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How Does Language Modulate the Association Between Number and Space? A Registered Report of a Cross-Cultural Study of the Spatial–Numerical Association of Response Codes Effect

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Past investigations into the connection between space and numbers have revealed its potential vulnerability to external influences such as cultural factors, including language. This study aims to examine whether language moderates the association between space and number in the spatial–numerical association of response codes (SNARC) effect, which is demonstrated in an interaction between number magnitude and response side. The SNARC effect has been observed across various stimuli. However, research on the influence of linguistic factors, such as reading direction, on the SNARC effect has yielded contradictory findings. We systematically examined the moderating effect of language on the SNARC effect in a cross-cultural design. A group of British English speakers and a group of Iranian Farsi speakers performed four SNARC tasks including both explicit (magnitude classification) and implicit (parity judgment) processing of number magnitude in two modalities of visual and auditory presentations. To the best of our knowledge, this is the first systematic investigation of language, magnitude processing, and sensory modalities altogether. While our registered analyses found no group differences in SNARC tasks, nonregistered analyses using a Bayesian ex-Gaussian framework revealed novel findings: a stronger SNARC effect in slower responses and auditory tasks. These findings challenge the idea of a substantial language role in shaping the SNARC effect but also indicate large uncertainty regarding the exact nature of language-induced effects, highlighting the need for further investigations of spatial–numerical interactions that may be differently influenced by linguistic and cultural factors.

Public Significance Statement

This registered report examines the spatial–numerical association of response codes effect, which demonstrates the links between number processing and spatial representations. By studying English and Farsi speakers using implicit and explicit number processing tasks in visual and auditory modalities, we aimed to uncover how cultural and linguistic contexts shape our cognitive mapping of numbers to space. While we found no significant language group differences, we observed a stronger spatial–numerical association of response codes effect in slower responses and auditory tasks. Our findings suggest that language's impact on spatial–numerical associations may be more subtle than previously thought. Our research advances understanding of how language, mental representations, and sensory input interact in shaping number–space associations. It also highlights the need to investigate various spatial–numerical phenomena across different linguistic contexts, potentially informing educational approaches in multicultural settings.

Keywords: numerical cognition, spatial–numerical association, spatial–numerical association of response codes, language, cross-cultural

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The associations between space and numbers have been the subject of much interest in the field of cognitive psychology due to the manifold relationships within the processing and learning of both concepts. The neurocognitive mechanisms underlying the space–number associations (SNAs) have been the subject of numerous studies (Farshad et al., 2024; Hawes et al., 2019), as their developmental basis (Bulf et al., 2016; McCrink & Opfer, 2014). However, evidence suggests that these associations may be fragile (Cipora et al., 2015; Cipora & Nuerk, 2013) and susceptible to modulation by external factors such as culture (Toomarian & Hubbard, 2018). A potential external influence on numerical cognition is language influence (Dowker & Nuerk, 2016), which has been shown to affect early numerical developments (Silver & Libertus, 2022). In this registered report, we examine whether language moderates the association between space and number in one of the most studied effects of space–numbers associations, the spatial–numerical association of response codes (SNARC) effect. This investigation provides a deeper understanding of cultural influences on shaping the cognitive skills such as spatial and numerical cognition.

The SNARC effect highlights the connection between numerical magnitude and the side of response, where responses to smaller numbers are quicker on the left hand and larger numbers on the right hand (Cipora, Soltanlou, et al., 2019; Dehaene et al., 1993). This effect, observed also in different stimuli like dice patterns and finger-signed numbers (Chinello et al., 2012; Nuerk et al., 2004), is seen as evidence of an embodied stimulus–response compatibility effect, meaning that our cognitive processes are grounded in our physical interaction with the environment (Fischer & Brugger, 2011; Fischer & Shaki, 2018). The embodied nature of the SNARC effect is illustrated through the mental number line (MNL) theory (Dehaene et al., 1993), a theoretical construct suggesting numbers and other ordinal sequences like letters and days of the week are mentally organized in the way they are typically written in Western cultures, that is, with smaller values on the left and larger values on the right (Gevers et al., 2003, 2004). Various embodied factors like finger counting habits have been examined to influence the SNARC effect. For instance, Fischer (2008) found that the SNARC effect is weaker among right-hand starters compared to left-hand starters due to their finger counting habits associating smaller numbers with their right hand and larger numbers with their left (see also Sabaghypour et al., 2023; cf. Hohol et al., 2022). As finger counting habits are culturally influenced (Lindemann et al., 2011), Fischer's (2008) findings illustrate a cultural linkage to the SNARC effect.

The findings about the influences of linguistic factors, such as reading and writing direction, on the SNARC effect are inconsistent. One group of studies has shown a significant effect of reading and writing direction on the direction and size of the SNARC effect. A study among Chinese readers found that when the stimuli were Arabic numerals, participants exhibited a typical left-to-right SNARC effect, but when the stimuli were Chinese number words, a vertical SNARC effect was observed, which is consistent with the Chinese top-to-bottom writing system (Hung et al., 2008; cf. Kopiske et al., 2016). Another line of research explored the influence of language priming on the SNARC effect in Russian–Hebrew bilinguals (Fischer et al., 2009; Shaki & Fischer, 2008). These languages are of particular interest because Russian is written left to right, while Hebrew is written right to left. The results showed a typical SNARC effect after being primed with Russian text and a significantly reduced SNARC effect after being primed with Hebrew text (see also Fischer et al., 2010). These findings suggest that the SNARC effect aligns with other cognitive effects that demonstrate the influence of the writing system on spatial–numerical associations (Cipora, Schroeder, & Nuerk, 2018; Fischer & Shaki, 2014; Göbel et al., 2011; Hawes & Ansari, 2020; McCrink et al., 2014). This is consistent with the idea that language serves as a scaffold for the development and organization of numerical and spatial representations in the brain (Dehaene, 2011).

A second group of literature found marginal to no effect of language on spatial–numerical associations. For example, it was initially predicted that languages written from right to left, such as Hebrew, Farsi, and Arabic, would exhibit a "reversed SNARC" effect, with faster responses to small magnitudes with the right hand and larger numbers with the left hand. However, evidence for this reverse effect has been mixed. Studies reported the reversed SNARC (Shaki et al., 2009; Zebian, 2005), or a null SNARC effect (Dehaene et al., 1993; Shaki & Fischer, 2012), in right-to-left reading populations, while some studies found a typical SNARC effect (see supplementary in Cipora, Soltanlou, et al., 2019; Zohar-Shai et al., 2017). A null SNARC effect has also been reported in Turkish, a left-to-right reading language (Bulut et al., 2023). Similarly, Japanese speakers, who read and write from top to bottom and would expect to have a top–down SNARC effect, showed a rather bottom–up SNARC effect with smaller numbers associated with the bottom of the line and larger numbers with the top of the line (Ito & Hatta, 2004). These inconsistencies, likely influenced by factors such as mono- or bilingualism of the subjects, design, and experimental manipulation, raise the question about the role of cultural and linguistic factors on the SNARC effect (Pitt & Casasanto, 2020).

Our study aims to address these challenges by adopting a robust mixed-design approach that manipulates modality and task type across two languages with monolingual participants. Methodological disparities in the existing literature, especially those associated with variations in tasks such as the parity judgment and magnitude classification, which are known to differ in their demands on numerical processing (Shaki & Petrusic, 2005; Tzelgov et al., 2009), are a key focus of this research. The parity judgment task, which involves identifying "odd numbers" with the left hand and "even numbers" with the right hand in alternating blocks, does not require explicit processing of numerical magnitude, whereas the magnitude classification task, which involves responding with the left hand to numbers "smaller" or "larger" than a reference such as five depending on the block, demands explicit processing of numerical magnitudes (see also "indirect" and "direct" tasks in Prpic et al., 2020). Due to these different underlying cognitive processes of the tasks (Cipora et al., 2020; Fias et al., 2011; van Dijck et al., 2014), the choice of either task may significantly impact the detection of language on the SNARC effect and the cross-literature comparisons. This is exemplified by SNARC research among Hebrew speakers (see in Chinese in Kopiske et al., 2016), where Fischer and Shaki (2016) observed the SNARC effect using the magnitude classification task, while Zohar-Shai et al. (2017) did not find the SNARC effect using the parity task, but only when using a multisession design and specific mappings. These findings suggest that cultural and linguistic influences might be more pronounced in the explicit processing of number magnitude (i.e., magnitude classification) than in the implicit processing of number magnitude (i.e., parity judgment). To better understand the impact of language on the SNARC effect, the present study employs both implicit and explicit tasks in Farsi and English speakers.

In addition to the level of processing required by the task, the modality of the task (e.g., visual or auditory presentation of numbers) may influence the SNARC effect when examining the role of language. Although the SNARC effect has primarily been studied in the visual modality, it has also been observed in the auditory modality (Hesse et al., 2016; Nuerk et al., 2005; Wood et al., 2006). Nevertheless, only a few studies have examined the SNARC effect in different modalities and languages (e.g., Fischer et al., 2009; Pitt & Casasanto, 2020). Fischer et al. (2009) explored this relationship in Russian–Hebrew bilinguals and discovered the SNARC effect for Russian number words when presented visually and auditorily, but only auditorily for Hebrew number words. These findings imply that cultural and linguistic influences may be more pronounced in the linguistically dependent processing of numbers (i.e., auditory). Therefore, modality consideration is critical to our research as the use of visual stimuli inevitably triggers visuospatial scanning and subsequent directionality, both of which are key determinants of the SNARC effect as a numerical–spatial phenomenon. In contrast, auditory modality-based number processing primarily relies on language comprehension processes, potentially presenting more pronounced language-related differences. Therefore, modality comparison could substantially enhance our understanding of language's impact on the SNARC effect.

The current work is of particular importance due to the recent growing interest in understanding the mechanism of the SNARC effect (Basso Moro et al., 2018; Cipora et al., 2020; Zhang et al., 2022) and inspecting its relations to other mathematical abilities (Cipora, Soltanlou, et al., 2019; Cipora & Nuerk, 2013; He et al., 2021; Kramer et al., 2018). As described above, the SNARC effect seems to be more robust in Western cultures than in some non-Western cultures, leading to the hypothesis that cultural learning contexts may play a role in the development of spatial–numerical associations (Silver & Libertus, 2022). By comparing Western and non-Western populations using parity judgment and magnitude classification tasks in two modalities, we can gain a deeper understanding of the role of cultural learning context (i.e., language) in modulating spatial–numerical associations. This study aims to expand the knowledge of how cognitive skills are impacted by language by expanding the understanding of the interplay of cognitive and cultural factors in shaping spatial–numerical associations. Beyond the theoretical importance of these insights, they could also have important implications for educational achievement and other areas, as they could progress existing knowledge to optimize learning and performance in different cultural contexts.

In the present study, we focus on the comparison between English and Farsi speakers, as these languages offer a unique opportunity to investigate the influence of language on the SNARC effect. While English is written from left to right for both letters and numbers, Farsi presents an interesting case: It is written from right to left for letters and sentences, but crucially, it follows a left-to-right direction for numbers, just like English (Rashidi-Ranjbar et al., 2014). This distinctive feature of Farsi allows us to explore the potential impact of language on the SNARC effect in a more nuanced manner. We hypothesize that the compatibility of number writing direction between English and Farsi may lead to similar SNARC effects in the visual modality. However, in the auditory modality, where linguistic processing is more involved, the mismatch between the directionality of letter and number writing in Farsi may accentuate the influence of language on the SNARC effect, potentially leading to more pronounced differences between English and Farsi speakers. Similarly, we expected that a more explicit processing of numerical information, such as in magnitude comparison tasks, will further accentuate these language-induced differences in the SNARC effect.

The primary objective of the present study is to investigate the potential moderating role of language in the relationship between numbers and space. In particular, we examine if the SNARC effect, which quantifies the association between numerical processing and spatial responses, is differentially influenced by language in English and Farsi native speakers. Our study identifies five hypotheses (Hypotheses 1–5):

- Hypothesis 1 posits that the SNARC effect will be more pronounced in explicit processing of numerical magnitudes (magnitude classification task) compared to implicit processing (parity judgment task).
- Hypothesis 2 proposes that the SNARC effect will be more salient in the visual modality than in the auditory modality, thereby replicating previous studies (Shaki et al., 2009; Wood et al., 2006).
- Hypothesis 3 follows the hypothesis stating that while the auditory modality inherently involves language comprehension, the visual modality does not. Thus, we would expect a language effect between the modalities in the SNARC effect such that the difference between the languages will be more pronounced in the auditory modality.
- Hypothesis 4 is based on the observations of different outcomes in the studies conducted by Fischer and Shaki (2016) and Zohar-Shai et al. (2017), which potentially stem from methodological discrepancies in task types. These results suggest that the impact of language on the SNARC effect may depend on the explicitness of the task, with explicit tasks being more sensitive to language-induced differences. We therefore hypothesize that language will have a more pronounced effect on the SNARC effect in the explicit magnitude classification task compared to the implicit parity judgment task.
- Hypothesis 5, our central hypothesis, postulates that the influence of modality and task requirements together will moderate the influence of language. This is because both factors potentially tap language processing. Therefore, we hypothesize that the most substantial differences between English and Farsi speakers will emerge in explicit auditory processing, whereas the smallest differences will be evident in implicit visual processing. Implicit auditory processing and explicit visual processing are anticipated to lie between these two extremes.

Material and Method

Sample Size and Power

G*Power 3.1 (Faul et al., 2007) was used for power estimates of our central Hypothesis 5, which tests a five-way interaction. Specifically, this interaction involves the between-subject variable of native language (two levels: English, Farsi) and the four within-subject variables: responding hand (two levels: right, left), task (two levels: parity judgment task, magnitude classification task), modality (two levels: auditory, visual), and magnitude (four levels: 1–2, 3–4, 6–7, 8–9). A total sample size of 100 is sufficient to detect a medium-size effect of $f = 0.25$ ($\eta_p^2 = .06$) with $\alpha = .05$ and a power of .95 corrected for nonsphericity ($\varepsilon = 0.033$). The script from the G*Power 3.1 is available on the Open Science Framework (OSF) page of the project at https://osf.io/2xg7f/.

Participants

We recruited adults in the United Kingdom and Iran for this cross-cultural study. Recruitment criteria included participants aged 18–45, right-handed, with normal or corrected-to-normal vision, and having no diagnosis of hearing loss, attentional disorders, or learning difficulties. Various demographic information was collected such as their mother tongue, other languages they had learned or knew, and, most importantly, their primary numerical system (i.e., Arabic or Eastern Arabic numerals). We did not include participants who reported a language of schooling or numerical system that did not correspond to the common system in their country (e.g., English and Arabic numerals in the United Kingdom, and Farsi and Eastern Arabic numerals in Iran). The participants received course credit or monetary compensation for their participation. All procedures were in line with the latest Helsinki declaration of the studies in human populations. Ethics approval was received from the University of Surrey in the United Kingdom and the University of Tabriz in Iran.

The recruitment process was iterative where instances of participant exclusion initiated further recruitment efforts of replacement to ensure that we maintained our target sample size of 100 individuals. The registered exclusion criteria were based on participant performance in the computerized tasks and are described in more detail in the "Data Preparation" section. Overall, 133 participants (69 Iranian participants and 64 British participants) were tested. Twenty-one participants were excluded due to a low accuracy rate (<80%) in one of the computerized tasks. No additional participants were excluded due to other performance criteria. However, upon inspecting the demographic data, we found that the Iranian group included significantly more graduate students compared to the British group. To ensure similar education levels and maintain gender balance between the samples, we excluded the eight last-recruited Iranian female graduate students. Notably, even when including these eight Iranian female graduate students, the results remained largely unchanged, with no significant differences in the main findings or conclusions of the study.

The final sample included 105 participants: 55 Iranian (32 females, 23 males) and 50 British (31 females, 19 males), matched for age, mean age in the Iranian Farsi speaker group = 22.67 (SD = 2.76), mean age in the British English speakers group = 22.35 (SD = 3.92), $t(77.69) = 0.53$, $p = .59$, Cohen's $d = 0.11$, and with no difference in gender representation, $\chi^2(1) < 0.01$, $p > .99$. Participants reported their gender by selecting "female," "male," "other," or "prefer not to mention" options during demographic data collection.

Computerized Tasks

The four main tasks of the study were computerized and built using OpenSesame software (Mathôt et al., 2012). The visual stimuli were presented in the size of 100 pixels, colored black, and presented in the center of the screen with a gray background.

The numerals differed based on the mother tongue of the participants. For English speakers, the Arabic numerals 1, 2, 3, 4, 6, 7, 8, and 9 were shown, while for Farsi speakers, the Farsi or Eastern Arabic numerals ۱, ۲, ۳, ۴, ۶, ۷, ۸, and ۹ were shown. A female voice was recorded for the auditory stimuli uttered at normal speed and be played via headphones for the auditory tasks. The computerized tasks are available on the OSF page of the project at https://osf.io/2xg7f/?view_only=4ca1955e8c6143e3a3d739fccb21e05d.

The participants engaged in four tasks: (a) visual parity task, (b) visual magnitude classification task, (c) auditory parity task, and (d) auditory magnitude classification task. Parity tasks require the participants to determine whether a number is odd or even, while magnitude classification tasks require determining whether a number is smaller or larger than five. Each task included four blocks with interchanged instructions for responses to the left or the right depending on the task (e.g., the right-hand response to an odd number in one block and then the left-hand response to an odd number in the next block). The interchange block instructions were necessary to calculate the SNARC effect. The starting modality and the order of task types have been randomized across participants. The tasks were grouped within each modality so that the participants switched from one modality to the other only once during the experiment and only after completing two tasks. Each task started with written instruction in the mother tongue of the participant concerning the task and the mapping of the response hands and the numbers. Each block consisted of 240 trials, which are 30 repetitions for each number and preceded by 16 trials of a practice block. With two blocks for each mapping, each task was composed of a total of 480 trials. The numbers were shown in a pseudorandomized order in a way that the eight numbers are shuffled and presented once and then shuffled and presented for the second time until 30 repetitions.

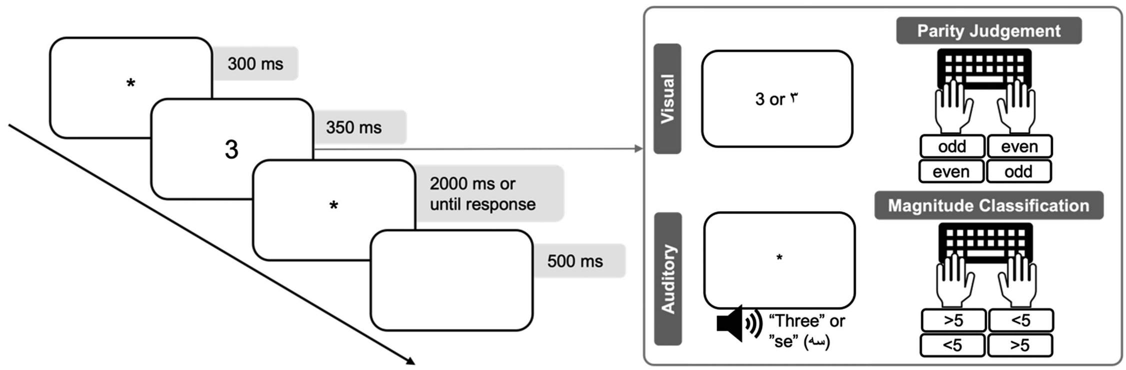
For the trial timeline, see Figure 1. Each trial started with a fixation point, presented for 300 ms. Following the fixation point, a number was presented for 350 ms or played via headphones. For the auditory task, the fixation point stayed on the screen. The participant was asked to respond as quickly and as accurately as possible according to the instructions with the Q key to left responses and P to right responses on standard keyboards. The participants had 2,000 ms time to respond; otherwise, the interstimulus interval appeared. After a blank interstimulus interval of 500 ms, the next trial started. No feedback has been given.

Noncomputerized Tasks

The participants answered several demographic questions and two questionnaires: the Abbreviated Math Anxiety Scale (Hopko et al., 2003) and the Math4Speed—an arithmetic fluency test (Loenneker et al., 2022). The Abbreviated Math Anxiety Scale is a self-report measure designed to assess math anxiety and consists of 10 items rated on a 5-point Likert scale, with higher scores indicating greater math anxiety. The scale has been shown to possess good reliability and validity and has been widely used in research and clinical settings in both English and Farsi (Vahedi & Farrokhi, 2011). The Math4Speed test measures arithmetic fluency. This paper-and-pencil speeded arithmetic test consists of four subtests that evaluate performance in the four basic arithmetic operations. Each subtest includes 50 items, with half being easy and the other half complex, and has a time limit of 2 min for each operation.

Importantly, as part of the demographic questioning, we asked for the participant's date of birth, gender, handedness, mother tongue, any other languages spoken, the language used in school, their

Figure 1
Trial's Timeline (Left) and Visualization of the Computerized Tasks (Right) With Numerosity 3 as an Example



Note. There were four computerized tasks: two visual tasks and two auditory tasks. In each modality, there was a parity task where participants were asked to determine whether the number presented is odd or even and a magnitude classification task where participants were asked to determine whether the number presented was smaller or larger than five. The keys for each decision alternate between left and right hands between blocks. The numerical system differed based on the participants' mother tongue. The asterisk (*) represents a fixation point that appeared at multiple stages throughout the trial to help participants maintain focus.

current highest level of education, the numerical system used in school, and whether they have any neurological or learning disorders. This demographic information allowed us to cross-compare the participants' characteristics and possibly control for potential confounding variables and explore any potential relationships. The noncomputerized tasks took a total of approximately 20 min to complete.

Procedure

After signing an informed consent form, the participants sat in front of a computer in a dimly lit room and did an auditory check. That allowed verifying, for both the participant and the experimenter, that the volume levels are sufficient to hear the stimuli clearly. Each participant completed all four tasks (two parity tasks and two magnitude classification tasks) grouped by modality, with a short self-paced break in between. In addition, each task consisted of two response mappings, with the left hand responding to odd or smaller than 5, and the right to even or bigger than 5, and vice versa. The starting modality and the starting task have been counterbalanced across participants. After completing the computerized tasks, the participants answered the math anxiety questionnaire and the math fluency task. The whole experiment lasted approximately 75 min.

Transparency and Openness

Our study is a registered report, which, in line with the transparency and openness guidelines (Nosek et al., 2015), inherently embodies the principles of registered reports through its rigorous two-stage peer-review process. Additionally, the sample size determination, any data exclusions, manipulations, and all measures are stated above. We share all anonymized data, the code used for analysis, and research materials on our OSF project at https://osf.io/2xg7f/?view_only=4ca1955e8c6143e3a3d739fccb21e05d. The analysis was conducted using the open-source program R, ensuring the reproducibility of our findings. By providing these resources, we aim to contribute to the ongoing efforts in the scientific community to foster transparency, reproducibility, and integrity in research.

Data Preparation

The exclusion criteria for this study are based on those of Cipora, Soltanlou, et al. (2019); analyses included only correct responses as we expected very high accuracy rates throughout the tasks that would reach a ceiling effect across the conditions (Cipora et al., 2016). Thus, participants who had less than 80% accuracy rates in one of the tasks have been replaced by a new participant. We trimmed response times (RTs) to be between 150 and 1,500 ms. Then, RTs that fell outside of ±2.5 median absolute deviations (MAD) from the median (Leys et al., 2013) were excluded. Overall, 8.3% of the trials were excluded. Our registered criteria determined that participants for whom more than 30% of the RT data has been discarded during the filtering procedure will be excluded from the analysis; however, no participant has been excluded for this reason. All anonymous data and the fully detailed data processing are available on the OSF page of the project at https://osf.io/2xg7f/?view_only=4ca1955e8c6143e3a3d739fccb21e05d.

Data Modeling

Our analytical approach is based on the work of Tzelgov et al. (2013), which involves analyzing and quantifying the SNARC through an analysis of variance (ANOVA) model framework (see also Pinhas et al., 2012). In this approach, an ANOVA model accounts for the magnitude of the participant's response (grouped into four categories) and the hand used to respond. The SNARC effect is tested as the two-way interaction between the hand and the linear contrast of magnitude. Consequently, to examine the SNARC effect between modalities, we investigated the three-way interaction of hand and the linear contrast of magnitude—representing the SNARC effect—and the modalities factor.

Therefore, the dependent variable of the model is the RTs, and the effects of the ANOVA include language (English, Farsi), task (parity judgment, magnitude classification), responding hand (left, right), modality (visual, auditory), and magnitude (1–2, 3–4, 6–7, 8–9).

The model fit using R software (R Core Team, 2022) with the modeling packages afex (Singmann et al., 2022), and the following contrasts were carried out using emmenas (Lenth, 2022). The analysis codes are available on the OSF page of the project (https://osf.io/2xg7f/?view_only=4ca1955e8c6143e3a3d739fccb21e05d).

Registered Analyses

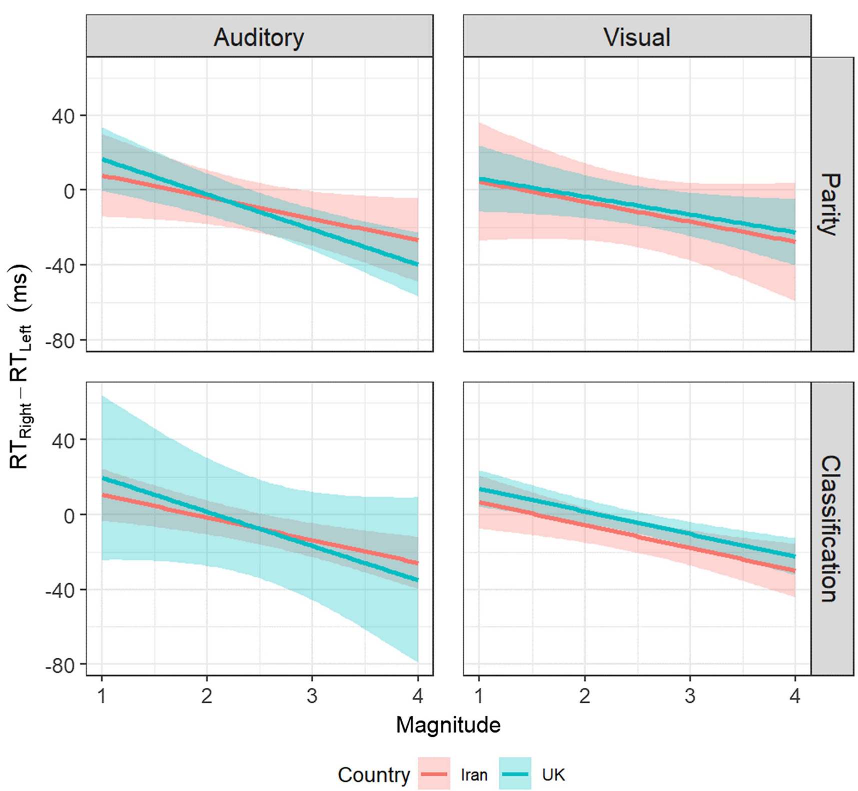
Hypothesis Testing and Results

Before inspecting the effects of the five-way ANOVA, we conducted full assumption checks. There was no evidence for different variances across groups, but there were violations of the sphericity and "normality of residuals" assumptions. Therefore, we used the Greenhouse–Geisser sphericity correction and we log-transformed the data to relax the normality violation. The full omnibus ANOVA can be found in the code book on the OSF page of the project. The SNARC effect in our study is statistically conceptualized as an interaction between the responding hands throughout the tasks and the linear contrast of the magnitude of the stimuli (Tzelgov et al., 2013), which indeed was found significant across groups and tasks, $t(103) = -7.67$, $p < .001$, Cohen's $d = -0.75$. The overall SNARC effect between groups was not found significant, $t(103) = 0.77$, $p = .440$, Cohen's $d = 0.07$, and both groups showed the effect going in the same direction—United Kingdom: $t(103) = -4.99$, $p < .001$, Cohen's $d = -0.49$; Iran: $t(103) = -5.83$, $p < .001$, Cohen's $d = -0.57$. The hypotheses are analyzed as planned follow-up contrasts of the main omnibus ANOVA model (Figure 2 presents the SNARC effects for each country in each of the task):

- Hypothesis 1 concerns the difference between task types. We expected a significant three-way interaction of hands, linear contrast of magnitude, and task type. We hypothesized that the SNARC effect will be more pronounced under the explicit condition, the magnitude classification task. Thus, we anticipated the three-way interaction will be driven by the linear contrast of magnitude between the hands and the task type, such that it will be significantly steeper for the magnitude classification task compared to the parity judgment task.

This contrast was not found to be significant, $t(103) = 1.10$, $p = .269$, Cohen's $d = 0.10$. Namely, there was no

Figure 2
SNARC Effects per Task for Each Country



Note. The y-axis represents the reaction time difference between the right and left hand (right hand reaction time − left hand reaction time). The x-axis represents grouped magnitudes: Magnitude 1 includes Numerosities 1 and 2, Magnitude 2 includes Numerosities 3 and 4, Magnitude 3 includes Numerosities 6 and 7, and Magnitude 4 includes Numerosities 8 and 9. Positive values on the y-axis indicate faster right-hand responses, while negative values indicate faster left-hand responses. The SNARC effect is demonstrated by a negative slope, with faster left-hand responses for smaller magnitudes and faster right-hand responses for larger magnitudes. SNARC = spatial–numerical association of response code; RT = response time. See the online article for the color version of this figure.

significant difference between the SNARC effects in the magnitude classification task and the parity judgment task. However, both SNARC effects were found significant—parity judgment task: $t(103) = -7.93$, $p < .001$, Cohen's $d = -0.78$; magnitude classification task: $t(103) = -5.41$, $p < .001$, Cohen's $d = -0.53$.

- Hypothesis 2 concerns the difference between modalities. We expect a significant three-way interaction of hands, linear contrast of magnitude, and modality. We hypothesized that the SNARC effect will be more pronounced under the visual stimuli condition. Thus, we anticipate the three-way interaction will be driven by the linear contrast of magnitude between the hands and the modalities, such that it will be steeper for the visual stimuli condition compared to the auditory stimuli condition.

  This contrast was not significant, $t(103) = 0.62$, $p = .535$, Cohen's $d = 0.06$. That is, there was no significant difference between the auditory SNARC effect and the visual SNARC effect. However, both SNARC effects were significant—auditory task: $t(103) = -5.13$, $p < .001$, Cohen's $d = -0.50$; visual task: $t(103) = -6.54$, $p < .001$, Cohen's $d = -0.64$.

- Hypothesis 3 concerns the difference between modalities and language. We expected a significant four-way interaction of hands, linear contrast of magnitude, modality, and language. We hypothesized that the language influence for the SNARC effect will be more pronounced under the auditory stimuli condition. Thus, we anticipate the four-way interaction will be driven by the linear contrast of magnitude between the hands, the modalities, and the language, such that there will be a bigger difference between the languages in the auditory stimuli condition than in the visual stimuli condition.

  This contrast was not significant, $t(103) = 1.14$, $p = .255$, Cohen's $d = 0.11$. Namely, the contrast between the SNARC effects of the auditory and the visual tasks among the Farsi speakers, $t(103) = 1.27$, $p = .203$, Cohen's $d = 0.12$, was not significantly different compared to the same contrast among the English speakers, $t(103) = -0.35$, $p = .720$, Cohen's $d = -0.03$.

- Hypothesis 4 concerns the difference between the task type and language. We expected a significant four-way interaction of hands, linear contrast of magnitude, task type, and language. We hypothesized that the language influence for the SNARC effect will be more pronounced under the explicit task condition, the magnitude classification task. Thus, we anticipate the four-way interaction will be driven by the linear contrast of magnitude between the hands, the task type, and the language, such that there will be a bigger difference between the languages in the magnitude classification task condition than in the parity judgment condition.

  This contrast was not found to be significant, $t(103) = -0.09$, $p = .926$, Cohen's $d < 0.01$. That is, the contrast between the SNARC effects of the parity judgment task and the magnitude classification task among the Farsi speakers, $t(103) = 0.73$, $p = .463$, Cohen's $d = 0.07$, was not significantly different compared to the same contrast among the English speakers, $t(103) = 0.83$, $p = .408$, Cohen's $d = 0.08$.

- Hypothesis 5, our central hypothesis, concerns group differences, referring to a five-way interaction of hands, linear contrast of magnitude, task type, modality, and language. As described earlier, the interaction between hands and the linear contrast of magnitude will allow testing whether the SNARC effect will differ between other conditions. We hypothesize that the effect of language on the SNARC effect will be most pronounced in the auditory tasks due to the involvement of language comprehension in this modality and even stronger in the explicit task. Concurrently, we further hypothesize that the effect of language will be least involved in the visual implicit task. We predict that the auditory parity judgment task and visual magnitude classification task will fall between these two extremes. To this end, the variables of modality and task type were coded to calculate a polynomial contrast that will show linear or quadratic differences between the levels of the interaction of modality and task type, between languages.

  Results indicated that neither the linear nor the quadratic contrasts were significant—linear: $t(103) = -0.86$, $p = .387$, Cohen's $d = -0.08$; quadratic: $t(103) = -0.14$, $p = .887$, Cohen's $d = -0.01$). This null result pertained to every order of the auditory parity and visual magnitude classification tasks. As such, no significant difference was found between countries when inspecting the four tasks as a spectrum.

Additional Analyses

In addition to the main analyses and hypotheses above, we explored the impact of additional variables when incorporated into the previously described model:

- Previous research has demonstrated that priming language before a task measuring the SNARC effect can significantly influence its outcome (Fischer et al., 2009). As a result, it is plausible that participants who complete the auditory tasks first, and thus actively recruit language comprehension in the context of the task, will experience a carryover effect of language that impacts their performance in the visual tasks. To explore this possibility, we incorporated the order factor as a variable in an additional model.

  The results from this model did not support our hypothesis, as there was no significant difference between the SNARC effects as a function of the first modality tested, $t(101) = 0.93$, $p = .350$, Cohen's $d = 0.09$. Moreover, controlling for this variable did not alter the conclusions in the main analyses described above.

- Research has shown gender differences in the SNARC effect, with men demonstrating steeper slopes in the parity judgment task (Bull et al., 2013). However, the consistency of this finding remains uncertain (Viarouge et al., 2014). To further explore this issue, we attempted to recruit a balanced number of males and females for each group and consider gender as a factor in an additional model. We did not have a defined hypothesis for this aspect of the investigation.

The results indicate that females and males exhibited SNARC effects—male: $t(98) = -5.97$, $p < .001$, Cohen's $d = -0.60$; female: $t(98) = -5.36$, $p < .001$, Cohen's $d = -0.54$—with no significant difference between them, $t(98) = 1.44$, $p = .151$, Cohen's $d = 0.14$. Controlling for this variable did not change the conclusions regarding the hypotheses delineated in the main analyses described above.

- The relationship between math anxiety and math fluency has been previously explored (e.g., Cipora et al., 2016; Núñez-Peña et al., 2021). However, we are not aware of any studies that have administered both types of tasks (parity judgment and magnitude classification) across two modalities (visual and auditory) when examining math anxiety and math fluency. In these exploratory analyses, we introduced the results of math anxiety and math fluency questionnaires as covariates to the SNARC effects in two separate additional models.

  Neither math anxiety nor math fluency scores significantly interacted with SNARC effects—math anxiety: $t(95) = -.022$, $p = .981$, Cohen's $d = -0.001$; math fluency: $t(95) = -0.95$, $p = .339$, Cohen's $d = -0.09$. These measures did not interact with either of the SNARC conditions, and controlling for these measures did not change the conclusions regarding the hypotheses delineated in the main analyses described above.

Nonregistered Analyses

Data Preparation and Bayesian Data Analysis

The following nonregistered analyses differ from the previous approach in two pivotal ways. First, we changed the exclusion criteria for RT trials from 2.5 MAD from the median to 3.29 MAD from the median. This change is in light of a recent study by Thériault et al. (2024), which advocated for more liberal criteria in RT exclusion. This alteration led to the inclusion of an additional 2.55% of trials, revising the rate of excluded trials to 5.7%. Second, we employed a Bayesian hierarchical linear model (BHLM) using the ex-Gaussian likelihood function.

These methodological changes, particularly the use of BHLM, offer several advantages over traditional approaches. Bayesian analysis provides a unique perspective on result interpretation, particularly for cases of null findings. Unlike traditional null hypothesis significance testing, it allows us to quantify the probability of an effect given the data, enabling more informed inferences about the presence, absence, and direction of effects (Kruschke, 2011). Additionally, the BHLM approach incorporates and extends the widespread method from Fias (1996) by simultaneously estimating individual- and group-level SNARC effect slopes. This balances individual differences with overall trends, allowing each participant's data to inform and be informed by the group results. Consequently, our approach provides more reliable estimates and offers a nuanced perspective on the variability and consistency of the SNARC effect across individuals in different conditions (Hoffman, 2015; Veenman et al., 2024).

Central to our BHLM approach is the use of the ex-Gaussian likelihood function, which is particularly well-suited for analyzing RT data (Faulkenberry, 2017; Matzke & Wagenmakers, 2009). The ex-Gaussian distribution captures both the central tendency and the skewness commonly observed in these data sets. The distribution effectively combines a Gaussian component (mu), which accounts for the bulk of the data, and an exponential component (tau), which models the tail representing the slower responses. These slower responses are crucial, especially when studying phenomena like the SNARC effect, where slower reaction times are known to reveal more pronounced effects (Cipora, Soltanlou, et al., 2019; Gevers et al., 2006a). Therefore, exploring the tau component of the ex-Gaussian distribution can offer deeper insights into how numerical cognition might influence spatial RTs.

To interpret the results of our Bayesian analysis, we rely on two key concepts that provide nuanced insights into the effects observed: the probability of direction (pd) and the region of practical equivalence (ROPE). The pd is the proportion of the posterior distribution that is above or below zero. It quantifies the certainty with which one can infer the direction of an effect (Makowski, Ben-Shachar, Chen, & Lüdecke, 2019; Makowski, Ben-Shachar, & Lüdecke, 2019). The pd can range from 50% to 100% and represents the certainty that an effect exists and its direction. The pd is highly correlated with p values (Makowski, Ben-Shachar, & Lüdecke, 2019), and as such, pd values of 97.5% and 99.95% could be respectively thought of as correlating with two-sided p values of .05 and .001. This relationship helps bridge the gap between Bayesian and frequentist approaches. However, it is important to note that while the pd establishes the existence and direction of an effect, it does not assess the effect's magnitude or practical significance, and to this purpose, the ROPE is used.

The ROPE is a range of values around zero that are considered practically equivalent to no effect (Kruschke, 2011, 2013, 2015). By calculating the proportion of the posterior distribution that falls within the ROPE, it is possible to determine the probability that the true effect is practically zero (Makowski, Ben-Shachar, Chen, & Lüdecke, 2019; Schwaferts & Augustin, 2020). In line with Cipora and Wood (2017), we considered SNARC effect differences of below ±2 ms as less than small and thus negligible. Notably, the mu and the tau components are both in ms scale and were analyzed separately for the same ROPE for each hypothesis. This approach ensures that our interpretations are consistent and grounded in established criteria for practical significance in the context of the SNARC effect.

We employed a BHLM using the brms package (Bürkner, 2017) to investigate the effects of modality, task type, responding hand, numerosity (entered as a continuous variable ranging from 1 to 9), and country on RTs. The model included both the main effects and interactions of these variables. Full specification of the model is presented in the Appendix, and the model, the code, and the data are provided in the OSF link: https://osf.io/2xg7f/.

The response variable, RT, was truncated at the upper response bound of 1.5 s. The fixed effects included the main effects and all interactions of modality, task type, response side, scaled numerosity, and country. Random effects were incorporated at the participant level in a maximal random effects structure (Barr et al., 2013). The random effects structure included all the within-subjects variables and their interaction, that is, random intercepts and slopes for the interaction of modality, task type, response side, and scaled numerosity.

Importantly, the model included a submodel for the tau parameter of the ex-Gaussian distribution. The fixed effects for tau were the same as those for the main model, and random effects were included at the participant level, with the same maximal random structure.

The model also included a separate submodel for the standard deviation of the Gaussian distribution (sigma), which was estimated with a random intercept varying across participants. This allowed for heterogeneous residual variances across participants.

To summarize, we employed a novel approach to analyze the SNARC effect by using a more liberal RT exclusion criterion and a BHLM with an ex-Gaussian likelihood function. The ex-Gaussian distribution, which combines a Gaussian component (mu) and an exponential component (tau), is particularly well-suited for capturing the central tendency and the skewness commonly observed in RT data. By separately modeling the mu and tau components, we aimed to gain deeper insights into how numerical cognition might influence spatial RTs, especially considering that slower responses are known to reveal more pronounced SNARC effects. To the best of our knowledge, this is the first study to rigorously investigate the tau component of the SNARC effect. We treated numerosity as a continuous variable and employed a Bayesian approach, which allows for a more intuitive and varied interpretation of null results compared to traditional null hypothesis significance testing.

By focusing on the posterior distribution and utilizing concepts such as the pd and ROPE, we aimed to quantify the probability of an effect given the data and assess the certainty of our inferences. This approach enables us to make more informed conclusions about the presence, absence, and direction of effects, particularly when dealing with null findings, offering a continuous perspective on the interpretation of results in the context of the SNARC effect and numerical cognition.

Hypothesis Testing and Results

Hypothesis 1

We hypothesized that the SNARC effect will be more pronounced under the explicit condition, the magnitude classification task, compared to the parity judgment task. See in Figure 3 the posterior distribution of the SNARC effects in the different conditions in the differences between them.

When inspecting the tasks separately, the pd for both the mu and the tau parameters was found to be higher than 99%, indicating strong evidence for the existence of the effect, but it is only for the tau parameter that the effect was found significant (see Figure 3; magnitude classification task: mu median slope = −2.85, 95% CI [−4.54, −1.06], pd = 99.9%, p-ROPE = 16.4%; tau median slope = −4.25, 95% CI [−6.10, −2.47], pd = 100%, p-ROPE = 0.7%; parity judgment task: mu median slope = −2.40, 95% CI [−3.74, −1.12], pd = 99.9%, p-ROPE = 27.5%; tau median slope = −4.36, 95% CI [−6.36, −2.33], pd = 100%, p-ROPE = 1.0%).

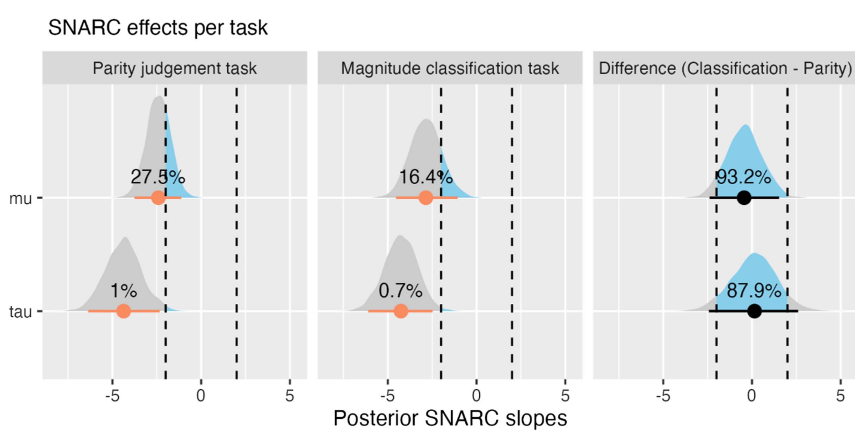
The results did not establish the existence of differences between the task types, and the posterior distribution remained uncertain regarding supporting the null hypothesis (mu median slope = −0.44, 95% CI [−2.39, 1.52], pd = 67.7%, p-ROPE = 93.1%; tau median slope = 0.14, 95% CI [−2.42, 2.60], pd = 54.7%, p-ROPE = 87.9%). While the high p-ROPE values suggest a lack of practical significance in the difference between tasks and support the null effect, the evidence is not definitive.

Hypothesis 2

We hypothesized that the SNARC effect would be more pronounced in the visual modality compared to the auditory

Figure 3

Posterior Distributions of SNARC Slopes for Mu and Tau Parameters in Parity Judgment and Magnitude Classification Tasks, and Their Difference



Note. Circles indicate the distribution medians; lines show 95% highest density intervals (HDI). Colors reflect the probability of direction: black (pd < 97.5%) and orange (negative, pd > 97.5%). Blue areas represent the part of the distribution within the ROPE (±2 ms slope), with percentages indicating p-ROPE values. Dashed lines mark the ROPE boundaries. Both tasks show negative SNARC effects, more pronounced for tau. The difference panel suggests uncertainty regarding the difference between tasks, with a considerably large proportion of the distribution falling within the ROPE. SNARC = spatial–numerical association of response code; pd = probability of direction; ROPE = region of practical equivalence. See the online article for the color version of this figure.

modality. See in Figure 4 the posterior distribution of the SNARC effects in the different conditions in the differences between them.

When inspecting the modalities separately, the pd for both the mu and tau parameters was found to be higher than 98%, indicating strong evidence for the existence of the SNARC effect in both modalities for both parameters. For the auditory modality, the mu parameter showed substantial uncertainty regarding the significance of the effect (median slope = −2.31, 95% HDI [−4.29, −0.295], pd = 98.7%, p-ROPE = 38.1%). The tau parameter revealed a more pronounced effect, providing very strong evidence against the null hypothesis (median slope = −6.65, 95% HDI [−9.37, −3.94], pd = 100%, p-ROPE = 0%). In the visual modality, the mu parameter provided strong evidence against the null hypothesis (median slope = −2.96, 95% HDI [−4.15, −1.71], pd = 100%, p-ROPE = 6.07%). The tau parameter showed large uncertainty regarding the null hypothesis compared to the mu parameter (median slope = −2.00, 95% HDI [−2.87, −1.16], pd = 100%, p-ROPE = 50%).

Interestingly, there is a dissociation between the mu and tau parameters in both modalities. In the visual modality, the SNARC effect is more pronounced in the mu parameter (central tendency of RTs) compared to the tau parameter (slower responses). Conversely, in the auditory modality, the SNARC effect is strongly pronounced in the tau parameter, while the mu parameter shows a less pronounced effect. This suggests that the SNARC effect manifests differently in the central tendency and the tail of the RT distributions depending on the modality.

When comparing the differences between modalities, the results for the mu parameter suggested uncertain evidence, yet inclined toward evidence for the null hypothesis of no practical difference between modalities (median difference in slopes = −0.65, 95% HDI [−2.98, 1.67], pd = 71.4%, p-ROPE = 86.2%). For the tau parameter, the results indicated a more pronounced SNARC effect in the auditory modality compared to the visual modality, providing strong evidence against the expected more pronounced SNARC effect in the visual modality (median difference in slopes = 4.64, 95% HDI [1.96, 7.48], pd = 99.9%, p-ROPE = 2.73%). This finding contradicts our hypothesis, providing strong evidence against the expected more pronounced SNARC effect in the visual modality.

While the high p-ROPE values for the mu parameter suggest a lack of practical significance in the difference between tasks and support the null effect, the evidence is not definitive. These results indicate a complex manifestation of the SNARC effect that varies across modalities and RT distributions. The pronounced SNARC effect in the auditory modality, particularly for the tau parameter, challenges the initial hypothesis and underscores the need for further research to fully understand these modality-specific effects and their implications.

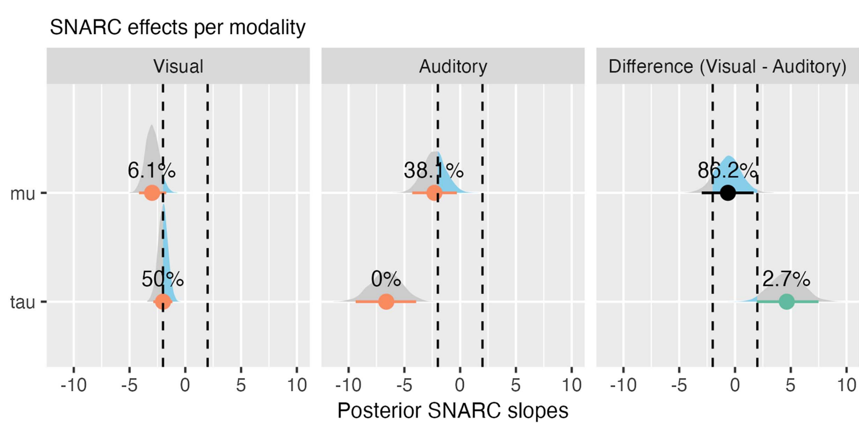
Hypothesis 3

We hypothesized that the language influence on the SNARC effect would be more pronounced under the auditory stimuli condition. See in Figure 5 the posterior distribution of the SNARC effects in the different conditions in the differences between them.

When inspecting the modalities and countries separately, the pd for both the mu and tau parameters was found to be higher than 97.5% in most cases, indicating strong evidence for the existence of the SNARC effect in both modalities and countries for both parameters, except for the mu parameter in the auditory modality for Iran (pd = 78.7%, p-ROPE = 76.2%) and the difference between

Figure 4

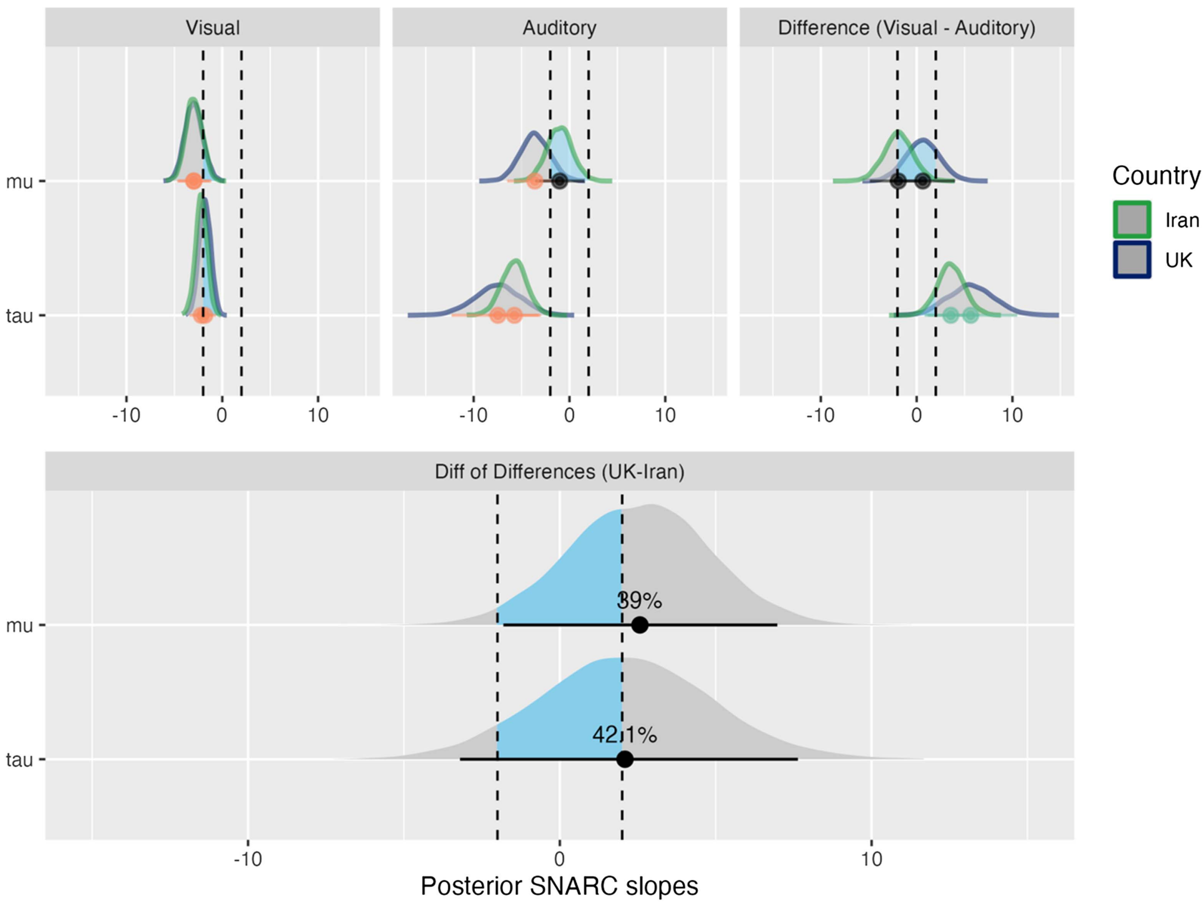
Posterior Distributions of SNARC Slopes for Mu and Tau Parameters in Visual and Auditory Modalities, and Their Difference



Note. Circles indicate the distribution medians; bottom lines show 95% highest density intervals (HDI). Bottom lines' colors reflect the probability of direction: black (pd < 97.5%), orange (negative, pd > 97.5%), and green (positive, pd > 97.5%). Blue areas represent the proportion within the ROPE (±2 ms slope), with percentages indicating p-ROPE values. Dashed lines mark the ROPE boundaries. Both modalities show negative SNARC effects, with the visual modality more pronounced for mu and auditory for tau. The difference panel suggests uncertainty for mu, but a stronger effect in auditory for tau, contrary to the initial hypothesis. SNARC =spatial–numerical association of response code; pd = probability of direction; ROPE = region of practical equivalence. See the online article for the color version of this figure.

Figure 5

Posterior Distributions of SNARC Slopes for Mu and Tau Parameters in Visual and Auditory Modalities for Iran and United Kingdom, and Their Differences



Note. Circles indicate the distribution medians; bottom lines show 95% highest density intervals (HDI). The bottom lines' colors reflect the probability of direction: black (pd < 97.5%), orange (negative, pd > 97.5%), and green (positive, pd > 97.5%). Line colors represent the countries: dark green (Iran) and dark blue (United Kingdom). Dashed lines mark the ROPE (±2 ms slope). Both countries show negative SNARC effects, generally stronger in auditory modality, especially for tau. The difference panel (Visual − Auditory) suggests variability between countries. The bottom panel shows the differences of differences (United Kingdom − Iran), with blue areas and percentages indicating uncertainty in the modality effect between countries for both mu and tau, providing inconclusive evidence for language influence on the SNARC effect in auditory versus visual modalities. SNARC = spatial–numerical association of response code; pd = probability of direction; ROPE = region of practical equivalence. See the online article for the color version of this figure.

modalities for the mu parameter in the United Kingdom (pd = 64%), which showed no evidence for the effect's existence.

In the Iranian sample, the auditory modality showed no evidence for the effect's existence for the mu parameter (median slope = −1.03, 95% HDI [−3.56, 1.56], pd = 78.7%, p-ROPE = 76.2%). The tau parameter revealed a more pronounced effect, providing very strong evidence against the null hypothesis (median slope = −5.78, 95% HDI [−8.46, −3.21], pd = 100%, p-ROPE = 0.18%). In the visual modality, the mu parameter provided uncertain evidence for its significance (median slope = −2.95, 95% HDI [−4.58, −1.33], pd = 100%, p-ROPE = 13.8%). Similarly, the tau parameter showed uncertain evidence for its significance (median slope = −2.19, 95% HDI [−3.44, −1.01], pd = 100%, p-ROPE = 38.3%).

In the British sample, the tau parameter of the auditory modality revealed a pronounced effect, providing very strong evidence against the null hypothesis (median slope = −7.52, 95% HDI [−12.3, −2.98], pd = 99.9%, p-ROPE = 0.8%). However, the mu parameter showed that while the effect exists, its significance is uncertain (median slope = −3.59, 95% HDI [−6.50, −0.605], pd = 99%, p-ROPE = 14.7%). In the visual modality, both parameters were found to exist but with substantial uncertainty regarding their significance. The mu parameter exhibited a median SNARC slope (median slope = −2.97, 95% HDI [−4.71, −1.14], pd = 100%, p-ROPE = 14.7%). The tau parameter provided weak evidence against the null hypothesis (median slope = −1.82, 95% HDI [−3.02, −0.631], pd = 99.9%, p-ROPE = 61.5%).

When comparing the differences between modalities within each country, the results for Iran suggested no evidence for the difference between modalities for the mu parameter (median difference in slopes = −1.92, 95% HDI [−4.88, 0.994], pd = 90.2%, p-ROPE = 52%). For the tau parameter, the results indicated a more pronounced

SNARC effect in the auditory modality compared to the visual modality, providing strong evidence for the effect's existence but uncertain evidence regarding the significance of the difference between modalities (median difference in slopes = 3.59, 95% HDI [0.841, 6.46], pd = 99.6%, p-ROPE = 12.5%).

In the United Kingdom, the median difference in slopes between modalities for the mu parameter suggested no evidence for the difference between modalities (median difference in slopes = 0.62, 95% HDI [−2.82, 4.02], pd = 64%, p-ROPE = 72.5%). For the tau parameter, the results indicated a more pronounced SNARC effect in the auditory modality compared to the visual modality, providing strong evidence for the difference between modalities (median difference in slopes = 5.69, 95% HDI [1.15, 10.5], pd = 99.2%, p-ROPE = 6.07%).

When comparing the differences in modality effects between countries, the results suggested no evidence for the difference in the modality effect between countries for the mu parameter (median difference = 2.54, 95% HDI [−1.81, 6.98], pd = 87.1%, p-ROPE = 39%) and the tau parameter (median difference = 2.10, 95% HDI [−3.20, 7.64], pd = 78.1%, p-ROPE = 42.1%), with uncertain evidence supporting either Hypothesis 1 or Hypothesis 0.

In conclusion, while there is evidence for a more pronounced SNARC effect in the auditory modality compared to the visual modality in both Iran and the United Kingdom, particularly for the tau parameter, the evidence for the difference in the modality effect between countries remains inconclusive. This finding does not provide strong support for our hypothesis that the language influence on the SNARC effect would be more pronounced under the auditory stimuli condition. While the high p-ROPE values suggest a lack of practical significance in the difference between modalities and support the null effect, the evidence is not definitive.

Hypothesis 4

We hypothesized that the language influence on the SNARC effect would be more pronounced under the explicit task condition, specifically in the magnitude classification task. See in Figure 6 the posterior distribution of the SNARC effects in the different conditions in the differences between them.

When inspecting the task types and countries separately, the pd for both the mu and tau parameters was found to be higher than 97.5% in most cases, indicating strong evidence for the existence of the SNARC effect in both task types and countries for both parameters.

In the Iranian sample, the magnitude classification task showed no evidence for the effect's existence for the mu parameter (median slope = −2.05, 95% HDI [−4.36, 0.260], pd = 95.8%, p-ROPE = 47.7%). The tau parameter revealed a more pronounced effect, providing very strong evidence against the null hypothesis (median slope = −4.63, 95% HDI [−6.71, −2.56], pd = 100%, p-ROPE = 0.62%). In the parity judgment task, the mu parameter provided no evidence for the effect's existence (median slope = −1.93, 95% HDI [−3.60, −0.266], pd = 98.9%, p-ROPE = 53.7%). The tau parameter showed strong evidence against the null hypothesis (median slope = −3.34, 95% HDI [−5.16, −1.57], pd = 100%, p-ROPE = 7%).

In the British sample, the magnitude classification task showed evidence for the mu parameter (median slope = −3.66, 95% HDI [−6.12, −1.12], pd = 99.7%, p-ROPE = 10%) and the tau parameter (median slope = −3.91, 95% HDI [−6.97, −1.05], pd = 99.6%, p-ROPE = 9.89%). In the parity judgment task, the mu parameter showed evidence (median slope = −2.90, 95% HDI [−4.90, −0.901], pd = 99.7%, p-ROPE = 18.4%) and the tau parameter provided very strong evidence against the null hypothesis (median slope = −5.43, 95% HDI [−8.94, −1.89], pd = 99.9%, p-ROPE = 2.96%). Notably, this latter finding provided very strong evidence against the null hypothesis, rather than merely inclining toward rejection.

When comparing the differences between task types within each country, the results for Iran suggested no evidence for the difference between task types for the mu parameter (median difference in slopes = −0.12, 95% HDI [−2.57, 2.30], pd = 53.7%, p-ROPE = 88.4%) and the tau parameter (median difference in slopes = −1.29, 95% HDI [−3.82, 1.16], pd = 84.4%, p-ROPE = 70.9%). The U.K. sample showed a similar pattern, suggesting no evidence for the difference between task types for the mu parameter (median difference in slopes = −0.76, 95% HDI [−3.64, 2.17], pd = 70.1%, p-ROPE = 77%). For the tau parameter, the results indicated a more pronounced SNARC effect in the parity judgment task compared to the magnitude classification task, but with no evidence for the difference between task types (median difference in slopes = 1.53, 95% HDI [−2.93, 5.74], pd = 77.2%, p-ROPE = 52.6%).

When comparing the differences of differences between countries, the results suggested no evidence for the difference in the task type effect between countries for the mu parameter (median difference = −0.64, 95% HDI [−4.25, 3.18], pd = 63.8%, p-ROPE = 68%) and the tau parameter (median difference = 2.81, 95% HDI [−2.13, 7.59], pd = 87.3%, p-ROPE = 33.3%), with uncertain evidence supporting either Hypothesis 1 or Hypothesis 0.

In conclusion, while there is evidence for the existence of the SNARC effect in both task types and countries, particularly for the tau parameter, the evidence for the difference in the task type effect within and between countries remains inconclusive. This finding does not provide strong support for our hypothesis that the magnitude classification task would show a more pronounced SNARC effect compared to the parity judgment task. While the high p-ROPE values suggest a lack of practical significance in the difference between tasks and support the null effect, the evidence is not definitive.

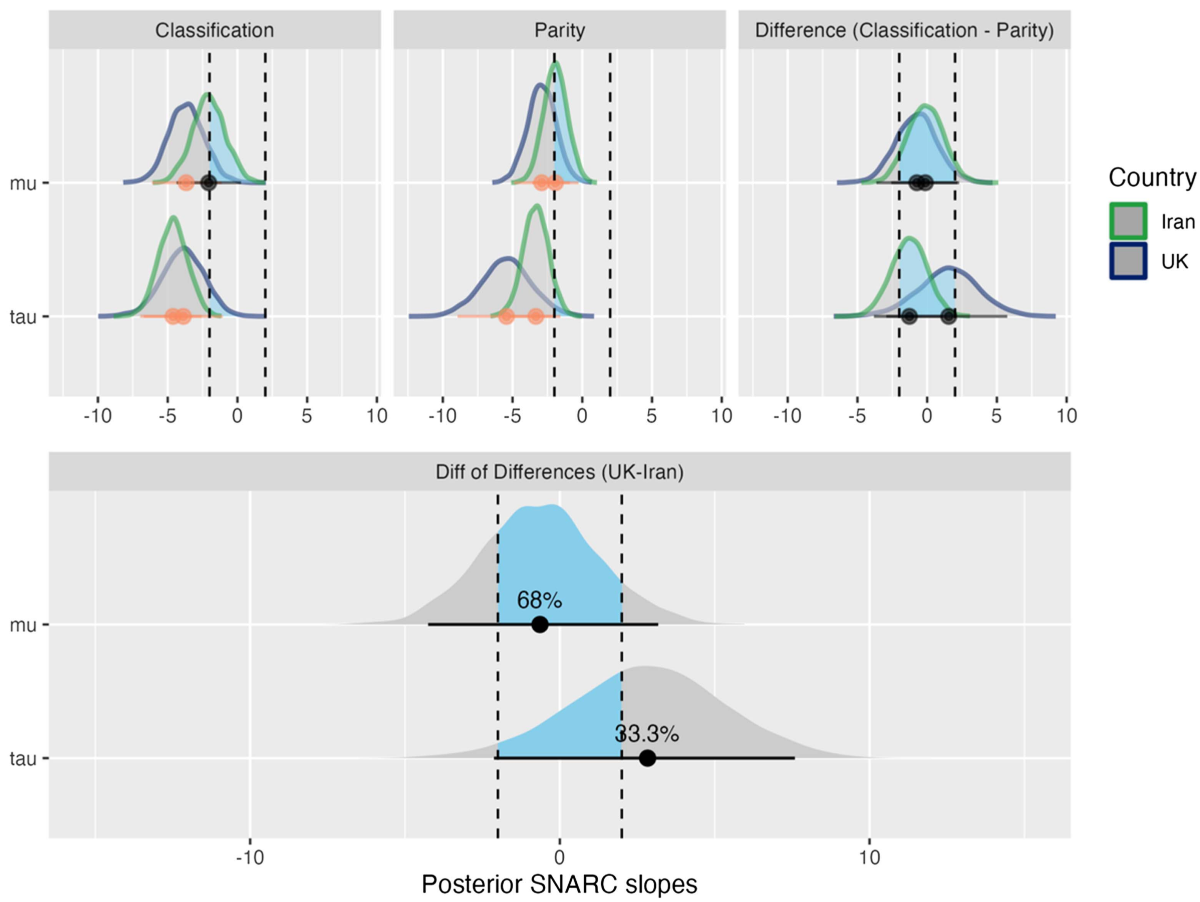
Hypothesis 5

We hypothesized that the effect of language on the SNARC effect would be most pronounced in the auditory tasks, particularly in the explicit task (magnitude classification), due to the involvement of language comprehension in this modality. We further hypothesized that the effect of language would be least involved in the visual implicit task (parity judgment). We predicted that the auditory parity judgment task and visual magnitude classification task would fall between these two extremes. To test this hypothesis, we coded the variables of modality and task type to calculate polynomial contrasts that would show linear or quadratic differences between the levels of the interaction of modality and task type, between languages. See in Figure 7 the posterior distribution of the SNARC effects in the different conditions in the differences between them.

When inspecting the countries separately, the pd for the linear effect of the tau parameter was found to be higher than 97.5% in both Iran (median slope = 16.7, 95% HDI [4.28, 29.8], pd = 99.6%, p-ROPE = 0.6%) and the United Kingdom (median slope = 19.6,

Figure 6

Posterior Distributions of SNARC Slopes for Mu and Tau Parameters in Classification and Parity Tasks for Iran and United Kingdom, and Their Differences



Note. Circles indicate the distribution medians; lines show 95% highest density intervals (HDI). The bottom lines' colors reflect the probability of direction: black (pd < 97.5%) and orange (negative, pd > 97.5%). Line colors represent the countries: dark green (Iran) and dark blue (United Kingdom). Dashed lines mark the ROPE (±2 ms slope). Both countries show negative SNARC effects in both tasks. The difference panel (Classification − Parity) suggests variability between countries. The bottom panel shows the differences of differences (United Kingdom − Iran), with blue areas representing the proportion within ROPE. Percentages indicate uncertainty in the task effect between countries for both mu and tau, providing inconclusive evidence for language influence on the SNARC effect in classification versus parity tasks. SNARC = spatial–numerical association of response code; pd = probability of direction; ROPE = region of practical equivalence. See the online article for the color version of this figure.

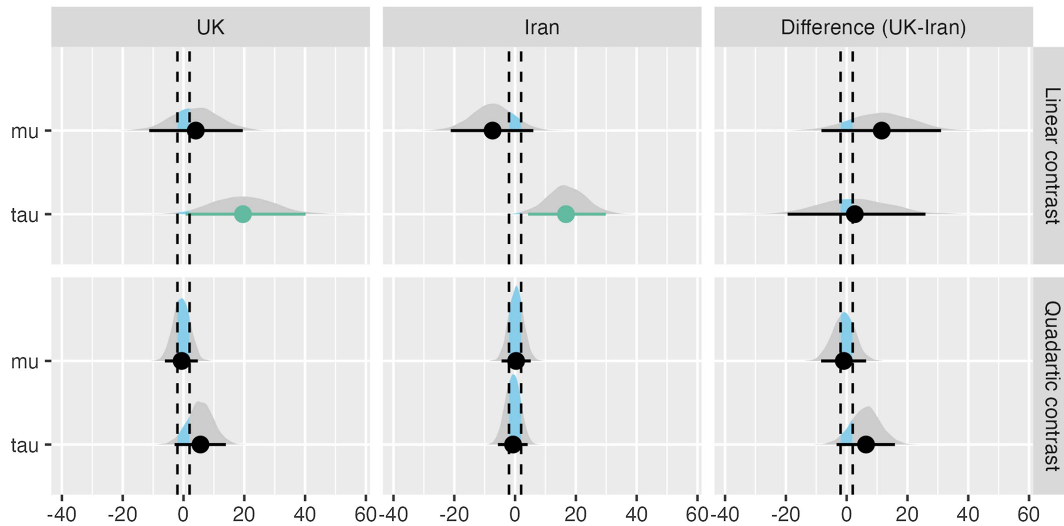
95% HDI [0.677, 40.1], pd = 97.8%, p-ROPE = 2.04%), indicating strong evidence for the existence of the linear effect. This suggests that there is a linear trend in the effect of language on the tau parameter of the SNARC effect across the levels of the interaction of modality and task type in both countries. However, for the quadratic effect of the tau parameter (Iran: median slope = −0.678, 95% HDI [−5.65, 4.14], pd = 60.5%, p-ROPE = 55.1%; United Kingdom: median slope = 5.58, 95% HDI [−2.94, 13.9], pd = 90.7%, p-ROPE = 15.9%) and both the linear (Iran: median slope = −7.41, 95% HDI [−21.2, 6.01], pd = 86.3%, p-ROPE = 12.9%; United Kingdom: median slope = 4.04, 95% HDI [−11.3, 19.5], pd = 69.5%, p-ROPE = 18.4%) and quadratic (Iran: median slope = 0.337, 95% HDI [−4.44, 5.15], pd = 55.5%, p-ROPE = 58%; United Kingdom: median slope = −0.618, 95% HDI [−6.12, 4.71], pd = 58.8%, p-ROPE = 50.8%) effects of the mu parameter, the pd was lower than 97.5% in both countries, suggesting no evidence for the existence of these effects.

When comparing the differences between countries, the pd for both the linear (median slope = 2.68, 95% HDI [−19.4, 25.9], pd = 58.5%, p-ROPE = 12.9%) and quadratic (median slope = 6.37, 95% HDI [−3.30, 15.9], pd = 90.2%, p-ROPE = 14.4%) effects of the tau parameter and the linear (median slope = 11.5, 95% HDI [−8.29, 31.1], pd = 87%, p-ROPE = 8.38%) and quadratic (median slope = −0.943, 95% HDI [−8.39, 6.40], pd = 59.4%, p-ROPE = 40.2%) effects of the mu parameter was lower than 97.5%, indicating no evidence for the difference in the language effect between countries.

In conclusion, while there is strong evidence for the existence of a linear trend in the effect of language on the tau parameter of the SNARC effect across the levels of the interaction of modality and task type in both Iran and the United Kingdom, there is no evidence

Figure 7

Posterior Distributions of SNARC Slopes for Mu and Tau Parameters in Linear and Quadratic Contrasts of the Modality and Task Type Interaction for United Kingdom and Iran, and Their Differences



Note. Circles indicate the distribution medians; lines show 95% highest density intervals (HDI). The bottom lines' colors reflect the probability of direction: black (pd < 97.5%) and green (positive, pd > 97.5%). Dashed lines mark the ROPE (±2 ms slope). Both countries show positive linear effects for tau, with no effects for other contrasts. The difference panel (United Kingdom − Iran) suggests high uncertainty between countries. Blue areas represent the proportion within ROPE. Results provide inconclusive evidence for language influence on the SNARC effect across modality and task type interactions for both mu and tau. SNARC = spatial–numerical association of response code; pd = probability of direction; ROPE = region of practical equivalence. See the online article for the color version of this figure.

for the existence of a quadratic trend on the tau parameter or both linear and quadratic trends on the mu parameter in either country. Furthermore, there is no evidence for the difference in the language effect between countries for both the linear and quadratic trends on the tau and mu parameters. These findings partially support our hypothesis, as they suggest that the effect of language on the SNARC effect follows a linear trend across the levels of the interaction of modality and task type, with the auditory explicit task showing the most pronounced effect and the visual implicit task showing the least pronounced effect. However, the lack of evidence for the difference in the language effect between countries suggests that this trend may not be significantly influenced by language (Farsi or English).

Discussion

Recent years have been characterized by an increased interest in understanding spatial–numerical associations (Cipora, Soltanlou, et al., 2019; Farshad et al., 2024; Hawes et al., 2019) as well as improving the methodological foundations allowing better studying of these associations (Cipora & Wood, 2017). This registered report focused on one specific directional spatial–numerical association: the SNARC effect. This effect emerges from the interaction between cognitive magnitude representation and the responding hand in numerical tasks. To this end, we aimed to use the methodological progress of recent years to further investigate the influence of language on the SNARC effect. Specifically, we recruited a group of British English speakers and Iranian Farsi speakers, each language characterized by a different writing direction—a fact that facilitated the idea of language-induced differences (see in the original SNARC effect article, Dehaene et al., 1993). We administered four tasks allowing us to investigate the SNARC effect on each group, two in each visual and auditory modality and two requiring either explicit (i.e., magnitude comparison task) or implicit (i.e., parity judgment task) processing of numbers. In our registered hypotheses, we speculated on five interactions between tasks and language based on previous research. However, none of these hypotheses was supported by the registered analyses based on our registered analyses.

It is important to consider the limitations of the methodological choices and statistical analyses registered for Stage 1. First, the decision to group the numerosities into four categories, following the guidance of Tzelgov et al. (2013), may have suppressed relevant variance for capturing the MNL. Second, the RT exclusion criteria registered in Stage 1 of the present study (2.5 MAD from the median) may have increased the difficulty in detecting significant results. Recent articles recommend more liberal thresholds, such as 3 MAD (Leys et al., 2019) or the most recent recommendation of 3.29 (Thériault et al., 2024). Adopting these more lenient criteria could result in the inclusion of a few additional percentage points of data, and while these values are extreme, their impact could be determinant for the effects. This consideration is particularly relevant given previous research showing that the SNARC effect is more pronounced in slower reaction times (Cipora, Soltanlou, et al., 2019; Gevers et al., 2006b). Thus, a breakdown of the reaction times into components reflecting the center of the distribution and the tail of the distribution (e.g., ex-Gaussian distribution; see, e.g., in Matzke & Wagenmakers, 2009) could provide valuable insights into the research question at hand. Finally, the absence of a significant finding in null hypothesis significance testing does not necessarily imply that the effect does not exist, which limits the possible conclusions that can be drawn from the study (Altman & Bland, 1995; Cohen, 1994; Greenland et al., 2016).

Altogether, the consideration above prompted a more elaborated nonplanned analysis employing a BHLM with an ex-Gaussian likelihood function. This novel approach allowed us to separately model the mu (central tendency) and tau (slower responses) components of the ex-Gaussian distribution, providing deeper insights into how numerical cognition influences spatial RTs. The nonregistered analyses revealed strong evidence for the existence of the SNARC effect in both modalities and countries for both the mu and tau parameters. Interestingly, we found a dissociation between the mu and tau parameters in both modalities, suggesting that the SNARC effect manifests differently in the central tendency and the tail of the RT distributions depending on the modality. Furthermore, contrary to our initial hypothesis, we found a more pronounced SNARC effect in the auditory modality compared to the visual modality. However, the evidence for the difference in the modality effect between countries remained inconclusive. Similarly, we did not find strong support for the hypothesis that the magnitude classification task would show a more pronounced SNARC effect compared to the parity judgment task. Neither did we find evidence for the difference in the language effect between countries for both the linear and quadratic trends on the tau and mu parameters.

These current null effects from the registered analyses, along with the mixed findings from the nonregistered analyses, align with the existing literature regarding the cultural differences in the SNARC effect. As outlined in the introduction, previous studies have yielded inconsistent findings when examining the influence of language and writing direction on the SNARC effect. For instance, while some studies have found a significant effect of reading and writing direction on the direction and size of the SNARC effect (Fischer et al., 2009; Hung et al., 2008; Shaki & Fischer, 2008), others have reported marginal to no effect of language on the SNARC effect (Bulut et al., 2023; Cipora, Loenneker, et al., 2019; Cipora, Soltanlou, et al., 2019; Dehaene et al., 1993; Heubner et al., 2018; Shaki & Fischer, 2012; Zohar-Shai et al., 2017). The present study's null results align with the latter group of studies, suggesting that the influence of language on the SNARC effect may not be robust. This notion is further supported by recent findings from Pitt and Casasanto (2020), who directly tested the effect of reading direction on spatial mappings of abstract concepts. In their experiments, they found that reading direction influenced spatial mappings of time but had no effect on spatial mappings of numbers, challenging the widespread claim that reading experience shapes both types of spatial associations. Instead, they propose that different abstract concepts are spatialized according to distinct experiences that provide correlations between space and the respective domain (e.g., space and time for reading direction, space and number for finger counting). These results, along with the present study's null findings, suggest that the influence of language and reading direction on the SNARC effect may be less substantial than previously thought.

The nonregistered analyses have yielded novel findings that shed new light on the SNARC effect and open up promising avenues for future research. First, in most cases, the SNARC effect was found to be more substantial in the tau parameter, which represents the tail of the RT distribution, than in the mu parameter, which represents the central tendency. This is in line with previous research suggesting that the SNARC effect may be more pronounced in slower responses, yet it has not been studied in the ex-Gaussian framework. This finding facilitates the possibility that many previous findings related to the SNARC effect may have been missed due to overlooking this component and invites extensive revisions of these findings. Second, the auditory SNARC effect was found to be stronger than the visual one on the tau parameter. This unexpected finding, going against our initial hypothesis, is particularly noteworthy, as the auditory SNARC effect has not been extensively researched in the past. This result suggests that the modality of stimulus presentation may play a crucial role in shaping the SNARC effect and that the auditory modality may be more sensitive to the effect than previously thought.

Nevertheless, the Bayesian analyses did not find clear evidence for language-induced differences in the SNARC effect. The SNARC effect was often found to be significant, but it was frequently uncertain regarding the ROPE. This suggests that while the data often support the effect existence in the various conditions, the evidence for its strength is uncertain. That could entail that the paradigms used for detecting the SNARC effect may only be capable of detecting only a small effect (see also in Cipora, Soltanlou, et al., 2019). This limitation might also explain why we were unable to find language-induced differences, as we were likely underpowered, assuming a medium-size difference. However, our findings do not conclusively support the null hypothesis or the alternative hypothesis regarding language-induced effects. This uncertainty encourages future research to continue investigating the potential influence of language on the SNARC effect, perhaps with more sensitive paradigms and larger sample sizes.

The present study's findings contribute to the ongoing debate regarding the role of language and culture in shaping spatial–numerical associations. Despite the null results, our findings support the continued investigation of this interaction due to its potential implications for our understanding of numerical cognition and its development across cultures (Cipora, Schroeder, Soltanlou, & Nuerk, 2018). As highlighted in the introduction, the SNARC effect has been a key focus of research in this area, with numerous studies examining its neurocognitive mechanisms (Farshad et al., 2024; Hawes et al., 2019) and developmental basis (Bulf et al., 2016; McCrink & Opfer, 2014). However, the inconsistencies in the literature regarding the influence of language and cultural factors on the SNARC effect underscore the need for further research to investigate the complex interplay of these factors. It is important to recognize that the SNARC effect is a measure of the MNL, and our study aims to explore how this underlying cognitive representation is influenced by language and culture. By employing more sophisticated methodological approaches, such as the ones suggested in this discussion (e.g., Bayesian analysis, fine-grained numerosity breakdown, and reaction time distribution analysis), future studies can provide a more comprehensive understanding of how language and culture shape spatial–numerical associations across different cognitive processes and levels of task difficulty. Moreover, investigating these associations in diverse cultural contexts can shed light on the universality or culture specificity of the SNARC effect and other spatial–numerical associations, ultimately advancing our knowledge of how the human mind processes and represents numerical information (Cipora et al., 2023; Sabaghypour et al., 2023). This line of research has important implications not only for theoretical models of numerical cognition but also for educational practices, as understanding the role of language and culture in shaping spatial–numerical associations can inform the development of culturally sensitive teaching methods and interventions aimed at enhancing numerical skills across different populations (Cipora, Schroeder, Soltanlou, & Nuerk, 2018).

The SNARC effect serves as a useful tool for probing the MNL—the theoretical structure on which numbers are represented. To this end, investigating the interaction between SNAs and culture is crucial for both theoretical and practical reasons. From a theoretical perspective, understanding how cultural factors interact with numerical cognition can inform theories of embodied cognition and contribute to the broader field of numerical cognition (Chiou et al., 2023; Fischer & Brugger, 2011; Fischer & Shaki, 2018; Sixtus et al., 2023). Moreover, this understanding can also provide valuable insights into biological accounts of SNAs—the nativist theory. As previous research showed (see, e.g., Eccher et al., 2023; Rugani et al., 2020), there appears to be a universal, biologically predisposed left-to-right SNA that emerges independently of culture and age. Investigating the interplay between this biologically determined SNA and culturally acquired SNAs can further our understanding of the complex nature of SNAs and their origins. From a practical standpoint, research on the influence of culture on spatial–numerical associations has important implications for education and cross-cultural communication, as it can inform the development of culturally sensitive educational practices and promote understanding in fields that rely heavily on numerical information. Although the present study did not find evidence for language-induced differences in the SNARC effect, it is essential to continue investigating this interaction using diverse methodological approaches to shed light on the complex interplay between language, culture, and numerical cognition.

Constraints on Generality

Our study's contextualized generalizability statement concentrates on the moderating role of language in the SNARC effect. Our focus is English and Farsi, two languages with distinct writing systems and numeral forms that could potentially influence spatial–numerical associations. English employs a left-to-right writing direction for both words and sentences, and it uses the left-to-right Arabic numeral system. In contrast, Farsi, with its right-to-left writing direction for words and sentences, intriguingly adopts the left-to-right Eastern Arabic numeral system. This unique combination within Farsi—right to left for words and sentences but left to right for numbers—provides a rich context for our examination of the SNARC effect. We aim to illuminate how such contrasting directionalities within a single language could interact and impact number–space associations, offering insights into the nuanced interplay of language and cognition, particularly in numerical cognition.

The populations targeted in our research include native English and Farsi speakers who have internalized the unique characteristics of their respective languages' writing and numeral systems. We emphasize that our findings, while shedding light on the influence of language on the SNARC effect, might not be universally applicable to all language comparisons. The patterns and results anticipated between English and Farsi due to their unique writing systems and numeral forms may not be replicated across other language pairs. This is attributable to the vast diversity in linguistic structures, like the directionalities of the writing systems, and the specific experimental procedures used in this study. Therefore, our conclusions primarily pertain to the context of English and Farsi speakers and the specific tasks and modalities explored in our research. We strongly encourage future research to consider this contextualized generalizability statement when assessing our study's claims and to expand the investigation to include a broader range of languages and different experimental conditions for a more comprehensive understanding of language's influence on the SNARC effect.

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(*Appendix follows*)

Appendix

Software and Code

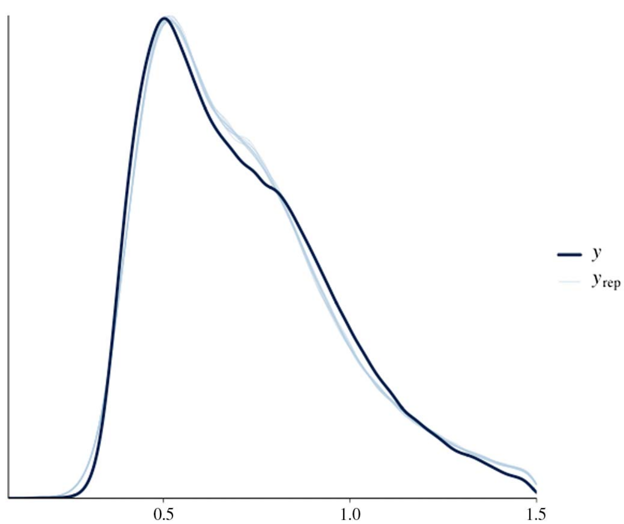
All the models and analyses used R (R Core Team, 2022). The models were implemented using the brms package (Bürkner, 2017), which is an R interface to the Stan probabilistic modeling language (Stan Development Team, 2023). Further analyses of the models and contrasts were conducted using the posterior (Bürkner et al., 2023) and bayestestr (Makowski, Ben-Shachar, & Lüdecke, 2019). Data handling and plots have been carried out using tidyverse (Wickham et al., 2019), ggdist, and tidybayes (Kay, 2023a, 2023b). Posterior estimation was executed via Markov Chain Monte Carlo sampling, consisting of three chains with a warmup period of 1,500 iterations and an additional 3,000 sampled iterations for the models. All Rhat values were below 1.01, and all effective sample sizes were larger than 1,000, suggesting proper model convergence and coverage (Bürkner, 2017). Additionally, results from posterior predictive checks were satisfactory (see Figure A1).

Priors

For all coefficients, we used a generic weakly informative prior of a normal distribution centered on 0 with a scale of 1.5. The priors for the random variances and covariances were a Student's *t*-distribution with 3 *df*, a location of 0, and a scale of 2.5 for the random variances, and an Lewandowski–Kurowicka–Joe correlation matrix with an eta of 1 for the covariances. These were the default wide priors provided by the brms package.

Figure A1

Posterior Predictive Check of the Model



Note. See the online article for the color version of this figure.

Formula

The brms package with which we modeled the data is following the lme4 syntax, and the formula for the model was as follows:

```
brm(data = Data_fs,
 bf(
 RT| trunc(ub = 1.5)~ Modality*TaskType*RespondSide*scale
   (Numerosity)*Country+(Modality*TaskType*RespondSide*scale
   (Numerosity)|p|File),
  sigma~1+(1|p|File),
  beta~Modality*TaskType*RespondSide*scale(Numerosity)*
     Country+(Modality*TaskType*RespondSide*scale
     (Numerosity)|p|File)
  ),
  prior = priors,
  chains = 3, cores = 9,
  threads = threading(3),
  family = exgaussian(),
  iter = 3000, warmup = 1500,
  init = 0,
  control = list(adapt_delta = 0.90),
  backend = "cmdstanr")
```

Model Fit

The explained variance of the mu parameter was 67% ($R_{\text{conditional}}{}^2$ = 0.67 [0.67, 0.67]), and the explained variance of the tau parameter was 26.7% ($R_{\text{conditional}}{}^2$ = 0.26 [0.25, 0.28]; on R^2 for Bayesian models, see Gelman et al., 2019), indicating substantial explanatory power for both parameters.

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