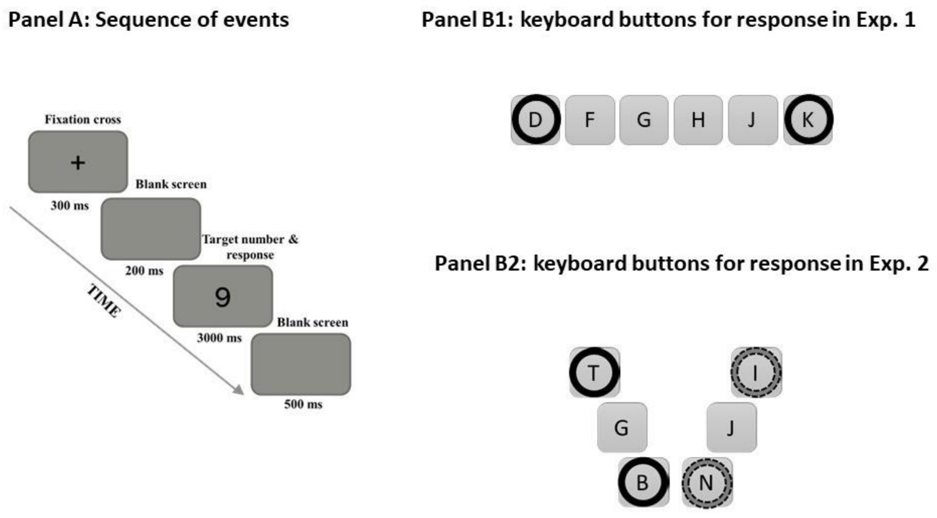

Figure 1. The panel A displays the sequence of events in Experiment 1 and 2. The panel B1 shows the keyboard buttons selected for the Experiment 1. The panel B2 shows the keyboard buttons selected for the Experiment 2: 'T' and 'B' buttons (black circles) for the diagonal axis incongruent with the MNL, 'N' and 'I' buttons (dashed circles) for the diagonal axis congruent with the MNL.

Brief Mathematical Assessment-3

The Brief Mathematical Assessment-3 (BMA-3; Steiner & Ashcraft, 2012) consists of 10 mathematical problems of increasing difficulty. During the BMA-3, the participants received English instructions to solve as many problems as possible, without any time pressure. To perform the calculations, they were allowed to use only their own paper and pencil and no other means such as calculators or web. The total of correct answers was considered as an index of general mathematical abilities.

All participants completed the Brief Mathematical Assessment-3. From 0 (no problem correct) to 10 (all problems correct), the mean score was 6.79 (1.73 SD).

Preprocessing

Excluding the practice blocks, the total number of trials was 14,080 (7,040 per task, 100%). Mean accuracy was 95.6% (6,728 trials) in the magnitude classification task, and 90.2% (6,354) in the distance classification task. Participants with less than 4 observations per cell (2 Tasks x 8 Digits x 2 Response sides) and 8 observations per condition of interest (2 Tasks x 2 Magnitudes/2 Distances x 2 Response sides) were discarded.

Nine trials with RTs shorter than 250 ms were removed from the analyses (7 in the magnitude classification, 2 in the distance classification). In addition, for each task separately, trials outside of 3 standard deviations (SD) from the mean were discarded from further analysis (241 trials: 106 in the magnitude classification, 135 in the distance classification). Again, participants with less than 4 observations per cell (2 Tasks x 8 Digits x 2 Response sides) and 8 observations per condition of interest (2 Tasks x 2 Magnitudes/2 Distances x 2 Response sides) were discarded.

The preprocessing procedure led to the exclusion of 5 participants because of accuracy, and of 2 participants based on RTs trimming criteria. In the end, 37 participants and 78.6% of trials (11,074 overall: 5,638 in the magnitude classification, 5,436 in the distance classification) were considered.

Analyses

First, we conducted an omnibus mixed analyses of variance (ANOVA) including 2 Tasks
PDJQLWXGH FODVVLILFDWLRQ YV GLVWDQFH FODVVLILFDWLRQ
‡ · ’LVWDQFHV QXPHULFDO GLVWDQFH EHWZHHQ WKH WDUJHW QXPEHU E
distance 1 vs. distance 2 vs. distance 3 vs. distance 4), 2 Response sides (left response button vs. right response button), and 2 Orders (magnitude classification as first task vs. distance classification as first task). All factors were manipulated within-subject, except for the Order of the tasks.

Second, to better characterize the SNARC effect, for each target number, we subtracted the RTs associated with the left response button from the RTs associated with the right response button. Then, we regressed this difference on the target number (see Fias et al., 1996) and extracted the individual regression slope with SPSS (Pfister et al., 2013). For each participant, we considered the unstandardized *b* coefficient as an index of the slope, and we ran a one sample *t*-test to test whether it differed significantly from zero (Van den Noortgate & Onghena, 2006). A typical SNARC is indicated by negative *b* coefficients (i.e., negative slopes).

Finally, to better characterize and compare the implicit-DE and the explicit-DE, two indices were computed. The first index was calculated using the formula reported in Goffin and Ansari (2016): DE= (mean RTs close distances - mean RTs far distances)/mean RTs all distances, where close distances represent numbers 3, 4, 6, and 7; and far distances represent numbers 1, 2, 8, and 9. A second, index (hereafter Delta_distance index) was inspired by Zorzi and colleagues (2012). Specifically, we subtracted the mean RTs associated with numerical distance 2 (i.e., numbers 3 and 7) from the mean RTs associated with numerical distance 1 (i.e., numbers 4 and 6), separately for the two tasks. As in Zorzi et al. (2012), a novel index was computed because it was more sensitive to the difference between two populations (healthy adults and neglect patients); also in the present study, the consideration of this second index was motivated by the need to better capture crucial differences between the two tasks. Both Goffin and A QVDUL¶V LQGH[DQG WKH 'HOWDBGLV to assess the correlation between the implicit-DE and the explicit-DE. The same indexes were considered to analyze the correlations between the implicit-DE/explicit-DE and general mathematical abilities, indicated by the score of the Brief Mathematical Assessment-3 (see Appendix A).

As complementary analyses, we also conducted Bayesian analyses to confirm our main findings. Results from Bayesian analyses are reported in Appendix B.

Results

Magnitude and Distance Classification Tasks

Our initial omnibus mixed ANOVA (including Task, Magnitude, Distance, Response side, and Order) revealed a main effect of Task ($F(1,35)=65.46$, $p<.001$, $\eta^2_p=.652$): The magnitude classification task was performed faster (mean=513.42 ms) than the distance classification task (mean=635.75 ms). Also a main effect of Distance arose (F(3,105)=23.97, p<.001, η^2_p=.406; see Figure 2). From 2-tailed paired-sample t-tests it emerged that all numerical distances differed significantly from each other (p<.001), except for Distance 1 and Distance 2 (p=.1). Neither Magnitude (p=.3) nor Response side (p=.1) reached significance.

Most important for the purpose of the present study, Distance was significantly influenced by Task (F(3,105)=17.78, p<.001, η^2_p=.337; see Figure 2). From 2-tailed paired-sample t-tests it emerged that in the magnitude classification task all numerical distances differed significantly from each other (p<.001), except for Distance 3 and Distance 4 (p=.7). In the distance classification task, all numerical distances differed significantly from each other (p<.01), except for Distance 1 and Distance 2 (p=.3). Notably, the direction of the difference between D2 and D1 was opposite in the two tasks, with slower responses for D1 (mean=532.07 ms) than for D2 (mean=508.21 ms) in the magnitude classification task, and faster responses for D1 (mean=629.52 ms) than for D2 (mean=676.30 ms) in the distance classification task.

Order approached significance (F(1,35)=4.04, p=.052, η^2_p=.104), and entered a triple interaction with Task and Response side (F(1,35)=5.81, p=.021, η^2_p=.142). Additional two repeated measures ANOVAs, one for each Order, revealed that a Task by Response side interaction emerged only when the magnitude classification was performed as first task (F(1,19)=10.03, p=.005, η^2_p=.346) and not as second (p=.9). Specifically, after the magnitude classification task, the distance classification task was performed significantly faster with the right response key (mean left minus right=15.97 ms, t(19)=2.890, p=.009) rather than with the left response key (p=.09).

In line with the literature, the significant Magnitude by Response side interaction indicated the presence of a SNARC effect (F(1,35)=12.23, p=.001, η^2_p=.259). Participants were faster at responding to small numbers with the left button (mean small left minus small right=-18.44 ms, t(36)=-2.289, p=.028, d=-0.376), and to large numbers with the right button (mean large left minus large right=29.43 ms, t(36)=3.761, p=.001, d=0.618). Moreover, responses with the left button were faster for small rather than for large numbers (mean small left minus large left=-27.94 ms, t(36)=-

4.043, p=<.001, d=-0.665), and responses with the right button were faster for large rather than for small numbers (mean small right minus large right=19.92 ms, t(36)=2.274, p=.029, d=0.374). The Task did not modulate the SNARC effect, as revealed by the absence of a triple interaction Magnitude by Response side by Task (F<2). No other interactions reached significance (p>.05).

The absence of an interaction of Task and SNARC effect was also demonstrated by the analysis of the b coefficients. Overall, the mean of the unstandardized b coefficient was negative (mean=-9.04; SD=14.66), thus indicating a typical SNARC, and it differed significantly from zero (t(36)=-3.753, p=.001, d=0.617). The best-fitting regression line was described by the equation y=-9.289x+40.77 (R^2=.90). A paired-sample t-test revealed that the b coefficient in the magnitude classification task (mean=-6.547, SD=23.80) and the b coefficient in the distance classification task (mean=-12.929, SD=14.19) did not differ significantly (p=.1). A visualization of the regression lines for each task is reported in Figure 2, panels C and D.

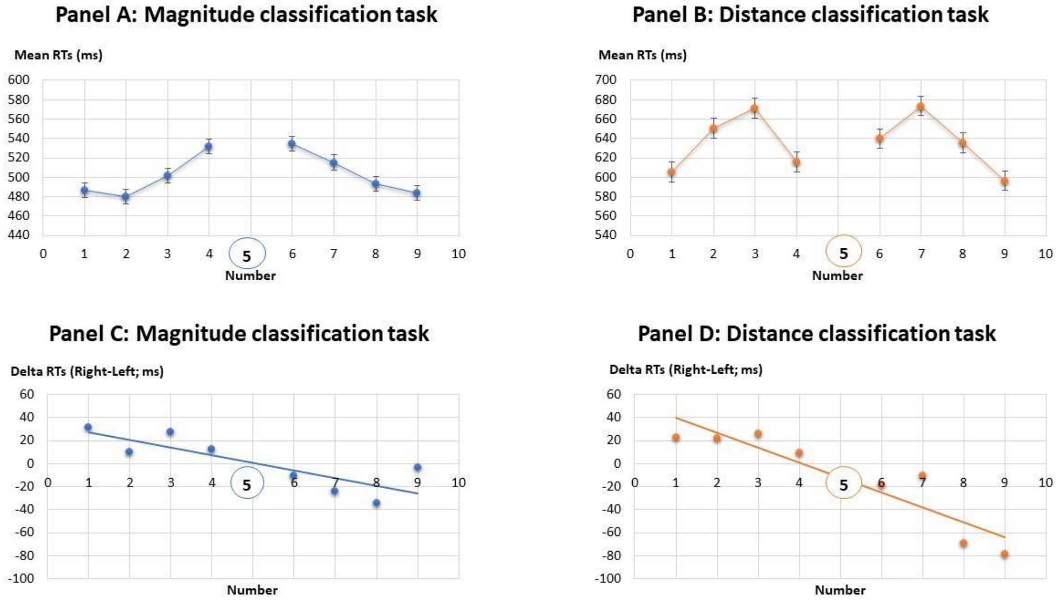

Figure 2. Panels A and B display the mean RTs as a function of the number in the magnitude classification task (panel A) and in the distance classification task (panel B), in Experiment 1. Error bars indicate +/-1 standard error of the mean. Panels C and D display the observed data and the fitted regression lines representing the RTs differences between right-handed and left-handed responses as a function of the number in the magnitude classification task (panel C) and in the distance classification task (panel D), in Experiment 1.

Implicit-DE and Explicit-DE

:KHQ WDNLQJ LQWR DFFRXQW *RIILQ DQG $QVDUL¶V LQG -DE and the explicit-DE were significantly different from zero (implicit-DE: mean=.064, SD=.044, $t(36)=8.822$, $p<.001$, $d=1.450$; explicit-DE: mean=.045, SD=.076, $t(36)=3.640$, $p=.001$, $d=.598$), but they were not correlated ($r(37)=.113$, $p=.5$; Figure 3, panel A). The implicit-DE differed statistically also from the mean DE reported by Goffin and Ansari (2016; mean=.097; $t(36)=-4.393$, $p<.001$). The consideration of the Delta_distance index corroborated the previous pattern of results: In particular, both the implicit-DE and the explicit-DE were significantly different from zero (implicit-DE: mean=23.86

ms, SD=28.123, t(36)=-5.160, p<.001, d=-.848; explicit-DE: mean=46.78 ms, SD=52.645, t(36)=5.406, p<.001, d=.889), and they were not correlated (r(37)=.091, p=.5; Figure 3, panel B).

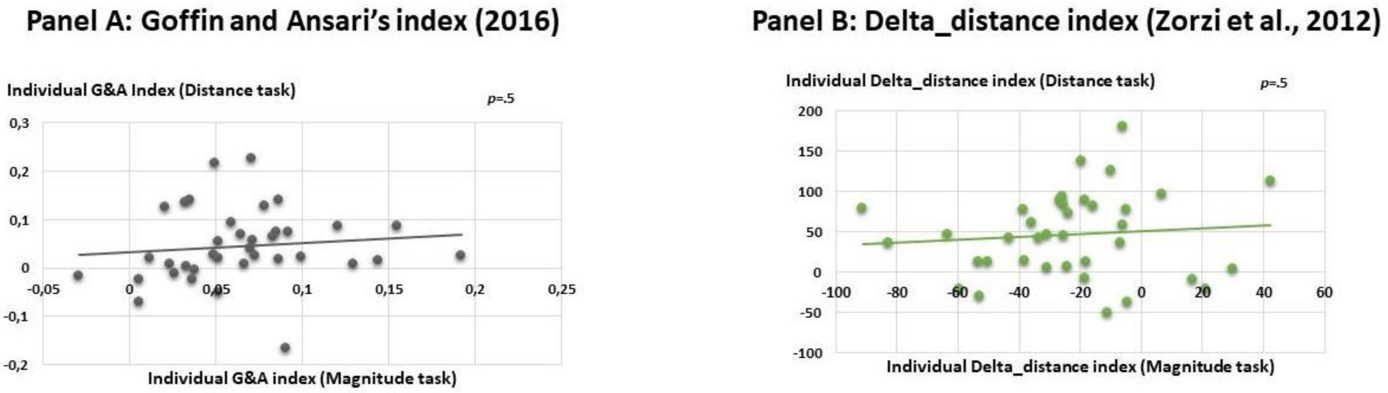

Figure 3. Panels A and B display the correlation between individual explicit-DE index and implicit DE- L Q G H [F R P S X W H G Z L W K * R I I L Q D Q G $ Q V D U L ¶ V I R U P X O D formula (panel B), in Experiment 1.

Discussion Experiment 1

In Experiment 1, the employment of the well-established magnitude classification task together with the novel distance classification task allowed us for the first time to directly compare the implicit-DE (implicit assessment: numerical magnitude as task-relevant property) and the explicit-DE (explicit assessment: numerical distance as task-relevant property). In line with our hypotheses, the results documented that the type of assessment significantly modulated the DE (confirmed by the Bayesian analyses, see Appendix B). From the magnitude classification task (implicit assessment), the canonical comparison DE appeared (implicit-DE), reflecting faster RTs for numbers numerically I D U U D W K H U W K D Q F O R V H W R W K H U H I H U H Q F H ‡ · 0 R \ H U classification task, a novel explicit-DE emerged, reflecting an advantage for both closest and farthest Q X P H U L F D O G L V W D Q F H V F R P S D U H G W R P H G L X P G L V W D Q F H similar effect in distance comparison task). In line with the dissociations found between different types of DE (Goffin & Ansari, 2016; Van Opstal et al., 2008; Vogel et al., 2021), implicit-DE and explicit-DE were not correlated. Consistent with the literature, a significant Magnitude by Response side interaction emerged, indicating the presence of a canonical SNARC effect (meta-analysis in Wood et al., 2008; confirmed by the Bayesian analysis, see Appendix B).

The reliability of the above results was further investigated in Experiment 2. In the second experiment, the employment of radial instead of horizontal response mappings allowed us to additionally address two issues: first, the generalizability of the association between implicit-DE and explicit-DE along the radial dimension; and second, the analogy between numerical and peripersonal distance. The general rationale underlying this experimental manipulation concerns the fact that not only magnitude but also distance is a property shared by both the numerical and the spatial domains (e.g., Erb et al., 2018; Song & Nakayama, 2008).

Experiment 2: Implicit and Explicit Numerical Distance Effect in the Radial Dimension

Numbers are strongly related to space: As previously mentioned, the SNARC effect is indicative of a spatial representation of numbers along a horizontal MNL (Dehaene et al., 1993; meta-analysis in Wood et al., 2008; review in Toomarian & Hubbard, 2018). More recent studies have extended previous findings onto the vertical and radial dimensions, thus documenting the presence of a three-dimensional SNARC effect with small/large numbers associated with down-left-close/right-up-far space, respectively (Aleotti et al., 2020; Chen et al., 2015; Felisatti et al., 2022; Gevers et al., 2006; Hesse & Bremmer, 2017; Holmes & Lourenco, 2011; Santens & Gevers, 2008; Sixtus et al., 2019; review in Winter et al., 2015).

To weight the relative contribution of each axis, some studies tested the SNARC effect along diagonal response mappings: Congruent diagonals are defined by Cartesian axes consistent with the MNL, instead, incongruent diagonals consist of at least one axis inconsistent with the MNL. While congruent response mappings always lead to significant SNARC effects, incongruent mappings have led to inconsistent results. When contrasting horizontal and radial dimensions, Holmes and Lourenco (2011, Exp. 1B) found significant positive slopes in the incongruent diagonal response mapping (i.e., from left-far to right-close), thus indicating a predominance of the radial over the horizontal dimension. Conversely, Gevers et al. (2006a) and Chen et al. (2015) did not find a significant SNARC effect in the incongruent diagonal response mapping, thus highlighting equivalent roles of both radial and horizontal axes. Recently, Aleotti and colleagues (2023) simultaneously manipulated all three Cartesian axes and documented significant SNARC effects whenever two or more dimensions were compatible with the MNL. Notably, most of these studies employed parity judgment task, i.e., implicit number magnitude processing. Only a few studies administered the magnitude classification task, allowing the investigation of spatial-numerical associations driven by the numerical distance. Santens and Gevers (2008) found that the radial location of the buttons evoked an association with numerical magnitude but not with numerical distance; instead, Felisatti et al. (2022) reported that downward attentional shifts speeded up the processing of close numerical distances.

In Experiment 2, we expected to corroborate the findings of Experiment 1, meaning a main effect of numerical Distance and an influence of Task (Gilmore et al., 2018; Holyoak, 1978; Ranzini et al., 2015; Shaki & Fischer, 2018; Turconi et al., 2006; Van Opstal et al., 2008). Moreover, we expected to find a Distance X Response side interaction, indicated by faster RTs at responding to close/far numerical distances with the close/far response button, respectively (Felisatti et al., 2022; but see Santens & Gevers, 2008). Finally, in line with the literature, we expected to find a radial SNARC effect, reflecting faster RTs at responding to small/large numbers with the close/far response button, respectively. Importantly, we predicted a modulation of the SNARC effect depending not on the task but on the diagonal response mapping (Aleotti et al., 2023; Gevers et al., 2006a, Exp. 2; Hesse & Bremmer, 2017; Holmes & Lourenco, 2011). In Experiment 2, the adoption of a diagonal rather than a pure radial mapping was motivated by the online nature of the study and, as a consequence, by the characteristics of international keyboards (the arrangement of the letters on the keyboard does not permit any pure radial mapping). Thus, we counterbalanced the diagonal mapping, gave us the possibility to explore the emergence of additive/competing different spatial-numerical associations depending on the in/congruence of different spatial dimensions with the MNL. So far, the literature on diagonal SNARC (Aleotti et al., 2023; Gevers et al., 2006a, Exp. 2; Hesse & Bremmer, 2017; Holmes & Lourenco, 2011) has provided inconsistent results. This motivated us to explore how properties of the tasks and sensorimotor manipulations contribute to the SNARC effect.

Method

In order to limit the risk of COVID-19 infection, the present study was administered online. It was conducted in accordance with the ethical standards stated in the Declaration of Helsinki. Prior to the experiment, all participants gave their informed consent and completed a sociodemographic questionnaire. The sociodemographic questionnaire included questions on native language, gender, age, country of residence, and diagnosis of dyscalculia/dyslexia. It is publicly available at: https://osf.io/vs6rw/?view_only=a5464f8f55b54d33a735899385ffe9bf

Transparency and Openness

We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study. The raw data for Experiment 2 are available in an OSF archive at https://osf.io/vs6rw/?view_only=a5464f8f55b54d33a735899385ffe9bf. Mean individual RTs were analyzed using SPSS Statistics, Version 27.0 (IBM SPSS Statistics for Windows, Version 27.0. Armonk, NY: IBM Corp). The results were obtained using Greenhouse-Geisser corrected analyses of variance and Bonferroni corrected t-tests. This study's design and its anal registered.

Participants

Forty-nine healthy human adults (7 males, 37 females, 1 blank answer, 4 non-binary/genderqueers; mean age = 25.02, SD = 7.8) enrolled at the University of Potsdam (Germany) completed the experiment for course credit or without any compensation. Four participants were left-handed, and one was ambidextrous. The average handedness score of our total sample indicated 81.97 (Edinburgh

Handedness Inventory, short version; Veale, 2014). All participants reported not to have received any diagnosis of dyscalculia and/or dyslexia.

As for Experiment 1, the sample size was determined prior to the start of data collection. In Experiment 2, after the two number classification tasks, two versions of the dot counting task (Fischer & Shaki, 2017; Shaki et al., 2012) were administered: In the horizontal version, the four black dots were horizontally displayed; in the vertical version, the four black dots were vertically displayed. Given the technical impossibility to assess counting direction habits along the radial axis remotely, a vertical version of the dot counting task was considered in light of the well established association between radial and vertical space (Levine & McAnany, 2005; Previc, 1990). In the horizontal version, among all considered participants, 36 completed the task: 30 participants counted from left to right, 4 counted from right to left, and 2 reported a random counting order. In the vertical version, all participants completed the task: 33 counted from top to bottom, 7 counted from bottom to top, and 2 counted in a random order.

Experimental Setup

The experimental setup was identical to Experiment 1.

Materials and Procedure

The tasks and procedure were identical to Experiment 1, with the only difference regarding the spatial layout of the response buttons in the number classification tasks. The details are described below.

Magnitude and Distance Classification Tasks

In Experiment 2, the response buttons were radially located with respect to the participants. Two GLDJRQDO D[HV ZHUH FRQVLGHUHG LQFRQJUXHQW Z‡L%W·K button=right‡ FORVH RU FRQJUXHQW ZLWK n=left‡ FORVH]‡Q·WEXOW 0LR far; see Figure 1, panel B2). Twenty-five participants performed the experiment with the MNL-incongruent response mapping, twenty-four participants performed the experiment with the MNL-congruent response mapping. As in Experiment 1, the response keys were labeled with the letters on the keyboard and no reference to left/right side or close/far distance were made. During the magnitude FODVVLILFDWLRQ WDVN LQ RQH EORFN VPDOOHU QXPEHUV button, and larger QXPEHUV L H ZLWK WKH ‡%· ‡,·- EXWW response association was reversed. During the novel distance classification task, in one block, QXPEHUV FORVH WR ‡ · L H) button, and numbers far from ZHUH DVVRFLDWHG Z ‡ · L H ZLWK WKH ‡%· ‡,· EXWWRQ response association LQ WKH RWKHU was reversed. Before starting the task, the participants were asked to shift the mouse cursor away from the screen and to UHVW WKHLU LQGH[ILQJHUV RQ WKH ‡7· ‡1· D A press on the space bar initialized each block. Participants were encouraged to respond as fast as possible without making errors.

Design

A 2 Tasks (magnitude classification vs. distance classification) X 8 Target numbers (1-9, excluding 5) X 2 Response sides (left button vs. right button) X 2 Diagonal response mappings (diagonal incongruent vs diagonal congruent with the horizontal MNL) mixed-subject design was used: All factors were manipulated within participants, except for the diagonal mapping that was manipulated between participants. Each task included two blocks with different stimulus-response associations. Both the order of the task and the order of the blocks were counterbalanced across participants.

Brief Mathematical Assessment-3

Among the 42 considered participants, all participants completed the Brief Mathematical Assessment-3 (BMA-3; Steiner & Ashcraft, 2012). From 0 (no problem correct) to 10 (all problems correct), the mean score was 6.30 (1.70 SD).

Preprocessing

Excluding the practice blocks, the total number of trials was 15,680 (7,840 per task, 100%). Mean accuracy was 96.5% (7,568 trials) in the magnitude classification task, and 89.9% (7,047) in the distance classification task. Participants with less than 4 observations per cell (2 Tasks x 8 Digits x 2 Response sides) and 8 observations per condition of interest (2 Tasks x 2 Magnitudes/2 Distances x 2 Response sides) were discarded.

One trial with RTs shorter than 250 ms was removed from the analyses (in the magnitude classification). In addition, for each task separately, all trials lying outside of 3 standard deviations from the mean were discarded from further analysis (263 trials: 118 in the magnitude classification, 145 in the distance classification). Again, participants with less than 4 observations per cell (2 Tasks x 8 Digits x 2 Response sides) and 8 observations per condition of interest (2 Tasks x 2 Magnitudes/2 Distances x 2 Response sides) were discarded.

The preprocessing procedure led to the exclusion of 7 participants because of accuracy and of no participant based on RTs trimming criteria. In the end, 42 participants (20 belonging to the MNL-incongruent response mapping, 22 belonging to the MNL-congruent response mapping) and 79.8% of trials (12,516 overall: 6,377 in the magnitude classification, 6,139 in the distance classification) were considered.

Analyses

First, we conducted two omnibus mixed ANOVAs. Both ANOVAs consisted of the following within-subject factors: 2 Tasks (magnitude classification vs. distance classification), 2 Magnitudes

VPDOOHU WKDQ ‡ · YV ODUJHU WKDQ ‡ · 'LVWDQFHV Q

WKH QXPEHU ‡ · GLVWDQFH YV GLVWDQFH YV GLVWD

response button vs. far response button). The first ANOVA included the Order of the tasks (magnitude classification as first task vs. distance classification as first task) as a between-subject factor, while the second ANOVA included the Diagonal response mapping (congruent with the MNL vs. incongruent with the MNL) as a between-subject factor.

Second, to better characterize the hypothesized SNARC effect driven by the numerical distance (distance based SNARC, hereafter dSNARC), for each numerical distance, we subtracted the RTs associated with the close response button from the RTs associated with the far response button. Then, we regressed this difference on the numerical distance (De Smedt et al., 2009) and extracted th individual regression slope (Pfister et al., 2013). For each participant, we considered the unstandardized *b* coefficient as an index of the slope, and we ran a one sample *t*-test to test whether it differed significantly from zero (Van den Noortgate & Onghena, 2006). Negative *b* coefficients (i.e., negative slopes) would indicate associations between close/far numerical distance and close/far buttons, respectively.

Third, to better characterize the SNARC effect driven by the numerical magnitude (magnitude based SNARC, hereafter mSNARC), for each target number, we subtracted the RTs associated with the close response button from the RTs associated with the far response button. Then, we regressed this difference on the target number (see Fias et al., 1996) and extracted the individual regression slope (Pfister et al., 2013). For each participant, we considered the unstandardized *b* coefficient as an index of the slope, and we ran a one sample *t*-test to test whether it differed significantly from zero (Van den Noortgate & Onghena, 2006). A typical SNARC is indicated by negative *b* coefficients (i.e., negative slopes).

Finally, to better characterize and compare the implicit-DE and the explicit-DE, two indexes were computed (see Analyses of Experiment 1). Both indexes were considered to assess the correlation between the implicit-DE and the explicit-DE. The same indexes were used to analyze the correlations between the implicit-DE/explicit-DE and general mathematical abilities, indicated by the score of the Brief Mathematical Assessment-3 (see Appendix A).

As complementary analyses, we also conducted Bayesian analyses to confirm our main findings (see Appendix B).

Results

Magnitude and Distance Classification Tasks

Our initial omnibus mixed ANOVA (including Task, Magnitude, Distance, Response side, and Order) revealed a main effect of Task ($F(1,40)=140.18$, $p<.001$, $\eta_p^2=.778$): The magnitude classification task (mean=509.78 ms) was performed faster than the distance classification task (mean=673.93 ms). Also a main effect of Distance arose ($F(3,120)=27.66$, $p<.001$, $\eta_p^2=.409$; see Figure 4). From 2-tailed paired-sample t-tests it emerged that all numerical distances differed significantly from each other ($p<.001$), except for Distance 1 and Distance 2 ($p=.4$). Neither the Magnitude ($p=.4$) nor the Response side ($p=.7$) reached significance.

Most important for the purpose of the present study, Distance was significantly influenced by Task ($F(3,120)=14.57$, $p<.001$, $\eta_p^2=.267$; see Figure 4). From 2-tailed paired-sample t-tests it emerged that while in the magnitude classification task all numerical distances differed significantly from each other ($p<.005$), except for Distance 3 and Distance 4 ($p=.5$), in the distance classification task, all numerical distances differed significantly from each other ($p<.005$), except for Distance 1 and Distance 3 ($p=.9$).

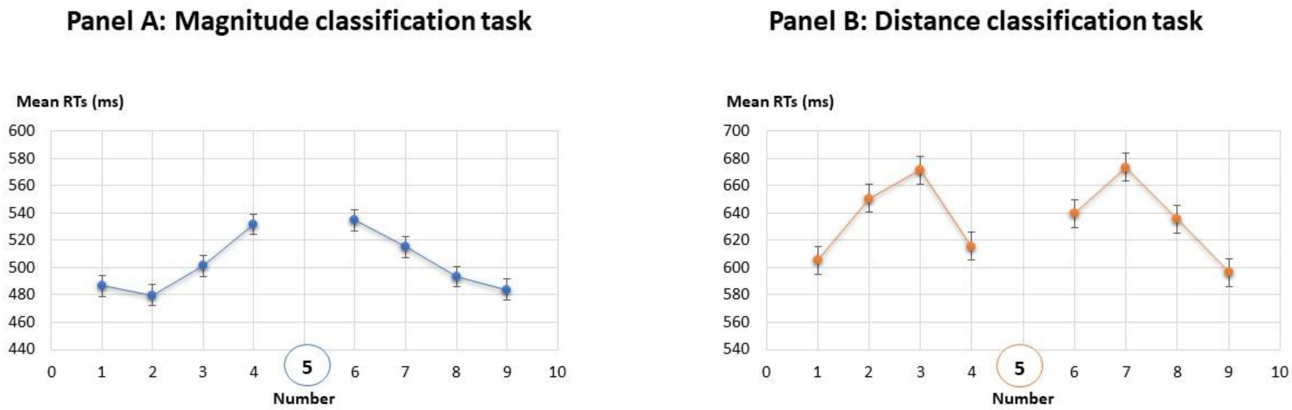

Figure 4. Panels A and B display the mean RTs as a function of the number in the magnitude classification task (panel A) and in the distance classification task (panel B), in Experiment 2. Error bars indicate +/-1 standard error of the mean.

Moreover, a Magnitude by Distance interaction appeared (F(3,120)=5.86, p=.001, η^2_p=.128). In particular, for numerical distances far from the reference, large numbers were responded faster (mean QXPEHU ‡ · PV PHDQ QXPEHU ‡ · PV WKDQ V ‡ · PV PHDQ QXPEHU ‡ · PV DV UHYHDOHG E\ -tailed paired-sample t-tests, p<.05).

Interestingly, Task modulated the Distance by Magnitude interaction (F(3,120)=8.62, p<.001, η^2_p=.177). In the magnitude classification task, a significant difference between small and large numbers appeared only at Distance 4 (p=.014), and not at Distances 1, 2 and 3 (p>.1). Instead, in the distance classification task, responses to small and large numbers differed significantly across all the Distances (p<.05), except for Distance 4 (p=.4).

In line with our hypotheses, the numerical distance was influenced by the physical distance of the response buttons (F(3,120)=3.20, p=.026, η^2_p=.074), although only marginally after applying the Greenhouse Geisser correction (p=.063). Specifically, numbers close/far from the reference were responded faster with the response buttons close/far from the body, respectively. Although a trend was present across all the distances, it turned out to be significant only at Distance 3 (mean D3 far button minus D3 close button: -18.52 ms; t(41)=-2.177, p=.035, d=-0.336).

Order did not reach significance (p=.2) but it approached a significant interaction with Distance (F(3,120)=2.62, p=.053, η_p^2=.062). In particular, performing the distance classification as the first task impacted the responses to numbers 3 and 7 (i.e., Distance 2).

In contrast with the literature, the Magnitude by Response side interaction was not significant, thus indicating the absence of an mSNARC effect along the radial dimension (p=.2).

No other interactions reached significance (p>.05).

The second omnibus mixed ANOVA (including Task, Magnitude, Distance, Response side, and Diagonal mapping) corroborated the previous results and, most importantly, it revealed that the radial mSNARC depended on Diagonal mapping (F(1,40)=13.15, p=.001, η_p^2=.247). Since also a 4-way interaction emerged involving Magnitude X Distance X Response X Diagonal mapping (F(3,120)=3.29, p=.023, η_p^2=.076), two further repeated measures ANOVAs including Magnitude, Distance and Response were conducted, one for each Diagonal mapping. When considering the GLDJRQDO FRQJUXHQW ZLWK WK‡H ·KRUL]RQWDO 01/ WKH 5HVSRQVH LQWHUDFWHG with Magnitude (F(1,21)=8.45, p=.008, η_p^2=.287) but not with Distance (p=.7), indicating a mSNARC effect that was not further modulated by Task (p>.1). Instead, when considering the GLDJRQDO LQFRQJUXHQW ZLWK -W%KH ·KRUL]RQWDO 01/ WKH 5HVSRQVH LQWHUDFWHG with Distance (F(3,57)=4.32, p=.030, η_p^2=.185) but not with Magnitude (p=.1).

SNARC Effect driven by the Numerical Distance: Slopes.

Overall, the mean of the unstandardized b coefficient was negative (mean=-12.49; SD=39.79), thus indicating the expected distance-based spatial-numerical association of response codes (dSNARC; faster RTs for close/far numerical distances with the close/far button, respectively). One-Sample t-test revealed that it differed significantly from zero (t(41)=-2.035, p=.048, d=-.314). The best-fitting regression line was described by the equation y=-13.03x+34.854 (R^2=.70).

When considering the diagonal incongruent with the MNL, the mean of the unstandardized b coefficient was negative (mean=-20.11; SD=34.78), thus indicating the expected dSNARC, and it differed significantly from zero ($t(19)=-2.586$, $p=.018$, $d=-.578$). The best-fitting regression line was described by the equation $y=-21.152x+62.963$ ($R^2=.74$; see Figure 5, panel A).

When considering the diagonal congruent with the MNL, the mean of the unstandardized b coefficient was negative (mean=-5.57; SD=43.49), thus indicating the dSNARC in the expected direction, but it did not differ significantly from zero ($t(21)=-0.601$, $p=.5$, $d=-.128$). The best-fitting regression line was described by the equation $y=-5.4071x+8.4213$ ($R^2=.54$; see Figure 5, panel B).

SNARC Effect driven by the Numerical Magnitude: Slopes. Overall, the mean of the unstandardized b coefficient was negative (mean=-1.85; SD=11.64), thus indicating a typical radial magnitude-based spatial-numerical association of response codes (mSNARC; faster RTs for small/large numbers with the close/far button, respectively), but it did not differ significantly from zero ($t(41)=-1.034$, $p=.307$, $d=-.160$). The best-fitting regression line was described by the equation $y=-1.8925x+11.743$ ($R^2=.07$).

When considering the diagonal incongruent with the MNL, the mean of the unstandardized b coefficient was positive (mean=4.53; SD=9.06), thus indicating a reverse radial mSNARC, and it differed significantly from zero ($t(19)=2.239$, $p=.037$, $d=.501$). The best-fitting regression line was described by the equation $y=4.5141x-12.529$ ($R^2=.15$; see Figure 5, panel C).

When considering the diagonal congruent with the MNL, the mean of the unstandardized b coefficient was negative (mean=-7.67; SD=10.78), thus indicating a typical radial mSNARC, and it differed significantly from zero ($t(21)=-3.338$, $p=.003$, $d=-.712$). The best-fitting regression line was described by the equation $y=-7.8445x+34.144$ ($R^2=.75$; see Figure 5, panel D).

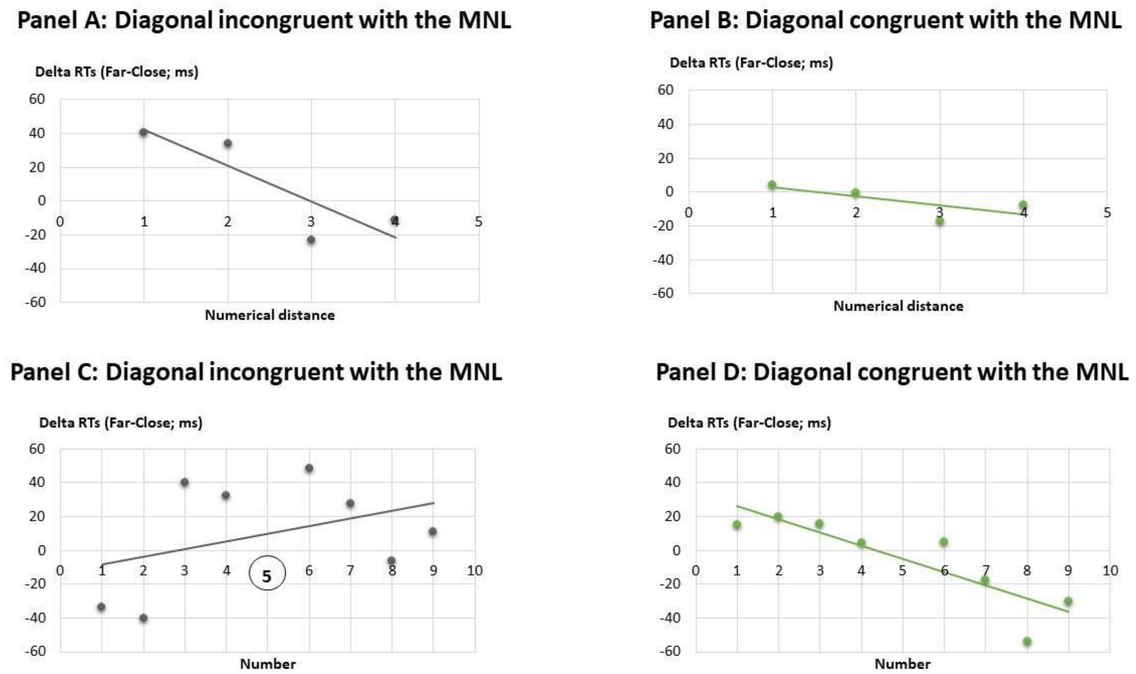

Figure 5. Panels A and B display the observed data and the fitted regression lines representing the RTs differences between far responses and close responses as a function of the numerical distance in Experiment 2. Panel A reports the results for the diagonal incongruent with the MNL (i.e., from left-far to right-close), Panel B reports the results for the diagonal congruent with the MNL (i.e., from left-close to right-far). Panels C and D display the observed data and the fitted regression lines representing the RTs differences between far responses and close responses as a function of the number, in Experiment 2. Panel C reports the results for the diagonal incongruent with the MNL (i.e., from left-far to right-close), Panel D reports the results for the diagonal congruent with the MNL (i.e., from left-close to right-far).

Implicit-DE and Explicit-DE

When taking into account Goffin and Ansari's ind -DE and the explicit-DE were significantly different from zero (implicit-DE: mean=.061, SD=.041, *t*(41)=9.503, *p*<.001, *d*=1.466; explicit-DE: mean=.053, SD=.088, *t*(41)=3.907, *p*<.001, *d*=.603). The implicit-DE differed statistically also from the mean DE reported by Goffin and Ansari (2016; mean=.097; *t*(41)=-5.550, *p*<.001). The implicit-DE and the explicit-DE did not differ significantly from each other, as revealed by a 2-tailed paired-sample t-test (p=.6), and they were not correlated (r(42)=-.091, p=.5; see Figure 6, panel A). A repeated-measure ANOVA including Task (within-subject factor) and Diagonal axis (between-subject factor) showed absence of main effects (ps>.6) and interaction (p=.3). The consideration of the Delta_distance index corroborated the previous pattern of results: In particular, both the implicit-DE and the explicit-DE were significantly different from zero (implicit-DE: mean=-33.42 ms, SD=28.70, t(41)=-7.545, p<.001, d=-1.164; explicit-DE: mean=39.91 ms, SD=80.69, t(41)=3.205, p=.003, d=.495), and they were not correlated (r(42)=-.184, p=.2; see Figure 6, panel B). A repeated-measure ANOVA including Task (within-subject factor) and Diagonal axis (between-subject factor) showed a main effect of Task (F(1,40)=28.07, p<.001, η^2_p=.412), in absence of other effects and interaction (p>.3). A 2-tailed paired-sample t-test revealed that while the magnitude classification task led to significantly faster RTs to Distance 2 compared to Distance 1 (mean D2 minus D1=-33.42 ms; t(41)=-7.545, p<.001, d=1.164), the distance classification task led to advantage for Distance 1 compared to Distance 2 (mean D2 minus D1=39.91 ms; t(41)=3.205, p=.003, d=-0.495).

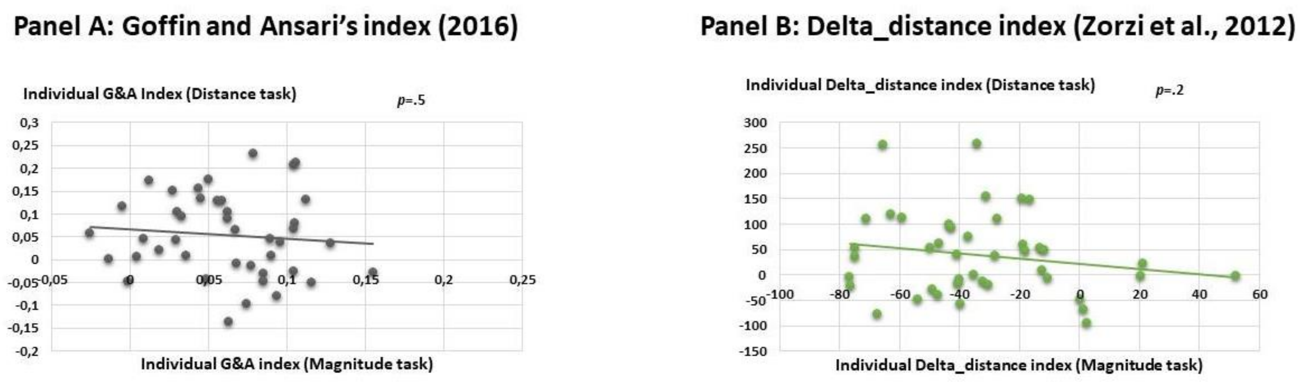

Figure 6. Panels A and B display the correlation between individual explicit-DE index and implicit DE- LQGH[FRPSXWHG ZLWK *RIILQ DQG $QVDUL¶V IRUPXOD formula (panel B), in Experiment 2.

Discussion Experiment 2

In Experiment 2, we compared the implicit-DE and the explicit-DE along the radial dimension: More precisely, we employed two diagonal response mappings, thus contrasting the horizontal and the radial dimensions. In line with our hypotheses, the results corroborated and generalized the findings of Experiment 1, extending the distinction between implicit-DE and explicit-DE from the horizontal to the radial dimension (confirmed by the Bayesian analyses, see Appendix B). As in Experiment 1, the correlation between implicit-DE and explicit-DE was not significant. As hypothesized, the SNARC effect driven by the numerical magnitude was modulated by the diagonal response mappings: Only the diagonal congruent with the MNL (i.e., from left-close to right-far) led to negative and significant regression slopes, indicating an association of small/large numbers with left-close and right-far space (Aleotti et al., 2023; Chen et al., 2015; Gevers et al., 2006a; confirmed by the Bayesian analyses, see Appendix B). Conversely, the diagonal incongruent with the MNL (i.e., from left-far to right-close) led to positive and significant regression slopes (the Bayesian analyses reported inconclusive evidence, see Appendix B). Interestingly, when considering the diagonal incongruent with the mental number line (i.e., from left-far to right-close), spatial-numerical associations driven by the numerical distance appeared: In particular, close/far numerical distances were responded faster with the close/far response buttons, respectively (the Bayesian analyses reported moderate evidence, see Appendix B). These findings indicate a predominance of the horizontal dimension over the radial one in the magnitude-based SNARC, and a predominance of the radial dimension over the horizontal one in the distance-based SNARC.

Thus, the properties of the task (i.e., explicit focus on magnitude or distance) and the arrangements RI WKH UHVSRQVH EXWWRQV ZLWK UHVSHFW WR WKH SDUW -space mappings. This calls for a distinction between different instances of the SNARC effect based on the numerical property (magnitude or distance) driving them. Furthermore, it informs that it is important to consider the critical role of task properties and sensorimotor aspects in the activation of different spatial organizations of numbers (Fischer, 2012).

General Discussion

The present study focuses on the comparison distance effect, a hallmark effect of numerical cognition emerging in number comparison tasks and reflecting better performance when comparing numerically distant rather than close numbers (Moyer & Landauer, 1967). Its robustness across cultures, ages, and mathematical competencies (Decarli et al., 2020; Göbel et al., 2011; Hohol et al., 2020), together with its sensitivity to properties of the task (Gilmore et al., 2018; Turconi et al., 2006; Van Opstal et al., 2008) call for a better understanding of its nature. The present study aims exactly to do so, first by directly comparing the comparison DE assessed implicitly (with numerical distance as task-irrelevant dimension) and explicitly (with numerical distance as task-relevant dimension); second, by investigating the correspondence between numerical and physical distance. To achieve this dual purpose, we introduced the distance classification task that requires participants to classify symbolic numbers with respect to their numerical distance from the reference 5. In Experiment 1, the response buttons were horizontally aligned, instead, in Experiment 2, they were radially located with respect to the participant, following two diagonals (from left-far to right-close vs. from left-close to right-far). Below, we interpret our main findings, separately for each purpose.

Explicit and Implicit DEs

Overall, the distance classification task was performed significantly slower than the magnitude classification task. This could be due to the fact that, even if participants were always instructed about the number-group associations, in the distance classification task, the categorization of numbers was more arbitrary, thus requiring more cognitive resources to learn and to remember it.

As predicted, in both experiments, the type of assessment significantly modulated the DE. From the magnitude classification task (implicit assessment), the canonical comparison DE appeared, reflecting faster RTs for numbers numerically far rather than close to the reference Landauer, 1967). Instead, from the new distance classification task, a novel pattern of DE emerged, reflecting advantages for both close and far numerical distances compared to medium distances from

QXPEHU ‡ · 2QH PD\ ZRQGHU ZKHWKHU WKH GLIIHUHQW SDV prototypicality of some stimuli. The literature on spatial cognition provides evidence on the critical role of the categorization and reference points in comparative judgment tasks. As grouping city locations into artificial states reduces/increases the representational distance between cities belonging to the same/different category (Maki, 1982; Hirtle & Jonides, 1985), also clustering numbers into close/far groups may influence their symbolic numerical distance. Furthermore, the proximity to reference points speeds up the localization of adjacent points in space (Sadalla et al., 1980). By applying this reasoning to our findings, the following picture should be expected: 1) comparable RTs for all numbers belonging to the same category (3,4,6,7 vs. 1,2,8,9), and 2) faster RTs for stimuli close to the number reference 5 (3,4,6,7) compared to stimuli far from the reference (1,2,8,9). Instead, our results, revealing an m-shape with nonlinear advantage for numerical stimuli far and close to the reference number 5, shed light on the sensitivity of the symbolic DE to both short- (e.g., task-specific) and long-term (e.g., learning-related) organizations of numbers, as explained below.

The observation that different numerical representations are activated depending on the implicit vs. explicit processing of numerical distance calls for a distinction between an implicit-DE, resulting from classification of symbolic numbers based on their numerical magnitude; and an explicit-DE, resulting from classification of symbolic numbers based on their numerical distance.

The novel explicit-DE is hard to explain with the Representational overlap view and the ANS. If the origin of the comparison DE was the distributional overlap in the number representation, one would have found similar patterns in the implicit-DE and explicit-DE, with a processing advantage for numbers far from the reference. On the contrary, the dissociation between the DE patterns when assessed implicitly and explicitly highlights the modulation of the symbolic DE based on the task properties. This supports accounts that emphasize the role of response-related processes in the DE, such as the Discrete Semantic System (Krajcsi et al., 2016; 2022). In line with the DSS model, the modulation of the DE is better explained by the strength of the association between the numbers and the properties that are salient for the current task: small vs. large numerical magnitude in the magnitude classification task, close vs. far numerical distance in the distance classification task. Specifically, according to the DSS, in the magnitude classification task, numbers numerically far IURP WKH UHIHUHQFH ‡ · L HDVVRFLDWDUH PRUH WKH UHJLRQV WKDQ · DQG ‡ODUJHU WKDQ · ,QVWHDG QXPEHUV FORVH PRUH ZHDNO\ DVVRFLDWHG ZLWK WKH ‡VPDOO· DQG ‡OD classification tDVN QXPEHUV QXPHULFDOO\ IDU IURP WKH UHIHU DVVRFLDWHG ZLWK WKH UHVSRQVH QRGHV ‡IDU IURP · UHIHUHQFH ‡ · L H DUH PRUH VWURQJO\ DVVRFLDWHG numbers 2,3,7,8 are more and more weakly associated with the task-relevant property.

However, it is worth noting that if the stimuli-response associations of one task are simply overwritten by the new associations of the other task, then flat lines and not a distance effect should be observed. Kojouharova and Krajcsi (2020) gradually changed the associations for the Indo-Arabic digits and found that the associations of the session drove the DE. Importantly, the much larger effect RI WKH VHVVLRQ¶V DVVRFLDWLRQV SUHYHQWHG WKH UHV contribution from the organization of numbers in long-term memory. In the present study, the manipulation of the categories salient for the task (small/large vs. close/far) allowed us to clarify that the DE does not only depend on the categories implied by the task, but also on long-term, stable DVVRFLDWLRQV EHWZHHQ QXPEHU DQG WKH ‡VPDOO ODUJH the implicit and the explicit comparison DE and the slower performance characterizing the distance classification task can only be explained by taking into account: 1) An organization of numbers stored in long-term memory, automatically and unconditionally activated (consider the dual route model by Gevers et al., 2006b); and 2) An additional association of numbers with close/far numerical properties, intentionally and conditionally activated in working memory to solve the novel distance classification task. Thus, the results of the present study support predictions made by the DSS model, not previously tested, and document the contribution of both properties reflecting the long-term organization of numbers and properties characterizing the short-term, task-specific, associations of numbers in the comparison distance effect. More generally, while some studies attribute to working memory a unique role in number representation and processing (e.g., van Dijck et al., 2009; Marzola & Cohen, 2023), other studies (reviewed by Fischer, 2012) support the joint contribution of multiple influences from vastly different time scales on numerical cognition. Future experiments are needed to weight the relative contribution of short-term and long-term numerical associations.

In the present study, the absence of correlation between the comparison-implicit DE and the comparison explicit-DE further supports the involvement of different cognitive processes such as long- and short-term memory retrieval. Previous studies have already shown that the comparison DE does not correlate with either the priming DE (. U D M F V L 6] & F V; van Opstal et al., 2008) or the reverse DE (Goffin & Ansari, 2016; Vogel et al., 2021). This opens the question of whether it is more appropriate to discuss the DE in terms of flexibility of a single effect, or to talk about different effects related to the same property (the numerical distance).

In Experiment 1, the explicit-DE has been shown to predict general mathematical abilities (see Appendix A). Instead, in Experiment 2, the correlation between DE and the 3-BMA was influenced by the diagonal response mappings (see Appendix A). Future studies will need to clarify the relation between mathematical proficiency and the DE when assessed either implicitly or explicitly.

mSNARC and dSNARC

The current study documented the presence of different spatial-numerical associations, driven by the numerical magnitude (magnitude-based Spatial-Numerical Association of Response Codes; mSNARC) and by the numerical distance (distance-based Spatial-Numerical Association of Response Codes; dSNARC). The facts that in Experiment 2: A) The Task (distance classification vs. magnitude classification) did not interact with Distance and Response side, and B) The association between physical and numerical distance selectively emerged only in the ordinal congruent with the MNL, motivates the consideration of the spatial association driven by the distance as an instance of the SNARC effect rather than a classical compatibility effect (Simon, 1969).

Concerning the well-documented mSNARC (meta-analysis in Wood et al., 2008; review in Toomarian & Hubbard, 2018), it emerged only in Experiment 1, indicating faster RTs at responding to small/large numbers with the left/right button, respectively. As predicted, in Experiment 2, it was modulated by the diagonal response mapping (review in Winter et al., 2015): Only the diagonal congruent with the MNL (i.e., from left-close to right-far) led to negative and significant regression slopes, indicating association between small/large numbers with left-close and right-far space (Aleotti et al., 2023; Chen et al., 2015; Gevers et al., 2006a). Conversely, the diagonal incongruent with the MNL (i.e., from left-far to right-close) led to positive and significant regression slopes, indicating predominance of the horizontal dimension over the radial one.

Interestingly, in Experiment 2, regression analyses on mean differences revealed that the diagonal incongruent with the mental number line (i.e., from left-far to right-close), triggered spatial-numerical associations driven by the numerical distance: In particular, when the response mapping was incongruent with the canonical spatial representation of numbers, close/far numerical distances were responded faster with the close/far response buttons, respectively. Previous studies have already reported a correspondence between numerical and physical distance with different experimental paradigms. With hand-tracking methodology, Song and Nakayama (2008) found that, when FODVVLI\LQJ QXPEHUV EDVHG RQ WKHLU PDJQLWXGH WKH WUDMHFWRULHV GHFUHDVHG DV WKH QXPHULFDO GLVWDQF colleagues (2018) replicated the findings in 5-6-year-old children. Zorzi et al. (2012) and Felisatti et al. (2022) highlighted the role of visuospatial attention in the correspondence between numerical and peri-personal distance. Most importantly, Santens and Gevers (2008) were the first to test spatial-numerical associations driven by numerical distance: They found an association of close/far buttons with small/large magnitudes, but not with close/far numerical distances. Considering the methodological differences between the above-mentioned studies and our study, to our knowledge, this is the first time that spatial-numerical associations driven by numerical distance are documented. The fact that, in the present study, the response buttons were named with the keyboard letters, thus avoiding explicit reference to close and far positions, justifies the consideration of the distance based SNARC as determined by the physical position of the body.

In general, the main findings are confirmed by the Bayesian analyses, i.e., the effect of Task on DE across all experiments, as well as regression analyses on the mSNARC and dSNARC effects. In Experiment 2, Bayesian ANOVAs did not perfectly replicate the results of frequentist ANOVAs concerning the effects of the diagonal layout (see Appendix B). Also in the literature, experiments on SNARC effect along diagonal response mappings revealed inconsistent results. These observations highlight the importance of future studies to replicate and extend these compatibility effects. In particular, it would be of great theoretical importance: 1) to explore whether spatial-numerical associations driven by numerical magnitude and numerical distance depend on the compatibility between the different Cartesian axes with the MNL (Aleotti et al., 2023; review in Winter et al., 2015); and 2) to replicate the current study using non-V\PEROLF VWLPXOL DQG D ‡SXU

Constraints on Generality

Our findings were obtained testing students from different fields of study. The participants were of different nationality (70% German, 14% Turkish, 16% Others: English, Italian, Portuguese, Spanish, French, Russian, Bosnian, Arabic), and they were living either in Germany or in Turkey at the time of the study. The study was conducted online, when access to public spaces was limited due to the COVID-19 pandemic. Despite asking participants to adopt several precautions to maximize the quality of the data, the setting could not be properly controlled, thus leaving open the possible influence of contextual and computer-related characteristics. The fact that the hallmark effects reported in the present article have widely been replicated across different settings and devices leads us to expect our results to generalize to situations in which healthy adults perform number classification tasks in lab-based studies. However, given the higher proportion of participants belonging to cultures with left-to-right counting habits, the pattern of results might hold only for participants with specific nationality. A direct replication would test the role of culture and counting habits on the implicit/explicit processing of numerical magnitude/distance, along the horizontal/radial dimensions. We have no reason to believe that the results depend on other characteristics of the participants, materials, or context.

Conclusions

The present study focuses on the numerical distance effect, a hallmark effect of numerical cognition that describes changes in performance as a function of the numerical distance between two numbers. The robustness of the DE across ages and cultures, together with its sensitivity to characteristics of the task call for a better understanding of its nature. This study entails a double contribution, at the methodological as well as the conceptual level. First, in Experiment 1 and 2, the introduction of the novel distance classification task allowed the distinction between the classical comparison DE, emerging from implicit processing of the DE, and a novel explicit-DE, resulting from explicit processing of the DE. Second, in Experiment 2, the diagonal displacement of response buttons revealed the presence of spatial-numerical associations driven by numerical distance. Together the impact of implicit/explicit processing of the DE and the correspondence between numerical and physical distance suggest the potential added value of integrating the distance classification task in evaluations of numerical skills in populations with different ages, mathematical and spatial abilities. The persistence of the DE in professional mathematicians, together with the observation of a stronger DE in children with developmental dyscalculia (Decarli et al., 2020), and of an asymmetric DE in patients with unilateral spatial neglect (Zorzi et al., 2012), calls for a more comprehensive understanding of this effect.

Declarations

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Authors' contributions

Arianna Felisatti: Conceptualization, Data Curation, Formal analysis, Investigation, Methodology, Project administration, Software, Visualization, Writing - Original Draft, Writing - Review & Editing; Mariagrazia Ranzini: Conceptualization, Formal analysis, Writing - Review & Editing; Samuel Shaki: Methodology, Writing - Review & Editing; Martin H. Fischer: Supervision, Methodology, Writing - Review & Editing, Funding acquisition.

Human Ethics: The present study was conducted on healthy human adults, and it did not involve invasive techniques or deception. Thus, it was not subject to ethical review by the local ethical committee. Nevertheless, it was conducted in accordance with the ethical standards stated in the Declaration of Helsinki. Prior to the experiment, all participants gave their informed consent and completed a sociodemographic questionnaire. The sociodemographic questionnaire used is publicly available at https://osf.io/vs6rw/?view_only=a5464f8f55b54d33a735899385ffe9bf

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Appendix A

Correlations between Distance indexes and mathematical abilities

In order to investigate whether the performance in the well-established magnitude classification task and in the novel distance classification task could predict general mathematical abilities, we assessed the correlation of the indexes of implicit-DE and explicit-DE with the score of the Brief Mathematical Assessment-3 (BMA-3). However, it is important to consider that these correlations have to be carefully interpreted as they were not corrected for multiple testing.

Experiment 1: Implicit and Explicit Numerical Distance Effect in the Horizontal Dimension

:KHQ FRQVLGHULQJ WKH LQGH[HV EDVHG RQ *RIILQ DQG $ the distance classification task, nor the DE from the magnitude classification task related to performance in the BMA-3, as revealed by the-1WDLOHG 3HDUVRQ¶V FRUUHODWLRQV (explicit-DE: r(37)=.098, p=.2; see Figure A1, panel A; implicit-DE: r(37)=.154, p=.1; see Figure A1, panel B). Instead, when considering the Delta_distance indexes (which are arguably more sensitive to the task differences), the implicit-DE did not correlate with general mathematical abilities (r(37)=-.062, p=.3; see Figure A1, panel D), but the explicit-DE did (r(37)=-.29, p=.04): In particular, the higher the explicit-'(LQGLFDWLQJ DGYDQWDJH IRU QXPEHUV FORVHU WR score (see Figure A1, panel C).

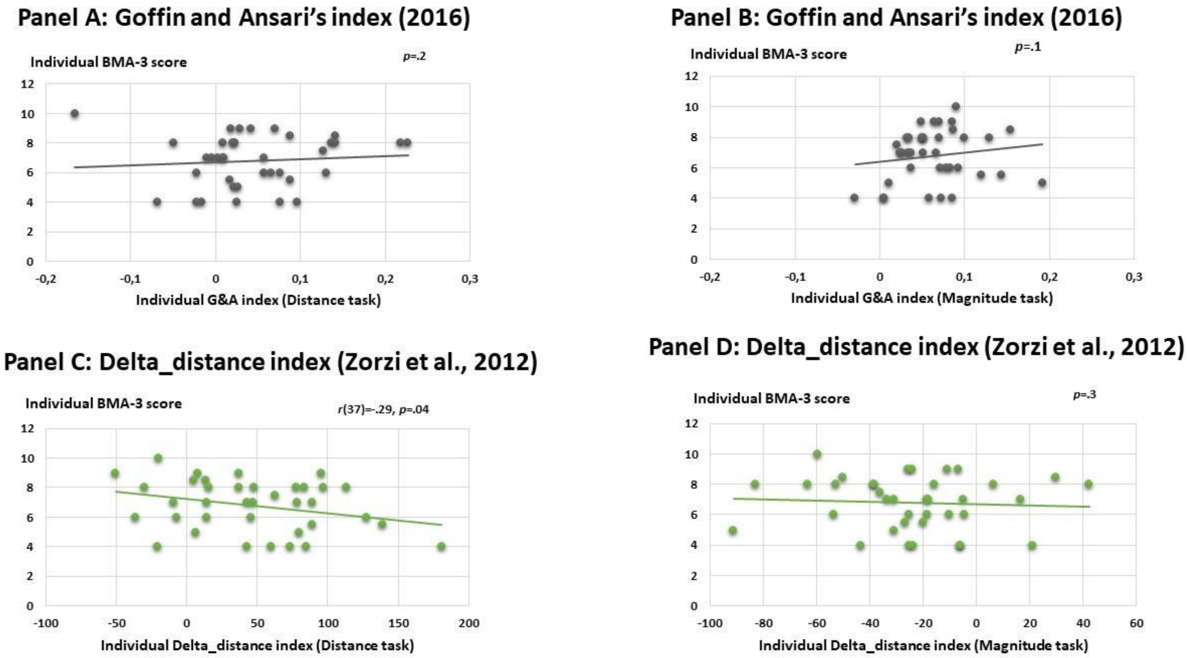

Figure A1. Panels A and B display the correlation between individual BMA-3 scores and individual explicit-DE (panel A) and implicit-' (S D Q H O % L Q G H [H V F R P S X W H G Z L W K * (2016) in Experiment 1. Panels C and D display the correlation between individual BMA-3 scores and individual explicit-DE (panel C) and implicit-DE (panel D) indexes, computed with the Delta-distance formula in Experiment 1.

Experiment 2: Implicit and Explicit Numerical Distance Effect in the Radial Dimension

: K H Q F R Q V L G H U L Q J W K H L Q G H [H V E D V H G R Q * R I I L Q D Q G $ the distance classification task, nor the DE from the magnitude classification task related to performance in the BMA-3, as revealed by the 1W D L O H G 3 H D U V R Q ¶ V correlations (explicit-DE: r(42)=-.211, p=.09; see Figure A2, panel A; implicit-DE: r(42)=-.145, p=.1; see Figure A2, panel B). The employment of the Delta_distance indexes (which are arguably more sensitive to the task differences) corroborated the previous null correlations (explicit-DE: r(42)=-.036, p=.4; see Figure A2, panel C; implicit-DE: r(42)=.187, p=.1; see Figure A2, panel D).

: K H Q W D N L Q J L Q W R D F F R X Q W W K H G L D J R Q D O L Q F R Q J U X H did not correlate with the BMA-3 score (implicit-DE: r(20)=-.070, p=.3; explicit-DE: r(20)=-.087, p=.3); while the Delta_distance index for implicit-DE, and not for explicit-DE (r(20)=.267,p>.1), positively correlated with the BMA-3, but this correlation only approached significance (r(20)=.36,p=.059).

:KHQ WDNLQJ LQWR DFFRXQW WKH GLDJRQDO FRQJUXHQW not correlate with the BMA-3 score (implicit-DE: r(22)=-.230, p=.1; explicit-DE: r(22)=-.313, p>.07); while the Delta_distance index for explicit-DE, and not for implicit-DE (r(22)=.026,p>.4), negatively correlated with the BMA-3, but this correlation only approached significance (r(22)=-.34, p=.058).

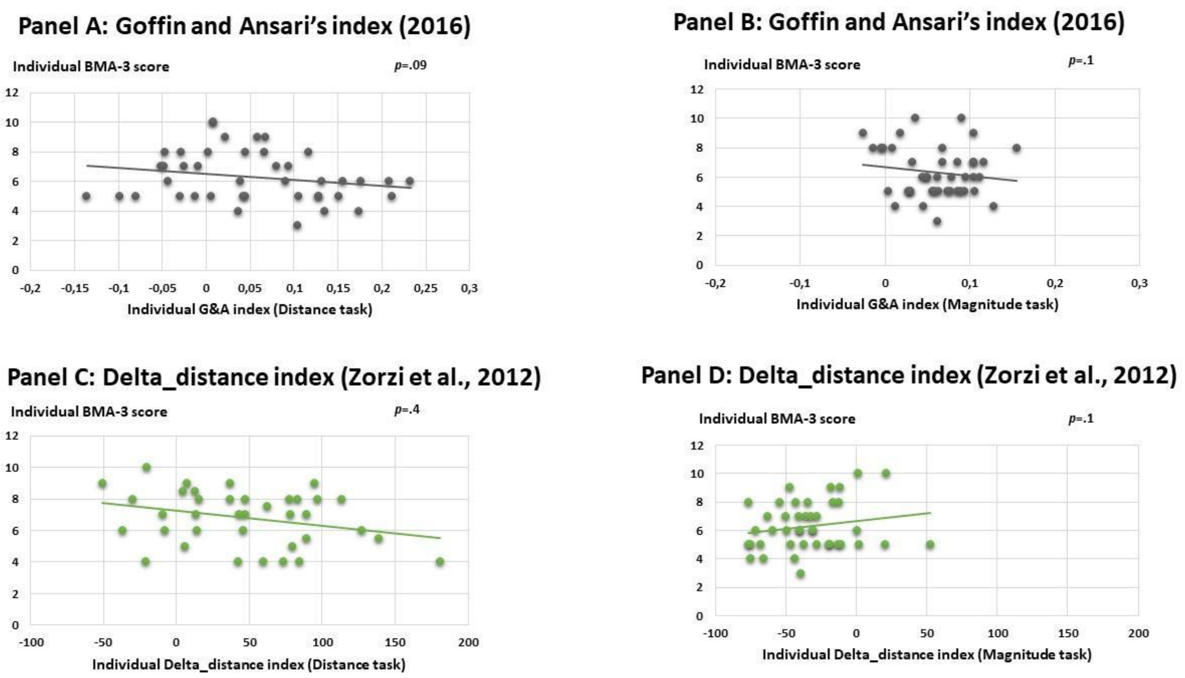

Figure A2. Panels A and B display the correlation between individual BMA-3 scores and individual explicit-DE (panel A) and implicit-’ (SDQHO % LQGH[HV FRPSXWHG ZLWK * (2016) in Experiment 1. Panels C and D display the correlation between individual BMA-3 scores and individual explicit-DE (panel C) and implicit-DE (panel D) indexes, computed with the Delta-distance formula in Experiment 1.

Discussion

In Experiment 1, the explicit-DE has been shown to predict general mathematical abilities, as indicated by the significant and negative correlation with individual scores in the Brief Mathematical Assessment. Previous studies have documented negative correlations between implicit-DE and mathematical abilities (Goffin & Ansari, 2016; Vogel et al., 2021). However, they all considered simple arithmetic problems, while the BMA-3 questionnaire used in our experiment includes a combination of mathematical problems of increasing difficulty. In Experiment 2, the correlation between DE and the BMA-3 did not emerge. Further analyses shed light on the role played by the diagonal response mappings. The diagonal congruent with the MNL led to an effect in the same direction as the one observed in Experiment 1, reporting a negative correlation between explicit-DE and BMA-3; instead, the diagonal incongruent with the MNL led to a positive correlation between the implicit-DE and the BMA-3. These correlations in Experiment 2 are, however, not significant. Future studies will need to clarify the relation between mathematical proficiency and the DE when assessed either implicitly or explicitly.

Appendix B

Bayesian analyses

In this Appendix we report the results from series of Bayesian analyses which have been run to verify the strength of the main findings observed by means of frequentist statistical methods. Bayesian analyses were conducted using JASP (version 0.11.1.0) and its default priors (Faulkenberry & Wagenmakers, 2020).

Experiment 1: Implicit and Explicit Numerical Distance Effect in the Horizontal Dimension

Two Bayesian repeated measures ANOVAs were run to substantiate the main findings of Experiment 1. In both analyses, the dependent variable was the mean of response latencies, following the same pre-processing of data used when applying frequentist statistics, as described in the main text.

In the first analysis, Task, Magnitude, Distance, and Response Side were included as within-subject factors. The best model included Task, Magnitude, Distance, and Response side as main factors, as well as the Task by Distance and the Magnitude X Response side interactions (BF_{10} = 3.814e+111; BF_{incl} I R U 7 D V N, BF_{incl} for Magnitude = 7.525, BF_{incl} for Distance = 1.030e+9, BF_{incl} for Response Side = 7.720, BF_{incl} for Task x Distance = 3259.894, BF_{incl} for Magnitude x Response side = 53.053).

From Bayesian 2-tailed paired-sample t-tests it emerged that in the magnitude classification task all numerical distances differed from each other (all BF_{10} > 614.633, extreme evidence for H_1), except for Distance 3 and Distance 4 (BF_{10} = 0.189, moderate evidence for H_0). Instead, in the distance classification task, Distance 2 differed from Distance 1 (BF_{10} = 4419.681, extreme evidence for H_1) and from Distance 4 (BF_{10} = 23507.769, extreme evidence for H_1). Also, the difference between Distance 3 and 4 reached a Bayes factor above 100 (BF_{10} = 1974.162, extreme evidence for H_1). Moderate evidence emerged for the differences between Distance 1 and 4 (BF_{10} = 9.674) and between

Distance 2 and 3 (BF_{10} = 5.450). In line with the frequentist analyses reported in the main text, Distance 1 did not differ from Distance 3 (BF_{10} = 0.326, moderate evidence for H_0).

From Bayesian 2-tailed paired-sample *t*-tests it emerged that participants were faster at responding to small numbers with the left button as compared to the right button (BF_{10} = 1.765, anecdotal evidence for H_1), and to large numbers with the right button as compared to the left button (BF_{10} = 49.121, very strong evidence for H_1). Moreover, responses with the left button were faster for small rather than for large numbers (BF_{10} = 102.217, extreme evidence for H_1), and responses with the right button were faster for large rather than for small numbers (BF_{10} = 1.717, anecdotal evidence for H_1).

Bayesian one sample *t*-test confirmed that overall, the mean of the unstandardized *b* coefficient differed from zero (BF_{10} = 48.086, very strong evidence for H_1). The *b* coefficient in the magnitude classification task and the *b* coefficient in the distance classification task did not differ (BF_{10} = 0.499, anecdotal evidence for H_0).

Experiment 2: Implicit and Explicit Numerical Distance Effect in the Radial Dimension

A series of Bayesian repeated measures ANOVA were run to substantiate the main findings of Experiment 2. In both analyses, the dependent variable was the mean of response latencies, following the same pre-processing of data used when applying frequentist statistics, as described in the main text.

In the first analysis, Task, Magnitude, Distance, and Response side were included as within-subject factors. The best model included Task and Distance as main factors, as well as their interaction (BF_{10} = 1.475e+182; BF_{incl} for Task = 1.230e+13, BF_{incl} for Distance = 1.217e+13, BF_{incl} for Task x Distance = 526846.011).

From Bayesian 2-tailed paired-sample *t*-tests it emerged that in the magnitude classification task all numerical distances differed from each other with extreme or strong evidence for H_1 (all BF_{10} > 20.704), except for Distance 3 vs. Distance 4 (BF_{10} = 0.195, moderate evidence for H_0). Instead, in the distance classification task, all numerical distances differed from each other with extreme or strong evidence for H_1 (all BF_{10} > 11.694), except for Distance 1 vs. Distance 3 (BF_{10} = 0.168, moderate evidence for H_0).

Bayesian 2-tailed paired-sample t-tests confirmed that in the magnitude classification task, a difference between small and large numbers appeared only at Distance 4 (BF_{10} = 3.009, moderate evidence for H_1), and not at Distances 1, 2 and 3 (all BF_{10} < 0.510). Instead, in the distance classification task, responses to small and large numbers differed across all the Distances with anecdotal to moderate evidence (all BF_{10} > 2.102), except for Distance 4 (BF_{10} = 0.233, moderate evidence for H_0).

Secondly, a within-subject Bayesian ANOVA was conducted for each Diagonal axis (i.e., MNL-incongruent and MNL-congruent). Magnitude, Distance, and Response side were included as within-subject factors.

:KHQ FRQVLGHULQJ WKH GLDJRQDO D[LV L-Q F%R QEJXUX W H R Q VZ best model included Task and Distance as main factors, as well as their interaction (BF_{10} = 3.657e+79; BF_{incl} IRU 7DVN $_{incl}$ for Distance = 5696741.833, BF_{incl} for Task x Distance = 607.758).

:KHQ FRQVLGHULQJ WKH GLDJRQDO D[LV F R Q JUXHQW WR QZL W best model included Task and Distance as main factors, as well as their interaction (BF_{10} = 3.362e+97; BF_{incl} for Task = 2.891e+13, BF_{incl} for Distance = 1222888.724, BF_{incl} for Task x Distance = 29.000).

Thus, different to what was found with frequentist analysis, no effect of Response side was observed since the best model included only Task and Distance as main factors, as well as their interaction, regardless of the diagonal axis considered.

SNARC Effect driven by the Numerical Distance: Slopes. Bayesian one sample t-test reported inconclusive evidence with respect to the difference of the mean of the unstandardized b coefficient from zero (BF10 = 1.078, inconclusive evidence for H1). When considering the diagonal incongruent with the MNL, the mean of the unstandardized b coefficient differed from zero with moderate evidence (BF_{10} = 3.136).

When considering the diagonal congruent with the MNL, the mean of the unstandardized coefficient did not differ from zero (BF_{10} = 0.262, moderate evidence for H_0).

SNARC Effect driven by the Numerical Magnitude: Slopes. Bayesian one sample *t*-test confirmed that overall, the mean of the unstandardized coefficient did not differ from zero (BF_{10} = 0.275, moderate evidence for H_0).

When considering the diagonal incongruent with the MNL, the mean of the unstandardized coefficient differed from zero only with anecdotal evidence (BF_{10} = 1.750).

When considering the diagonal congruent with the MNL, the mean of the unstandardized coefficient differed from zero with strong evidence (BF_{10} = 13.369).