Below zero? Universal distance effect and situated space and size associations in negative numbers

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Abstract

While some researchers place negative numbers on a so-called extended mental number line to the left of positive numbers, others claim that negative numbers do not have mental representations but are processed through positive numbers combined with transformation rules. We measured spatial associations of negative numbers with a modified implicit association task that avoids spatial confounds present in most previous studies. In two lab-based magnitude classification experiments (each including 24 participants) and two online replications (with 74 and 77 participants, respectively), positive and negative numbers were combined with two spatial contexts: either directional symbols (left- or right-pointing arrows) or rectangles of varying sizes. In all experiments, we found a robust distance effect for negative numbers. However, there were no consistent associations of negative numbers with directional or size contexts. In the context of directional symbols, holistic processing, i.e., processing in line with the extended mental number line hypothesis, was prevalent only in the small negative number range (-9, -8, -7, -6) when ensured by the stimulus set, supporting an extended mental number line. In the context of rectangles, however, large negative numbers from -4 to -1 were perceived as small, thus supporting rule-based processing. For negative number processing in the context of size, we further suggest the Semantic-Perceptual Size Congruity Cuing model (SPeSiCC model). We show that associations of size with negative numbers underly more complex processing mechanisms than mere recruitment of a transformation rule. In general, we conclude that associations of negative numbers with space and size are situated in the context, as they depend on the presented number range and differ for spatial direction and size.

Keywords

numerical cognition, mental number line, spatial-numerical associations, negative numbers, implicit association test, Semantic Perceptual Size Congruity Cuing model, SPeSiCC model

Space and size associations for negative numbers

Through schooling, individuals become familiar with the Arabic numbers from 0 to 9 and their combinations into multi-digit numbers, decimals, and fractions. However, while humans easily use the label "3" for a set of three apples, three stones, or any other triplet of objects, they hardly can apply its negative counterpart "minus 3" to any tangible set of things. Given that negative numbers lack real-world referents, they are perhaps more abstract cognitive concepts than positive numbers (e.g., Liebeck, 1990; Moreno & Mayer, 1999; but see Fischer & Shaki, 2017). Here we will investigate the cognitive status of negative numbers.

Researching negative numbers

There are several lines of research on the cognitive status of negative numbers. Firstly, developmental studies show how the concept of negative numbers is acquired as part of numeracy development (see, for example, Young & Booth, 2015). Secondly, research focuses on whether negative numbers have a neural basis in the brain in order to identify shared or distinct processing stages for positive and negative number concepts (Blair, Rosenberg-Lee, Tsang, Schwartz, & Menon, 2012; Chassy & Grodd, 2012; Gullick, Wolford, & Temple, 2012). Thirdly, cognitive processing of negative numbers is investigated in the broader context of negation and other linguistic transformations (see, for example, Aravena et al., 2012; de Vega et al., 2016; Dudschig & Kaup, 2018; Mazzarella & Gotzner, 2021; Ruytenbeek, 2020).

Speeded reaction time tasks are widely applied to gain insights into the cognitive processing of negative numbers. Adults process negative numbers considerably slower than positive numbers (e.g., Fischer & Rottmann, 2005; Shaki & Petrusic, 2005), perhaps reflecting their relative unfamiliarity: Negative numbers are acquired later and contain fewer tangible referents. However, there are also several interesting similarities between the cognitive processing of positive and negative numbers. We will review some key findings next. The present study aims to replicate these previous findings on the processing of negative numbers to better understand their cognitive representation. First, our goal is to replicate the numerical distance effect in negative numbers as an indicator of their semantic processing. This relates to the issue of whether negative numbers are processed holistically or decomposed into sign and number components, and we develop a novel rationale to ensure holistic processing. Secondly, we examine spatial-numerical associations in negative numbers under methodologically improved conditions to decide between two competing hypotheses about their cognitive representation (see Fischer and Shaki, 2017).

In the next paragraph, to contextualize these research aims, we briefly review and explain key signatures of numerical processing: the size effect, the spatial-numerical associations of response codes (SNARC), and the distance effect (for a more detailed review, see Mende, Shaki, & Fischer, 2018). We also introduce the mental number line metaphor and discuss methodological issues concerning previous studies on cognitive processing of negative numbers.

Review of the size effect, distance effect, and SNARC effect

When asked to identify the larger number in a number pair, given that the numerical distance between pairs of numbers is held constant (e.g., "2 or 4", "9 or 7" – in both cases, the distance is 2), participants need more time for pairs of larger numbers – in our example decisions are slower for the pair "9 or 7" than for the pair "2 or 4". This effect of number magnitude on processing speed is called *the size effect* (for positive numbers: Parkman, 1971; for negative numbers: Ganor-Stern & Tzelgov, 2008; Varma & Schwartz, 2011).

When comparing two numbers, participants respond slower to numerically close pairs (e.g., "4 or 6") than numerically distant pairs (e.g., "4 or 8"). This is called the *distance effect,* and it was also demonstrated for positive (Moyer & Landauer, 1967) and negative numbers (Ganor-Stern, 2012). This gradually increasing reaction time when comparing numerically closer instead of farther numbers also emerges when classifying single numbers as larger or smaller than a previously given reference number (e.g., Temple & Posner, 1998). The increase can be quantified via the slope of a regression line fit through the reaction time data and is a well-known signature of semantic number processing, indicating that number meaning has been understood (see, for example, Schneider et al., 2017, for a meta-analysis).

Most relevant in the present context are associations between numbers and either spatial direction or size that were inferred from speeded responses of participants' hands or eyes. Considering first the domain of space, participants respond to smaller numbers faster on the left side and to larger numbers faster on the right side, thus demonstrating Spatial-Numerical Associations of Response Codes, or the *SNARC effect*. This effect also holds for both positive and negative numbers, as indicated by congruency effects in speeded decision tasks involving parity or magnitude classifications (for positive numbers: Wood, Willmes, Nuerk, & Fischer, 2008; Fischer & Shaki, 2014; for negative numbers: Fischer, 2003; Fischer & Rottmann, 2005) (Footnote 1). Similar associations exist for size: Small-sized shapes are associated with left space and large-sized shapes with right space (see Bulf et al., 2014). We will revisit these claims after presenting methodological considerations below.

The mental number line metaphor

Size, SNARC, and distance effects have together inspired the influential conceptual metaphor of a mental number line, according to which people represent number concepts in a spatial layout where smaller numbers are located to the left of larger numbers (e.g., Dehaene et al., 1993; Fischer et al. 2003; Loetscher et al. 2008). The hypothesized spatial orientation of the mental number line can then explain the SNARC effect. In turn, postulating a stronger representational overlap between larger numbers and between numerically more similar numbers on the mental number line can then explain the size and distance effects, respectively (for review, see Fischer & Shaki, 2014; Toomarian & Hubbard, 2018).

Initially, the *mental number line* metaphor was established with research on positive numbers and is, to date, a widely accepted view for positive number processing. There is, however, a current debate between two major hypotheses of the cognitive representation of negative numbers: the *extended mental number line hypothesis* and the *rule-based account* (see Mende et al., 2018 for a review).

The extended mental number line hypothesis postulates that negative numbers are mentally represented left of zero. Instead, the rule-based account claims that negative numbers have no own conceptual representations, so that positive number representations must be augmented with a polarity mark whenever negative numbers are processed. These two competing hypotheses have different names in the literature: "ontogenetic" vs. "phylogenetic" (Fischer, 2003), "extended number line" vs. "magnitude polarity" (Shaki & Petrusic, 2005), or "analog+" vs. "symbol+" (Varma & Schwartz, 2011).

To illustrate, let us calculate "minus one minus three." According to the extended mental number line (MNL) hypothesis, one starts on the left side of zero, at minus one (Fig. 1A), and makes three steps to the left (Fig. 1B). The result of this operation is minus four (Fig. 1C), which lies to the left of the starting point. In contrast, according to the rule-based account, there is nothing on the left of zero. So, one starts on the right of zero, i.e., at one (Fig. 1D), while keeping in mind that the sign is negative. Then, according to previously learned rules, one transforms subtraction into addition and makes three steps rightwards (Fig. 1E). The result is four (Fig. 1D), i.e., it is on the right side from the starting point. When reporting this result, one adds the negative sign and obtains minus four. Figure 1 illustrates this computation under the two competing accounts.

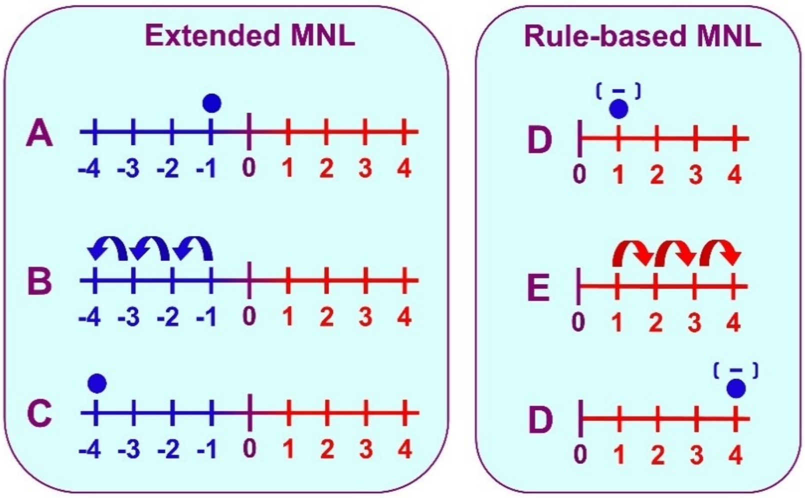

Figure 1. Visualizations of computing “minus one minus three” under the extended mental number line and rule-based accounts.

Measuring the cognitive representation of negative numbers: methodological issues

Previous studies on the cognitive representation of negative number concepts (reviewed in Mende et al., 2018) support either of the two hypotheses, possibly due to methodological inconsistencies. One methodological issue is the extent to which participants must process the sign of negative numbers: negative numbers have two components, namely sign and number symbol, and can thus be processed either holistically or component-by-component (Ganor-Stern & Tzelgov, 2008; Krajcsi & Igács, 2010). Zhang, Feng, and Zhang (2019) recently showed that holistic or componential representation of negative numbers depends on the experimental conditions used. These effects were found with a duration-comparison task: Participants estimated the duration of two numbers displayed successively. Zhang and colleagues used the fact that larger numbers induce longer duration estimates (Vicario et al., 2008) and found that estimates were biased by magnitude meanings for positive and negative numbers, both when shown in separate blocks and when a color code replaced the number sign. Because negative and positive numbers were processed following their numerical values, these results indicated holistic number processing.

However, participants in the same study apparently ignored the sign component when signed positive and negative numbers were mixed within an experimental block. Instead, they focused on the number component alone, as indicated by their duration estimates, which reflected absolute magnitude meaning. Valid inferences about negative number representation, therefore, require a method that ensures both holistic number processing and the need to pay attention to the sign. The present study set out to accomplish this requirement by presenting positive number foils among negative numbers in a magnitude classification task, thus requiring participants to attend also to the numbers' signs. We will explain this rationale further below (see also Figure 2).

Another methodological issue that remained unnoticed in previous studies is the use of lateralized button responses to measure spatial associations of negative numbers. Lateralized responses introduce extraneous spatial features that contaminate the intended measurements by activating pre-existing spatial-numerical associations. Fischer and Shaki (2017; see also Shaki & Fischer, 2018) addressed this concern by using a speeded go/no-go task with a single central response button to eliminate spatial response biases. Participants saw random sequences of single numbers from 1 to 9 intermixed with horizontally oriented spatial inducer object (a schematic duck or car facing either left or right; Footnote 2). All stimuli were centrally presented to eliminate their spatial coding relative to the participant's midline. Spatial compatibility was manipulated by imposing, before each block of trials, a new rule for responding that referred to both the numbers and the objects shown. For example, a compatible response rule was to "respond when a number is smaller than 5 or an object faces left". The two components of this rule are compatible due to a feature overlap in the instruction: Small numbers are represented on the left side of the mental number line, and left-facing objects are response-relevant. The same compatible relationship holds for the response rule "numbers larger than 5 or objects facing right". Correspondingly, there were two incompatible response rules (larger/left and smaller/right). Thus, the interspersed objects acted as spatial inducers that created a spatial context; nevertheless, number processing speed was measured without any confounding spatial features being present in either the stimulus or the response.

Fischer and Shaki (2017) already used this task to assess positive and negative numbers in separate blocks. They found that numerically smaller negative numbers (-8, -9) were more strongly associated with left space than - 1 or - 2, as predicted by the extended mental number line account; cf. Fischer, 2003). Thus, negative numbers were represented to the left of positive numbers even when spatial features were removed from the assessment method. However, this previous study did not address concerns about holistic vs. componential processing of numbers, and the stimulus range was limited to only four numbers. Moreover, the spatial inducers in the earlier study were rather idiosyncratic (duck and car). We addressed these three shortcomings in the present study.

First, we presented both positive and negative numbers randomly within the same procedure. Following Zhang et al. (2019; see also Shaki & Petrusic, 2005), this should ensure holistic number processing (see Figure 2 for further clarification of this rationale). Secondly, all negative single digits except -5 were used as stimuli to establish more conclusively whether negative numbers are conceptually represented in their own right (extended mental number line hypothesis) or merely by transforming or tagging positive number representations (rule-based account). And thirdly, we presented more generic spatial inducers, namely left- or right-facing arrows, instead of specific objects (Shaki & Fischer, 2018; Pinto et al., 2019).

Related to this last point about the nature of spatial inducers, we also took this opportunity to distinguish between contributions of directional features and size features in those spatial inducers. The association between magnitude and left-right space could be driven by either directional or size features or both (cf. Pinto et al., 2021). To assess these possibilities, we used, in separate experiments, either directional arrows or rectangles of differing sizes as inducers. While rectangles do not have a directional orientation, they still convey a spatial magnitude meaning through their area (small vs. large; cf. Bulf et al., 2014) (Footnote 3). This manipulation enabled us to replicate our results and to determine whether our findings pertaining to spatial associations of negative numbers are robust or depend on the presence of a direction- vs. magnitude-related context.

We used a magnitude classification task where numbers were categorized relative to the reference value - 5. The extended mental number line hypothesis predicts that numerically smaller negative numbers (- 9 to - 6) are associated with relatively more left space than numerically larger negative numbers (- 4 to - 1). Processing those numerically smaller numbers should then be facilitated when responding to them under congruent instructions (e.g., "respond when the number is numerically smaller than – 5 or the arrow points to the left"; or “respond when the number is numerically smaller than – 5 or the rectangle is small”). Similar facilitation would be expected for numerically larger negative numbers (- 4 to - 1) under conditions that are congruent with an extended mental number line ("respond when the number is numerically larger than - 5 or the arrow points to the right" or respond when the number is numerically larger than - 5 or the rectangle is large”).

Facilitation should be reflected in reaction times of the magnitude classification task. Thus, we expected faster processing in blocks with response rules compatible with an extended mental number line compared to incompatible conditions. For example, numerically small negative numbers (-6 to -9) relative to -5 should be processed faster in the context of left-pointing arrows or small rectangles than in the context of right-pointing arrows or large rectangles. Instead, the rule-based account predicted a reverse spatial mapping relative to -5, such that, for example, numerically smaller negative numbers (-6 to -9) would be represented progressively to the right of -5. This should induce a reversal of the compatibility effect when numerically smaller negative numbers are processed in the context of either left-pointing arrows or small rectangles, leading to slower responses compared to the other contexts.

Experiments 1 and 2 (lab-based) and Experiments 3 and 4 (online) on space- and size associations of negative numbers

We conducted four experiments. The first two experiments were lab-based, and the remaining two were online replications of the first two experiments with increased sample sizes. In Experiment 1 (lab-based, n = 24) and Experiment 3 (online, n = 74), we showed negative numbers to the participants together with directional inducers (arrows) that either pointed to the left or right side. With this paradigm, we aimed to extend previous findings which showed spatial-numerical associations with real-world objects (see Fischer & Shaki, 2017). Also, we changed the inducer set from left vs. right arrows to small vs. large rectangles to test associations between negative numbers and non-directional magnitude (size) in Experiment 2 (lab-based, *n*=24) and Experiment 4 (online, *n* = 77).

Materials and Methods

Participants

Consider first the lab-based experiments. Data of 24 participants were collected in Experiment 1. Participants did not receive monetary compensation; most of them were students who received course credit. Due to an administrative error, nineteen participants' personal information was not recorded. The remaining five female participants were between 18 and 23 years old (mean age: 19 years and 9 months); one was left-handed. Twenty-four new individuals participated in Experiment 2 (mean age: 23 years and 3 months, range: 19-32 years). One participant was left-handed, and five were male. All participants in Experiments 1 and 2 were from Western cultures, read and counted from left to right, and were naïve about our hypotheses (based on a survey after the experiment, see Appendix I on OSF, https://osf.io/qys4k/?view_only=9511ffd79f4d40e4b19292ffafb9e957).

Consider now the online experiments. Seventy-eight participants took part in Experiment 3 (mean age: 24 years, range: 18 –56 years), 13 were left-handed, and 16 were male. Four participants were excluded from the analysis because of accuracy below 80% in at least one of the experimental blocks. Data of 74 participants were included in the study. Finally, 82 individuals participated in Experiment 4 (mean age: 24 years and 2 months, range: 18-47 years). Ten participants were left-handed, and 16 were male. Five participants were excluded from the analysis due to accuracy below 80% in at least one of the experimental blocks. Data of 77 participants were included in the analysis. All participants of Experiments 3 and 4 were from Western cultures, and all were left-to-right readers and counters (assessed via a post-questionnaire in the online Experiment, see Appendix I on OSF, https://osf.io/qys4k/?view_only=9511ffd79f4d40e4b19292ffafb9e957).

This study was conducted following the guidelines of the Declaration of Helsinki (2013). Participants gave their informed consent by signing a paper document (lab-based experiments) or by submitting their consent online before the experiment began. In the online experiments, participation was only possible with PCs or laptops with physical keyboards and not with smartphones or tablet PCs (set via the Gorilla experiment platform). Participants received course credits for their participation.

Apparatus

All stimuli in lab-based Experiments 1 and 2 were presented on a 13'' MacBook with 1440 x 900 pixels screen resolution placed centrally on a desk in front of each seated participant. Reaction times were recorded on the space bar of the QWERTY keyboard, and the experiment was controlled with the OpenSesame software (Mathôt, Schreij, & Theeuwes, 2012). The online Experiments 3 and 4 were created and hosted with Gorilla (Anwyl-Irvine et al., 2020).

Stimuli

Stimuli were eight negative numbers (-1, -2, -3, -4, -6, -7, -8, -9), four positive numbers (+6, +7, +8, +9, presented with the plus-sign), and either two arrows of 30 x 128 pixels size which differed in pointing direction (left vs. right; Experiment 1 and 3) or two rectangles which clearly differed in size (small: 64 x 32 pixels; large: 1024 x 128 pixels; Experiment 2 and 4). All stimuli were presented centrally in black on a white background.

Design

In separate blocks of their respective experiments, participants responded with a single button when a specific response rule applied: numbers were either numerically larger than -5 (i.e., numbers -4, -3, -2, -1, +6, +7, +8, and +9) or numerically smaller than -5 (i.e., numbers -6, -7, -8, and -9). Inducer stimuli were either arrows (left- vs. right-facing) or rectangles (small vs. large). This resulted in four different instruction blocks for each participant: In Experiments 1 and 3 with directional inducers: smaller + left; smaller + right; larger + left; larger + right; in Experiments 2 and 4 with size inducers: smaller + small; smaller + large; larger + small; larger + large). Each block contained 50% go trials and 50% no-go trials. As previously demonstrated by Fischer and Shaki (2016, 2017; see also Shaki & Fischer, 2018), this method measures purely conceptual spatial congruency effects without peripheral spatial bias because neither stimuli nor responses have spatial features when their processing speed is measured. Figure 2 describes the rationale for including positive numbers into the stimuli set.

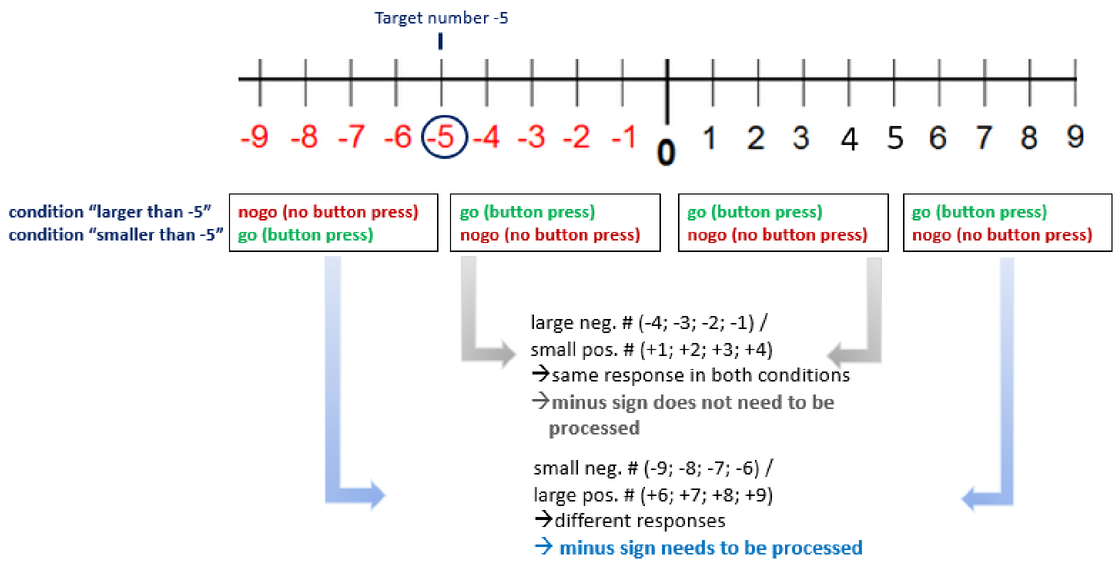

Figure 2. Rationale for including positive numbers 6-9 into the stimuli set. Our argument requires separate reflection on the two sub-ranges of negative numbers that we aimed to study. Consider first the number range from -1 to -4: When a response to numbers numerically larger than -5 was required, these numbers required go responses. Note that this same rule also required go responses if positive numbers +1, +2, +3, or +4 were displayed. Therefore, these numbers were not included in the stimulus set because performance with those items would not be diagnostic of processing of the number sign. Consider now the other negative numbers of interest. Negative numbers -9, -8, -7, and -6 require different answers compared to their positive counterparts +6 to +9: in the condition where participants

had to respond to numbers smaller than -5, the negative numbers -9, -8, -7, -6 were correctly classified with a button press. On the other hand, the numbers +6, +7, +8, +9 were correctly classified by withholding a button press. Here the behavior is diagnostic of holistic negative number processing: To force participants to decide which of the numbers -9, -8, -7, -6, or +6, +7, +8, +9 they compared against -5, the positive counterparts were included. By including positive numbers as counterparts to negative numbers, we ensured that participants needed to process the minus sign: if positive numbers are included in the set, then the sign has to be processed to compare negative and positive numbers efficiently.

Each experimental block consisted of 96 trials: 64 with negative numbers, 8 with positive numbers, and 24 with context objects. There were 12 small and 12 large rectangle context trials per block. However, depending on the response rule, the arrow context trials were divided into 8 left and 16 right arrows, or vice versa. Their purpose was to keep an overall equal balance between go and no-go trials (50%) per block. For example, under the rule "respond to numbers numerically larger than -5 or arrows facing left", all positive numbers were go trials, and therefore only 8 left-facing arrows were presented. Trial lists were generated randomly before testing, and positive numbers were distributed approximately equally throughout each list. Participants completed all four instruction blocks in a counterbalanced order (Latin square).

Procedure

In the two lab-based experiments, participants were instructed in English, German or Dutch (depending on their native language) and provided their informed consent at the beginning of the experiment. Each block started by stating the response rule. Participants performed a practice block until they reached at least 80% accuracy. Each stimulus was presented for 2,000 ms or until response. Participants were free to use their preferred hand to press the space bar. Trials were separated with a blank screen of 500 ms. The entire experiment took approximately 30 minutes. After the experiment ended, participants were asked to fill out a demographic questionnaire that assessed handedness, reading direction, counting direction, cultural background, and knowledge about our hypothesis (see Appendix I on OSF, https://osf.io/qys4k/?view_only=9511ffd79f4d40e4b19292ffafb9e957). The procedure was the same in the two online experiments, except that the participants completed the entire study online. Figure 3 illustrates the procedure.

Figure 3. Experimental stimuli and setup. Participants saw randomly intermixed negative or positive numbers and shapes. In experiment 1, left- and right-pointing arrows were the shapes shown. Only one stimulus was shown at a time. In the example above, the participant was displayed -3, followed by a right-oriented arrow, followed by a left-oriented arrow, followed by -7. Depending on the response rule for this block, the participant either pressed the space bar (go trials) or refrained from pressing the space bar (no-go trials). For example, when the response rule was " numerically smaller than -5 + left-pointing arrows", participants had to respond to the -7 and the left-pointing arrow. Therefore, only two of the four example stimuli displayed required a response. The same stimuli were displayed in each block through this procedure but received different answers due to the response rule

communicated before each block. Figure adapted from Shaki and Fischer (2018, p. 111; Source: Anna Matheja).

Analysis and Results

Analyses were conducted in Microsoft Excel 365 and JASP statistics, version 0.16.0.0. All practice trials, no-go trials, and trials with positive numbers were discarded. 25,472 trials remained (3,072 trials in Experiment 1; 3,072 trials in Experiment 2; 9,472 trials in Experiment 3; 9,856 trials in Experiment 4). Error trials (*n* = 7 or 0.2 % in Experiment 1; *n* = 15 or 0.5 % in Experiment 2; *n* = 513 or 5.4 % in Experiment 3; *n* = 620 or 6.3 % in Experiment 4) were excluded and not further analyzed due to their small number. Average accuracy of all participants across experiments was above 95 %. Thresholds of 300 ms and 1,500 ms (Footnote 4) were applied to reaction times to identify anticipations and procrastinations, respectively, and all trials outside of this interval were deleted (*n* = 12 in Experiment 1; *n* = 5 in Experiment 2; *n* = 72 in Experiment 3; *n* = 56 in Experiment 4). Finally, all trials outside of two standard deviations from each response-rule-condition mean were discarded (*n* = 116 in Experiment 1; *n* = 105 in Experiment 2; *n* = 1,438 in Experiment 3; *n* = 746 in Experiment 4). The rules "smaller number + left arrow" (in Experiments 1 and 3) / "smaller number + small rectangle" (in Experiments 2 and 4) and "larger number + right arrow" (in Experiments 1 and 3) / "larger number + large rectangle" (in Experiments 2 and 4) were defined as mental number line compatible, and the rules "smaller number + right arrow" (in Experiments 1 and 3) / "smaller number + large rectangle" (in Experiments 2 and 4) and "larger number + left arrow" (in Experiments 1 and 3) / "large number + small rectangle" (in Experiments 2 and 4) were defined as mental number line incompatible under the extended mental number line account. This was done to be able to evaluate our hypotheses.

Given that the distance effect is a hallmark of semantic number processing, we first examined the effect of numerical distance on decision speed in our magnitude classification task. Individual linear regression slopes were computed for each number magnitude range (numerically small: -9, -8, -7, -6; numerically large; -4, -3, -2, -1; see Pfister et al., 2013), resulting in two slope coefficients per person in each experiment. These non-standardized slope coefficients were analyzed with one-sample t-tests. Results are summarized in Table 1.

Slope Coefficients Descriptive Statistics			**Slope Coefficients One-Sample T-Test**		
Lab-based					
Experiment 1 (*n* = 24), negative numbers and arrows					
	Mean	*SD*	*t*	*df*	*p*
large numbers	-8.130	10.195	-3.906	23	< .001
small numbers	9.452	9.012	5.138	23	< .001
Experiment 2 (*n* = 24), negative numbers and rectangles					
	Mean	*SD*	*t*	*df*	*p*
large numbers	-8.167	13.246	-3.020	23	.006
small numbers	5.617	10.214	2.694	23	.013
Online					
Experiment 3 (*n* = 74), negative numbers and arrows					
	Mean	*SD*	*t*	*df*	*p*
large numbers	-9.828	16.442	-5.142	73	< .001
small numbers	12.339	16.246	6.533	73	< .001
Experiment 4 (*n* = 77), negative numbers and rectangles					
	Mean	*SD*	*t*	*df*	*p*
large numbers	-11.085	10.568	-9.204	76	< .001
small numbers	10.117	11.528	7.701	76	< .001

Table 1. Average slopes and one-sample t-tests for the large number range (-4, -3, -2, -1) and the small number range (-9, -8, -7, -6) in all four experiments.

As shown in Table 1, all slopes for both the large and the small number range are significantly different from zero in all four experiments (all $p < .05$). The opposite signs for the two ranges indicate the typical pattern, reflecting slower responses for numbers near the comparison value -5. These results indicate that the numerical distance effect was present regardless of number range and context and that negative number meanings were accurately activated by our participants in all conditions.

Next, to measure the effect of Mental-number-line compatibility across Experiments, we calculated individual compatibility scores based on reaction times. The average reaction time was 545 ms in Experiment 1, 584 ms in Experiment 2, 548 ms in Experiment 3, and 555 ms in Experiment 4. We subtracted individual reaction time means in mental-number-line compatible blocks from individual reaction time means in mental-number-line incompatible blocks to receive Mental-number-line compatibility scores in milliseconds. If this calculation resulted in a positive compatibility score, the effect was as expected because faster answers in mental number line compatible blocks reflect processing facilitation congruent with the extended mental-number-line account. Given that Experiments 3 and 4 replicated Experiments 1 and 2, data were aggregated across the lab-based (1, 2) and the online experiments (3, 4) (Footnote 5). Compatibility scores are as follows: Experiment 1,3 (arrows), large negative number range: *mean* = -2.72, *SE* = 3.36; small negative number range: *mean* = 10.39, *SE* = 3.78; Experiment 2,4 (rectangles), large negative number range: *mean* = -17.73, *SE* = 3.80; small negative number range: *mean* = -5.25, *SE* = 3.09. To evaluate differences in number-space and number-size associations, individual compatibility scores were analyzed in a one-way ANOVA, aggregated across lab-based and online experiments and also across number range (Footnote 6), with inducer type (spatial inducers, i.e., arrows, versus size inducers, i.e., rectangles) as a factor. Results showed a reliable main effect of inducer type, with $F(1, 197) = 18.91$, $\eta 2 = .088$, $p < .001$. These results show that different mechanisms underly processing of negative numbers depending on the context (spatial inducers versus size inducers).

First, we conducted one-sample t-tests on mental number line compatibility scores separately for each experiment and each number range. Figure 4 displays these results.

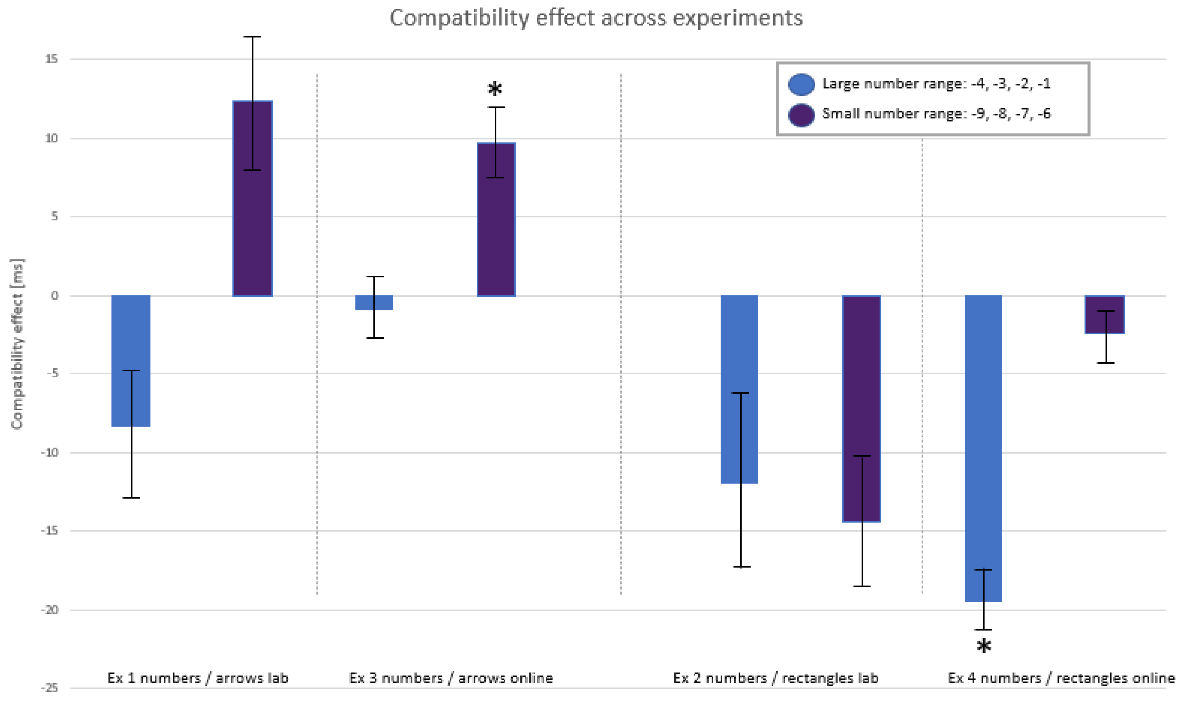

Figure 4. Mental-number-line-compatibility effects in all experiments. The effect was calculated by subtracting the average reaction times for mental-number-line-compatible blocks from the average reaction times for mental-number-line-incompatible blocks, separately for the numerically large (light blue bars) and the numerically small (dark purple bars) negative number ranges. Vertical bars indicate the standard error of the mean. A positive compatibility effect follows the direction predicted by the extended mental number line hypothesis; negative values indicate a reverse effect. Asterisks indicate a significant Mental-number-line compatibility effect calculated with one-sample t-tests.

As Figure 4 shows, similar patterns emerged for the lab-based and the online versions of the experiments. Thus, we merged data across lab-based and online experiments, since stimuli and procedure we identical.

One-sample t-tests were applied separately on the large and small negative number ranges and again separated across inducers (spatial inducers, Experiments 1 and 3; size inducers, Experiments 2 and 4) to statistically assess in which conditions Mental-number-line compatibility was significant. Results showed a positive Mental-number-line compatibility effect for the experiments with spatial inducers (Experiment 1, 3) in the small negative number range (-9; -8; -7; -6), where these negative numbers were presented together with their positive counterparts (+6; +7; +8; +9) and left-facing arrows, with t = 2.749, p = .007, *mean* = 10.39, *SE* = 3.78.

In addition, when negative numbers were presented together with size-inducers (Experiment 2, 4), we found a reverse Mental-number-line compatibility effect in the large negative number range (-4; -3; -2; -1), denoting facilitation with small rectangles, with t = 4.671, p < .001, *mean* = -17.73, *SE* = 3.80. Figure 5 shows a summary of these results.

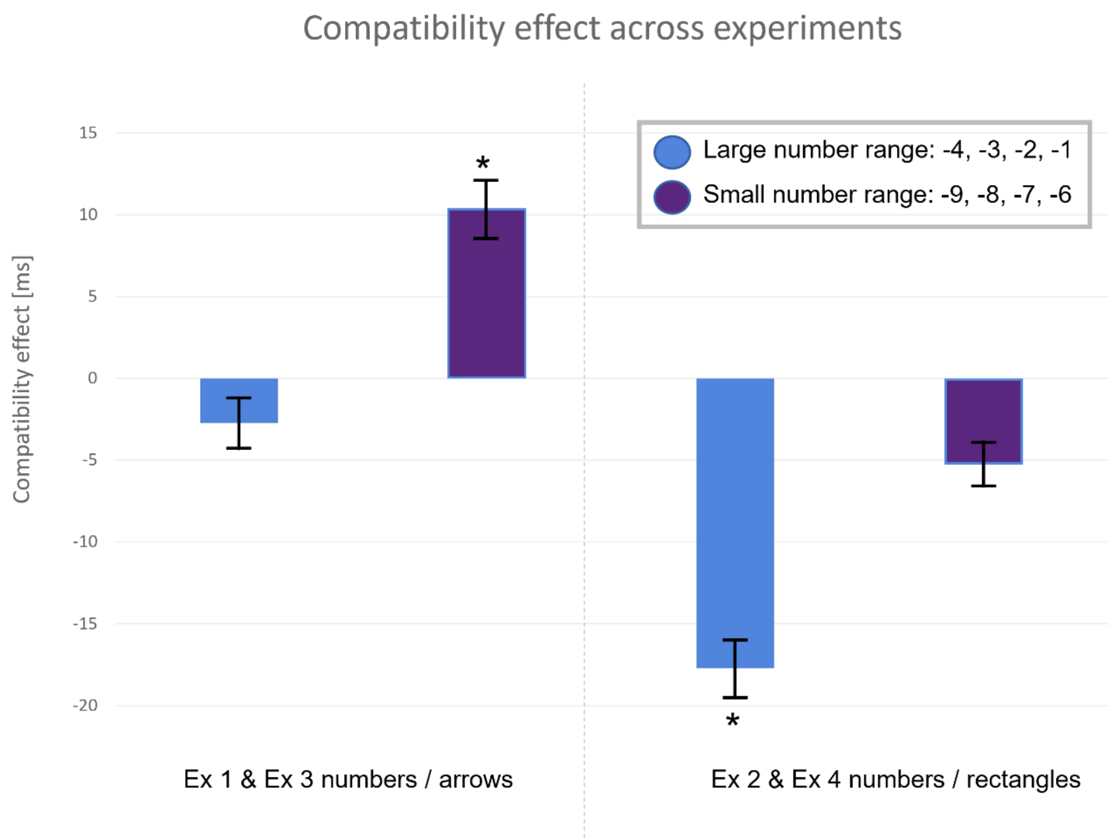

Figure 5. Mental-number-line-compatibility effects in all experiments aggregated across inducers (spatial inducers: arrows, Experiment 1,3; size inducers: rectangles, Experiment 2,4) separately for the large and the small negative number range. The effect was calculated by subtracting the average reaction times for mental-number-line-compatible blocks from the average reaction times for mental-number-line-incompatible blocks, separately for the numerically large (light blue bars) and the numerically small (dark purple bars) negative number ranges. Vertical bars indicate the standard error of the mean. A positive compatibility effect follows the direction predicted by the extended mental number

line hypothesis; negative values indicate a reverse effect. Asterisks indicate a significant Mental-number-line compatibility effect calculated with one-sample t-tests.

Discussion

The present study aimed to replicate and extend findings by Fischer and Shaki (2017, see also Fischer, 2003), according to which negative numbers are cognitively represented on an extended mental number line to the left of positive numbers. Our findings show the following main results: Firstly, robust distance effects in negative numbers were revealed, independent of the displayed spatial inducers (arrows, Experiments 1 and 3, vs. rectangles, Experiments 2 and 4). Further, we found reliable number-size associations in accordance with our expectations only in the context of directional inducers in the small negative number range (-9, -8, -7, -6) and not in the context of size inducers. Instead, and contrary to our hypothesis, in the context of size inducers, we found an opposite compatibility effect in the large negative number range (-4, -3, -2, -1), denoting their faster comprehension with small than with large rectangles. In the following, these findings will be discussed in turn.

The distance effect for negative numbers

The reliable distance effects we obtained for negative numbers in magnitude classification indicate semantic processing of the numerical value of negative numbers. Our findings are in line with several previous experiments. For instance, Ganor-Stern et al. (2010) found a distance effect in a spatial numerical comparison task with polarity-mixed pairs (i.e., positive and negative numbers) only for sequential presentation of numbers (i.e., magnitude classification task) but not for simultaneous presentation (i.e., magnitude comparison task). Their finding held independent of visual complexity, both when positive numbers were presented with and without the plus sign. It is in line with our results: constant comparison to the reference number -5 kept in memory is similar to being presented with one number first and comparing the number to a sequentially presented second number.

Moreover, our results extend previous findings by Gullick, Wolford, and Temple (2012), who reported a distance effect in mixed polarity pairs only in polarity sensitive comparisons (3 vs. -5) but not in polarity insensitive comparisons (-3 vs. 5). In our paradigm, presentation of positive numbers ensured processing of the number polarity so that differences in comparisons induced by polarity can be ruled out. The results of all present experiments thus confirm that the semantic processing signature for negative numbers is similar to those of positive numbers.

Spatial-numerical associations

In contrast to our hypothesis, we did not detect an overall congruency effect of spatial-numerical associations across experiments. We used a method with non-spatial responses first introduced by Fischer and Shaki (2016, on spatial-numerical associations in positive numbers; 2017, on spatial-numerical associations in negative numbers). The method eliminates peripheral spatial biases and uses interspersed spatial inducer stimuli; its main objective is to elicit and measure purely conceptual spatial-numerical associations.

We found spatial-numerical associations in the expected direction in Experiments 1 and 3, reflected by positive Mental-number-line compatibility scores, but only in the small negative number range (-9; -8; -7; -6), where also positive counterparts (+6; +7; +8; +9) of the negative numbers were present. It shows that our experimental design worked: presenting positive counterparts to negative numbers ensured holistic processing (see also Figure 2 for a motivation), so that spatial-numerical associations were elicited as if negative numbers were represented on an extended mental number line.

In contrast, in Experiments 2 and 4, we found a processing advantage for numerically large negative numbers (-4, -3, -2, -1) combined with small objects, reflected by negative Mental-number-line compatibility scores. This result suggests that these numbers are perceived as “small” and are thus processed more easily when shown together with small objects. Therefore, we suspect that participants may have co-activated, together with their numerical value, a linguistic label shared with the small rectangle inducers. The fact that this was not apparent in the directional inducers illustrates that different mechanisms might work when mapping number magnitude onto space (cf. Pinto et al., 2021).

In a recent publication, Vellan and Leth-Steensen (2022) measured different effects in processing of positive numbers simultaneously: the size congruity effect, the SNARC effect, and the combination of the two – the spatial-size association of response codes. The size congruity effect measures the relation between number magnitude and physical number size. For instance, when a number is numerically larger than the target number, i.e., the number 9 compared to target 5, and when it is displayed in a large physical size, processing is facilitated compared to when the number is displayed in a small font. On the other hand, the spatial-size association of response codes effect combines the size congruity effect with the SNARC effect. In the comparison mentioned above between number 9 and target 5, facilitation should be present when the number 9 is displayed in a large font and when the participant responds with the right hand in the right space. Interestingly, the authors found the spatial–numerical association of response codes only when participants were asked to judge physical size of the numbers and when the physical size of stimuli was varied on four levels (Experiment 2) and not on two levels (Experiment 1) (see also Weis et al., 2018 for a discussion on the relation of these effects and Fitousi et al., 2009, who also did not find a spatial-size association of response codes effect, i.e., interaction between number magnitude, number size, and response location).

Note that the authors used positive numbers and spatially aligned response keys in their experiment. Thus, we cannot compare our results to these findings in a one-to-one fashion. One strength of our study is that we removed the spatial component of responses. Consequently, we were not able to measure a direct link between response location and other parameters such as number magnitude and physical number size. However, these previous results enable us to explain our results in Experiments 2 and 4 by similar mechanisms. In our experiments, in contrast to Vellan and Leth-Steensen's (2022) findings, the physical size of numbers was not varied and not task-relevant. Instead, we suggest an implicit size congruity effect of number magnitude and physical size of inducers (rectangles) were at play because participants were exposed to semantic number size and the size of objects in our paradigm. Figure 6 provides an overview of the assumed mechanisms for both the large and the small negative number range. We introduce here the novel *Semantic Perceptual Size Congruity Cuing* (SPeSiCC) model.

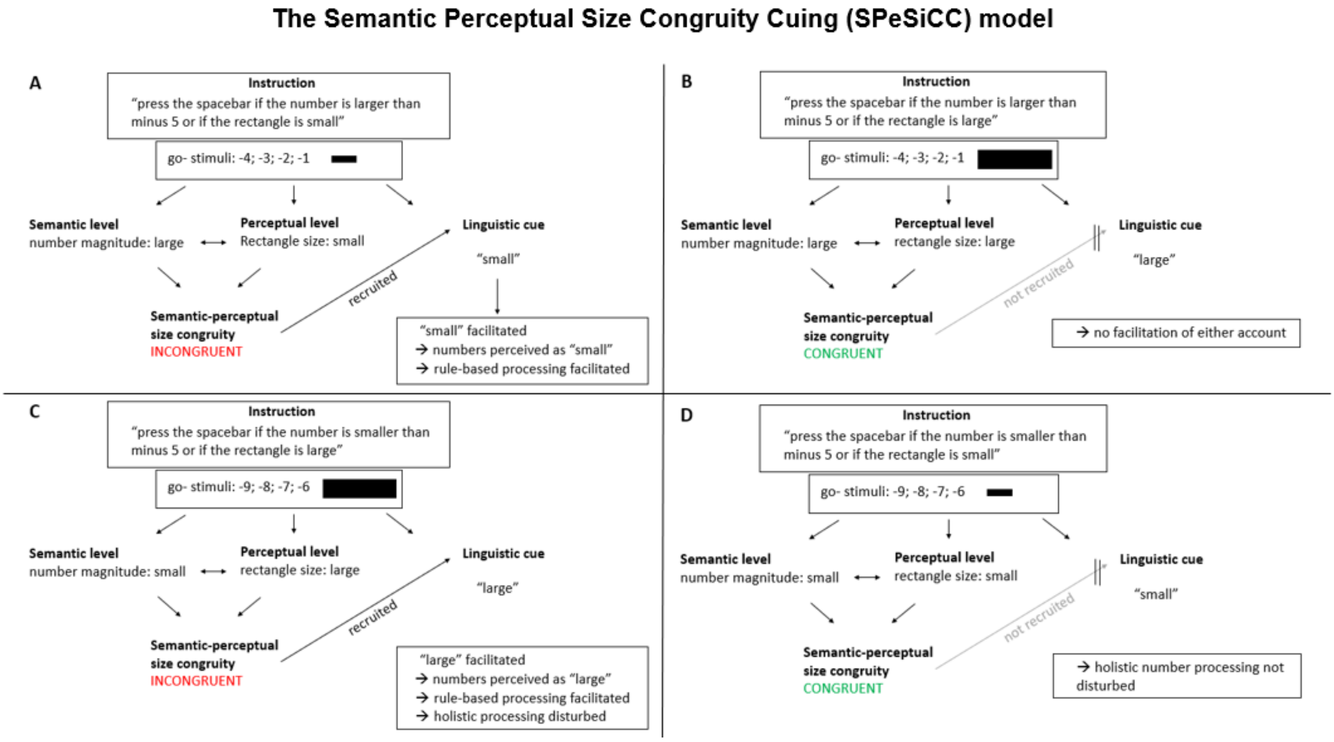

Figure 6. The Semantic Perceptual Size Congruity Cuing (SPeSiCC) model. **Panel A**: processing mechanism for large negative numbers (-4; -3; -2; -1) together with small rectangles; **Panel B**: processing mechanism for large negative numbers (-4; -3; -2; -1) together with large rectangles; **Panel C**: processing mechanism for small negative numbers (-9; -8; -7; -6) together with large rectangles; **Panel D**: processing mechanism for small negative numbers (-9; -8; -7; -6) together with small rectangles. From instruction and stimuli set follows the activation of congruity comparisons between the semantic (number magnitude) and the perceptual (rectangle size) level and an optional activation of a linguistic cue (last word in the instruction). If semantic and perceptual levels are incongruent, as in Panels A and C, then the linguistic cue is recruited, i.e., "small" in Panel A and "large" in Panel C, respectively. This cue led in both cases to rule-based processing because it

facilitated processing of the absolute number value, on which, in turn, transformation rules were applied.

As displayed in Figure 6, the SPeSiCC model assumes processing of numbers and object size in a parallel fashion on three levels: The semantic level (number magnitude), the perceptual level (object size), and the linguistic level (linguistic cue = last word in the instruction). The linguistic cue is only recruited when the semantic and perceptual levels lead to incongruent outcomes. Thus, semantic-perceptual congruity is hierarchically higher than linguistic cueing. Importantly, in our design the mechanisms differed across the large negative number range (-4; -3; -2; -1) and the small negative number range (-9; -8; -7; -6). For the latter number range, we had added positive numbers to the stimuli set to ensure holistic processing. However, as shown in Figure 6, in this number range (-9; -8; -7; -6), semantic-perceptual congruity effects disturbed the “default” holistic processing when the linguistic cue was recruited (Figure 6, Panel C). The suggested mechanism in the SPeSiCC model explains the absence of the expected size congruency effect of numbers and size-inducers within this number range. On the other hand, in the large negative number range (-4; -3; -2; -1), the rule-based processing strategy was facilitated (Figure 6, Panel A). Following these results, we see that the processing mechanisms suggested within the SPeSiCC model are stronger than the effect of the stimuli set, i.e., to ensure holistic processing.

Theoretical Implications

Our experiments contrasted two contradicting accounts of processing negative numbers: the extended mental-number line and the rule-based account. Overall, our findings cannot conclusively support either of these accounts. Instead, we showed here that processing of negative numbers is situated in the context: when holistic processing was ensured and when numbers were presented together with directional inducers, we found evidence for the extended mental-number line account. Nonetheless, we found tentative evidence against the extended mental number line account in Experiments 2 and 4: Numerically large negative numbers were not processed according to their numerical value but their absolute value. Here, the rule-based account applies better to explain the results. We explain both sets of results in the framework of the novel SPeSiCC model. Thus, we suggest that a simple rule-based processing strategy is not the only mechanism that drives negative number processing. This proposal awaits further examination. Moreover, we found a consistent distance effect across experiments that indicates similar semantic processing for positive and negative numbers. Taken together, our results show that associations of negative numbers with space and size are highly situated in their context.

Outlook

This study reports an extensive assessment of the cognitive representation of negative numbers with several methodological improvements over previous work. In contrast to the study conducted by Fischer and Shaki (2017), we extended the stimuli set to present all single digits except a reference value. We used this extended stimuli set to measure the numerical distance effect. Indeed, we successfully replicated the distance effect in negative numbers (see also Ganor-Stern, 2012). Nevertheless, we did not find the expected effects of direction and size associations in numbers. Instead, our data show a hybrid processing account of both the extended mental-number-line and the rule-based account. Fischer and Shaki (2017) used real-world objects (ducks and cars) as directional stimuli. In the current work, geometrical objects were used to examine the inducer function of directional versus magnitude features. Therefore, the absence of real-world objects with more semantic features than geometric shapes could be another reason for different patterns of results across the two studies. Specifically, the absence of semantic features in the present inducer objects might have caused the perceptual effects in Experiments 2 and 4 (see Figure 6).

Shaki and Fischer (2018) successfully measured both horizontal and vertical spatial associations using arrows as inducers. The authors concluded that "the presence of horizontal [spatial-numerical associations] (…) requires contextual priming" (p. 112) and that only vertical spatial-numerical associations might be inherent to the representation of numbers. They researched spatial-numerical associations in the context of arrows pointing in different directions. Sixtus, Lonnemann, Fischer, and Werner (2019) presented similar results: they investigated the influence of spatial-numerical associations on spatial attention and searching behavior in a number search task and found a measurable effect only in the vertical dimension but not in the horizontal. Crucially, both studies used positive but not negative numbers as stimuli. The present study supports the assumption by Shaki and Fischer (2018) that horizontal spatial-numerical associations might not be inherent to number concepts but are highly situated and dependent on the experimental context. Finally, our results show that in the spatial domain, associations of numbers with space and size depend on the context, i.e., the set size and congruity effects between stimuli, supporting a situated hybrid account of the extended mental-number-line and the rule-based account. Future studies should incorporate both object features simultaneously, i.e., direction and size, to further test our suggested SPeSiCC model. A follow-up experiment would thus explore directional objects that also vary in size. As a result, it will be possible to measure whether our hybrid account also holds when the size of directional stimuli is varied.

Conclusion

The findings from four experiments suggest that the distance effect is robust across negative numbers. At the same time, associations of numbers with space and size are not inherent but are elicited by the task and experimental context (see Fischer & Shaki 2017; Shaki & Fischer, 2018), such as the direction of inducer objects or their relative size, as well as the available number range. We conclude that a hybrid account is more favorable in the given context: we found evidence for both the extended mental-number-line account and the rule-based account for the cognitive representation of negative numbers. Specifically, we found evidence for the holistic processing of negative numbers in the context of directional inducers. In contrast, in the context of size inducers, we found tentative evidence for disturbed holistic processing or stronger rule-based processing, as explained by the SPeSiCC model. Further research is needed to investigate the associations of negative numbers with space and size with different stimuli sets and in varying dimensions, including vertical and sagittal planes.

Footnotes

1. Similarly, spatial associations between left space and odd numbers and between right space and even numbers also extend across both positive and negative number ranges. This so-called linguistic markedness effect was found for positive (Nuerk, Iversen, & Willmes, 2004) and negative numbers (Fischer & Rottmann, 2005). It is also easier to compare two numbers in a pair of either larger or smaller numbers. This effect is called the semantic congruity effect, and it appears when positive and negative numbers are not mixed. It also was demonstrated for both positive (Banks, Fujii, & Kayra-Stuart, 1976) and negative numbers (Ganor-Stern, Pinhas, Kallai, & Tzelgov, 2010).

2. Note that regardless of the nature of the stimuli, i.e., simple pictures in the context of numbers, this was not a developmental study: On average, participants in that study were 22.5 years old (range: 19–27).

3. We refrained from using circles as inducers because their shape might have instantiated the critical number concept of zero.

4. We inspected the data visually to identify the lowest and highest thresholds. Such thresholds can clearly be seen on a histogram, especially the lower threshold. Another source of our decision was information from previous studies: the average reaction time in various number processing tasks is around 600 ms (see Wood et al., 2008, Table 1). The average reaction time for negative numbers might be somewhat longer, either due to additional processing steps (rule-based account) or merely due to the lower frequency of negative numbers. So, we decided to set the upper threshold at 1,500 ms.

5. In our analyses, we aggregated data across lab-based and online experiments because of the limited sample size of the lab-based versions of the experiments. In both the lab-based

and the online-setting, the experiments were identical. Nonetheless, future studies might research different outcomes of lab-based versus online-experiments. For our research, this is not applicable due to the highly varying sample sizes of the lab-based and online-experiments.

6. We aggregated data across number range. Nonetheless, also when calculated for the large and small number range separately, the effect reached significance: p = .004 for the small negative number range and p = 002 for the large negative number range.

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Statement of Ethics

Hereby we confirm that the research has been carried out in accordance with relevant ethical principles and standards. Participants gave their informed consent at the start of the experiment, in accordance with the principles specified in the Declaration of Helsinki.

Statement of Originality

We confirm that the submitted work has not been previously published, nor is it under simultaneous consideration by another journal.

Funding/Financial Support

We agree to the following statement: "The authors have no funding to report."

Other Support/Acknowledgement[1]

We agree to the following statement: "The authors have no support to report."

Competing Interests[1]

We agree to the following statement: "The authors have declared that no competing interests exist."