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Vice Versa?

The Bidirectionality and Symmetry of Associations between Size and Space in S-R Compatibility Effects

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Abstract

The *spatial-numerical association of response codes (SNARC) effect* denotes faster and more accurate left responses to small(er) numbers and faster and more accurate right responses to large(r) numbers, as compared to the reverse assignment. The *spatial-size association of response codes (SSARC) effect* describes a similar observation for physical instead of numerical size: left responses are faster and more accurate to physically small(er) stimuli whereas right responses are faster and more accurate to physically large(r) stimuli, as compared to the reverse assignment. Both compatibility effects provide evidence that the processing of size-related information affects the processing of spatial information and thus reveal associations between size and space, which underlie the selection and execution of human actions.

However, it is yet unknown if the underlying associations between size and space are bidirectional, that is, if the processing of spatial information in turn also affects the processing of size-related information, which would allow not only for a regular but also for a reciprocal SNARC/SSARC effect. Crucially, the existing theoretical accounts of the SNARC/SSARC effect differ in whether they predict bidirectional or unidirectional effects and in whether they predict symmetrical or asymmetrical effects. Therefore, the major objectives of the present dissertation, which comprises four studies and seven experiments, were to a) investigate the bidirectionality and symmetry of associations between numerical/physical size and space as they emerge as S-R compatibility effects and b) differentiate between the theories accounting for the effects. To investigate the bidirectionality and symmetry of the SNARC/SSARC effect, we compared the compatibility effect of a number-/size-location (i.e., typical SNARC/SSARC) task, in which participants responded to numerical/physical stimulus size with horizontal location responses, to the compatibility effect of a location-number/-size (i.e., reciprocal SNARC/SSARC) task, in which participants responded to horizontal stimulus location with responses referring to numerical/physical size. In both tasks, participants were asked to respond once according to a compatible and once according to an incompatible mapping.

In Studies 1 and 2, we investigated the bidirectionality and symmetry of the SNARC effect. In Study 1, we employed numerosity (Exp. 1)/digit (Exp. 2) stimuli and manual location responses in the number-location task as well as physical location stimuli and manual number responses in the location-number task. In Study 2, we employed digit (Exp. 1 & 2)/verbal number (Exp. 3) stimuli and vocal location responses in the number-location task as well as physical (Exp. 1 & 2)/verbal (Exp. 3) location stimuli and vocal number responses in the location-number task. Results revealed that with numerosity or digit/physical location stimuli and manual or vocal location/number responses, spatial-numerical associations are strongly asymmetrical allowing for the regular but not for the emergence of a reciprocal SNARC effect. However, with verbal number/location stimuli and vocal location/number responses, spatial-numerical associations are bidirectional and symmetrical allowing for a regular and reciprocal SNARC effect of similar size.

In Studies 3 and 4, we investigated the bidirectionality and symmetry of the SSARC effect. In Study 3, we employed physical size stimuli and vocal location responses in the size-location task as well as physical location stimuli and vocal size responses in the location-size task. In Study 4, we employed verbal size stimuli and vocal location responses in the size-location task as well as verbal location stimuli and vocal size responses in the location-size task. Results revealed that with physical size/location stimuli and vocal location/size responses, spatial-size associations are strongly asymmetrical allowing for the regular but not for the emergence of a reciprocal SSARC effect. However, with verbal size/location stimuli and vocal location/size responses, spatial-size associations are bidirectional and symmetrical allowing for a regular and reciprocal SSARC effect of similar size. Thus, most interestingly, for both the SNARC and the SSARC effect, reciprocal effects emerge with verbal location stimuli but not with physical location stimuli. The effect of stimulus mode on the emergence of reciprocal (but not regular) SNARC and SSARC effects points towards some crucial feature of verbal location stimuli in eliciting reciprocal effects.

Furthermore, the pattern of results observed in the four studies of this dissertation entails important theoretical implications for the existing accounts of the SNARC/SSARC effect. In particular, the accounts need to explain the emergence of bidirectional and symmetrical SNARC/SSARC effects as well as the impact of stimulus mode on the emergence of the reciprocal (but not the regular) SNARC/SSARC effect. Since in their current form, none of the existing theories can explain the complete pattern of results without making additional assumptions, the results underpin the necessity to further develop and advance the theoretical accounts.

Kurzfassung

Der sogenannte “spatial-numerical association of response codes (SNARC)” Effekt drückt schnellere und fehlerfreiere linke Reaktionen auf kleine(re) Zahlen sowie schnellere und fehlerfreiere rechte Reaktionen auf große (größere) Zahlen im Vergleich zur entgegengesetzten Zuordnung aus. Der sogenannte “spatial-size association of response codes (SSARC)” Effekt beschreibt eine ähnliche Beobachtung für physikalische statt numerische Größe: linke Reaktionen auf physikalisch kleine(re) Stimuli und rechte Reaktionen auf physikalisch große (größere) Stimuli sind schneller und fehlerfreier im Vergleich zur entgegengesetzten Zuordnung. Beide Kompatibilitätseffekte belegen, dass die Verarbeitung von größenbezogener Information die Verarbeitung von räumlicher Information beeinflusst, und weisen somit auf Assoziationen zwischen Größe und Raum hin, welche der Auswahl und Ausführung von menschlichen Handlungen zugrunde liegen.

Es ist allerdings fraglich, ob diese zugrundeliegenden Assoziationen zwischen Größe und Raum bidirektional sind, das heißt, ob die Verarbeitung von räumlicher Information umgekehrt auch die Verarbeitung von größenbezogener Information beeinflusst. Die Existenz solcher bidirektionalen Assoziationen würde nicht nur einen regulären, sondern auch einen reziproken SNARC/SSARC Effekt entstehen lassen. Da sich die existierenden theoretischen Erklärungsansätze des SNARC/SSARC Effekts darin unterscheiden, ob sie bidirektionale oder unidirektionale und ob sie symmetrische oder asymmetrische Effekte vorhersagen, können Befunde zur Bidirektionalität und Symmetrie die Haltbarkeit der verschiedenen Ansätze testen und zwischen diesen differenzieren. Die beiden primären Ziele der hier vorliegenden Dissertation bestehen daher darin, zum einen die Bidirektionalität und Symmetrie der Assoziationen zwischen numerischer/physikalischer Größe und Raum, wie sie in der Form von

Reiz-Reaktions-Kompatibilitätseffekten entstehen, zu untersuchen und zum anderen zwischen den theoretischen Erklärungsansätzen der Effekte zu differenzieren.

In vier Studien und sieben Experimenten untersuchten wir die Bidirektionalität und Symmetrie des SNARC/SSARC Effekts, indem wir die Kompatibilitätseffekte aus zwei Aufgaben miteinander verglichen. In einer Zahl-/Größe-Position (d.h., einer typischen SNARC/SSARC) Aufgabe antworteten die Probanden auf die numerische/physikalische Stimulusgröße mit horizontalen Positionsreaktionen. In einer Position-Zahl/-Größe (d.h., einer reziproken SNARC/SSARC) Aufgabe antworteten die Probanden auf die horizontale Stimulusposition mit zahlen-/größenbezogenen Reaktionen. In beiden Aufgaben reagierten die Probanden einmal gemäß einer kompatiblen und einmal gemäß einer inkompatiblen Zuordnung.

In den Studien 1 und 2 untersuchten wir die Bidirektionalität und Symmetrie des SNARC Effekts. In Studie 1 verwendeten wir Anzahlen (Exp. 1)/Ziffern (Exp. 2) als Stimuli und manuelle Positionsreaktionen in der Zahl-Position Aufgabe sowie physikalische Stimuluspositionen und manuelle Zahlreaktionen in der Position-Zahl Aufgabe. In Studie 2 verwendeten wir Ziffern (Exp. 1 & 2)/verbale Zahlen (Exp. 3) als Stimuli und vokale Positionsreaktionen in der Zahl-Position Aufgabe sowie physikalische (Exp. 1 & 2)/verbale (Exp. 3) Positionsstimuli und vokale Zahlreaktionen in der Position-Zahl Aufgabe. Die Ergebnisse zeigten, dass die räumlich-numerischen Assoziationen unter Verwendung von Anzahlen oder Ziffern/physikalischen Positionen als Stimuli und manuellen oder vokalen Positions-/Zahlreaktionen stark asymmetrisch sind und lediglich einen regulären, aber keinen reziproken SNARC Effekt entstehen lassen. Unter Verwendung von verbalen Zahl-/Positionsstimuli und vokalen Positions-/Zahlreaktionen sind die räumlich-numerischen Assoziationen hingegen bidirektional und symmetrisch und resultieren in einem regulären und reziproken SNARC Effekt von ähnlicher Stärke.

In den Studien 3 und 4 untersuchten wir die Bidirektionalität und Symmetrie des SSARC Effekts. In Studie 3 verwendeten wir physikalische Größenstimuli und vokale Positionsreaktionen in der Größen-Position Aufgabe sowie physikalische Positionsstimuli und vokale Größenreaktionen in der Position-Größe Aufgabe. In Studie 4 verwendeten wir verbale Größenstimuli und vokale Positionsreaktionen in der Größe-Position Aufgabe sowie verbale Positionsstimuli und vokale Größenreaktionen in der Position-Größe Aufgabe. Die Ergebnisse zeigten, dass die Assoziationen zwischen Raum und Größe unter Verwendung von physikalischen Größen-/Positionsstimuli und vokalen Positions-/Größenreaktionen stark asymmetrisch sind und lediglich einen regulären, aber keinen reziproken SSARC Effekt entstehen lassen. Unter Verwendung von verbalen Größen-/Positionsstimuli und vokalen Positions-/Größenreaktionen sind die Assoziationen zwischen Raum und Größe hingegen bidirektional und symmetrisch und resultieren in einem regulären und reziproken SSARC Effekt von ähnlicher Stärke. Überraschenderweise entstehen reziproke Effekte sowohl in Hinblick auf den SNARC als auch auf den SSARC Effekt daher lediglich mit verbalen jedoch nicht mit physikalischen Positionsstimuli. Dieser Effekt der Stimulusmodalität auf die Entstehung von reziproken (aber nicht regulären) SNARC und SSARC Effekten deutet darauf hin, dass verbale Positionsstimuli bestimmte Eigenschaften aufweisen, die für die Entstehung von reziproken Effekten bedeutsam sind.

Darüber hinaus besitzt das Ergebnismuster, welches sich über die vier Studien hinweg zeigt, relevante theoretische Implikationen für die existierenden Erklärungsansätze des SNARC und SSARC Effekts. Die theoretischen Ansätze müssen zum einen die Entstehung von bidirektionalen und symmetrischen SNARC/SSARC Effekten und zum anderen den Einfluss der Stimulusmodalität auf die Entstehung des reziproken (aber nicht des regulären) SNARC/SSARC Effekts erklären können. Da keine der existierenden Theorien in ihrer jetzigen Form das gesamte Ergebnismuster begründen kann, ohne zusätzliche Annahmen zu treffen, bekräftigen die Ergebnisse die Notwendigkeit, die theoretischen Ansätze weiterzuentwickeln.

1. General Introduction

Stimulus-Response (S-R) compatibility denotes the match or mismatch between certain elements of a stimulus set and certain elements of a response set. In a so-called compatible assignment, matching stimulus and response alternatives allow for a better performance than mismatching stimulus and response alternatives in a so-called incompatible assignment. This performance difference between compatible and incompatible mapping conditions is termed *S-R compatibility effect* (Alluisi & Warm, 1990; Proctor & Vu, 2006)[1]. Compatibility effects are a widely studied phenomenon in cognitive research because they provide valuable insights into the mental representation of stimulus and response dimensions and, importantly, reveal associations between them, which underlie the selection and execution of human actions (Alluisi & Warm, 1990; Kornblum et al., 1990; Proctor & Vu, 2006). Apart from revealing important cognitive mechanisms underlying human action control, the relevance of compatibility effects is expressed by their omnipresence in everyday life: When dialing a phone number, we press a small number more easily with our left index finger and a large number more easily with our right index finger, as compared to the reverse assignment. When going for a drink, we grasp a small shot glass more easily with our left hand and a large beer glass more easily with our right hand, as compared to the reverse assignment.

Both practical examples refer to compatibility effects between spatial response location on the one hand and two types of stimulus size on the other hand: numerical and physical size. The so-called *spatial-numerical association of response codes (SNARC) effect* (Dehaene et al., 1990; Fischer & Shaki, 2014; Gevers & Lammertyn, 2005) denotes the observation that left

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[1] Please note that while the works cited in each article will be listed in the corresponding reference list within each article, the works cited in the General Introduction, General Discussion and Conclusion of this dissertation will be listed under the heading “7. References”.

responses are faster and more accurate to small(er) numbers whereas right responses are faster and more accurate to large(r) numbers, as compared to the opposite assignment. The so-called *spatial-size association of response codes (SSARC) effect* (Ren et al., 2011; Weis et al., 2018; Wühr & Seegelke, 2018) denotes the observation that left responses are faster and more accurate to physically small(er) stimuli whereas right responses are faster and more accurate to physically large(r) stimuli, as compared to the opposite assignment. Both the SNARC and the SSARC effect constitute the research objects and thus the main focus of this present dissertation.

In contrast to the widely studied SNARC effect, only several studies have so far investigated the characteristics of the SSARC effect. Still, it has already been demonstrated that the two effects share some of their characteristics. For example, both spatial-numerical and spatial-size associations do not only emerge as compatibility effects when numerical/physical size is the task-relevant stimulus feature but also as correspondence effects when numerical/physical size is completely irrelevant for the successful task completion (Gevers et al., 2006; Mapelli et al., 2003; Wühr & Richter, 2022; Wühr & Seegelke, 2018). Moreover, both the SNARC and SSARC effect emerge with manual as well as vocal responses (Gevers et al., 2010; Wühr et al., 2024). The independence of response mode suggests that neither spatial-numerical nor spatial-size associations rely on direct pathways between specific stimulus and response codes. Rather, they seem to be situated on a more central, intermediate representational level, which allows them to generalize across motor systems.

Despite those similarities, some differences have been demonstrated, which allow dissociating between the SNARC and the SSARC effect and simultaneously preclude generalizing across both effects. First, while the generation of response codes is strongly based on external spatial coding in the SNARC effect (Crollen et al., 2013; Dehaene et al., 1993; but see Wood et al., 2006 for a joint influence of anatomical and external spatial coding), it is more anatomically based in the SSARC effect (Seegelke et al., 2023). Second, while handedness does not affect the SNARC effect (Cipora et al., 2019; Dehaene et al., 1993), handedness and effector strength do in fact influence the SSARC effect (Wühr et al., 2024). Moreover, Vellan and Leth-Steensen (2022) found that even if conditions allowed the emergence of both effects, the SNARC and SSARC effect do not occur simultaneously. This finding suggests that, in case both physical and numerical magnitude information is present, the processing of the more salient type of space-magnitude-associations is prioritized whereas the processing of the less salient type is blocked. Even though this finding does not rule out a single mechanism underlying both effects, the empirically observed differences between both effects rather suggest different underlying mechanisms.

Research questions

The SNARC and SSARC effect provide evidence that the processing of size-related information affects the processing of spatial information. However, it is yet unknown if the processing of spatial information in turn also affects the processing of size-related information in the form of a reciprocal SNARC and SSARC effect, which would indicate the bidirectionality of the effects and their underlying associations. The major aim of this dissertation is thus to examine if the associations between size and space, which emerge as SNARC and SSARC effects, are bidirectional and, provided that they are bidirectional, to determine if they are symmetrical or asymmetrical. Since, in this dissertation, size is defined twofold in the sense of numerical and physical size, two pairs of research questions arise from the overall objective.

Research question 1a addresses the bidirectionality and symmetry of the SNARC effect: Is the SNARC effect bidirectional allowing for the emergence of a regular and reciprocal SNARC effect? Provided that the SNARC effect is bidirectional, research question 1b arises: Are the regular and reciprocal SNARC effect symmetrical or asymmetrical? Recall that the SNARC effect denotes that numerical sizes prime the selection and execution of spatial responses. Following research question 1, I seek to answer if the SNARC effect also emerges in the opposite direction in the form of a reciprocal SNARC effect, that means, if spatial locations in turn also prime the selection and execution of numerical responses. In case a reciprocal SNARC effect emerges, I seek to answer if the regular and reciprocal SNARC effect are of similar size and thus symmetrical or of different sizes and thus asymmetrical.

Research question 2a addresses the bidirectionality and symmetry of the SSARC effect: Is the SSARC effect bidirectional allowing for the emergence of a regular and reciprocal SSARC effect? Provided that the SSARC effect is bidirectional, research question 2b arises: Are the regular and reciprocal SSARC effect symmetrical or asymmetrical? Recall that the SSARC effect denotes that physical sizes prime the selection and execution of spatial responses. Following research question 2, I seek to answer if the SSARC effect also emerges in the opposite direction in the form of a reciprocal SSARC effect, that means, if spatial locations in turn prime the selection and execution of responses that vary in physical size. In case a reciprocal SSARC effect emerges, I seek to answer if the regular and reciprocal SSARC effect are of similar size and thus symmetrical or of different sizes and thus asymmetrical. The present dissertation comprises four articles and a total amount of seven experiments. While Article 1 (Study 1: Exp. 1-2) and Article 2 (Study 2: Exp. 3-5) examine the bidirectionality and symmetry of spatial-numerical associations and thus address research questions 1a/b, Article 3 (Study 3: Exp. 6) and Article 4 (Study 4: Exp. 7) examine the bidirectionality and symmetry of spatial-size associations and thus address research questions 2a/b.

To differentiate between the directions of effects, I employ the term *regular*

SNARC/SSARC effect to denote the compatibility effect in a number/size-location task, that is, between numerical/physical stimulus sizes and spatial responses. In contrast, I employ the term *reciprocal* SNARC/SSARC effect to denote the compatibility effect in a location-number/size task, that is, between spatial stimuli and responses referring to numerical/physical size. The term *bidirectionality* refers to effects in both the regular and the reciprocal direction. For both the SNARC and the SSARC effect, three potential patterns of associations are conceivable: First, a significant regular SNARC/SSARC effect but a non-significant reciprocal SNARC/SSARC effect would indicate unidirectional associations between numerical/physical size and space. Second, a significant regular SNARC/SSARC effect and a significant reciprocal SNARC/SSARC effect that differ in size would indicate bidirectional but asymmetrical associations between numerical/physical size and space. Third, a significant regular SNARC/SSARC effect and a significant reciprocal SNARC/SSARC effect of similar size would indicate bidirectional and symmetrical associations between numerical/physical size and space.

Motivation of research

Despite the prevalence of studies investigating the SNARC effect, only a few studies have so far investigated the reciprocity of spatial-numerical associations. Employing random number generation tasks, Loetscher and colleagues (2008, 2010) demonstrated that head movements to the left or eye movements to the bottom-left corresponded with the production of small numbers while head movements to the right or eye movements to the top right corresponded with the production of large numbers. Despite corroborating the close link between spatial and numerical information processing, those correlational results in the form of response-response (R-R) priming effects do not prove any causal influence of spatial information processing on the processing of numbers.

Shaki and Fischer (2014) extended those findings by demonstrating that spatial actions in the form of prescribed turns influenced the generation of random numbers: prescribed left turns facilitated the production of small numbers whereas prescribed right turns facilitated the production of large numbers. Since this effect might either be caused by the given instruction (turn to the left) in the form of a S-R priming effect or by the planning of the spatial action in the form of a R-R priming effect, the processing level involved is still ambiguous. Similarly, Stoianov and colleagues (2008; see also Kramer et al., 2011) demonstrated that spatial prime stimuli may affect numerical judgements made by “neutral” vocal responses in the form of a stimulus-stimulus (S-S) congruency effect thereby showing that spatial information may affect numerical processing at a central stage of processing. Taken together, it still remains an open question if a spatial stimulus can facilitate or impede the selection and execution of a numerical response in the form of a S-R priming effect, which thus motivates Studies 1 and 2.

No study has so far addressed the question of reciprocity with regards to the SSARC effect. The observed differences between the SNARC and SSARC effect, which indicate different underlying mechanisms and preclude generalizing findings across both effects, however, underline the necessity to investigate the bidirectionality and symmetry of both the SNARC and the SSARC effect separately and thus motivate Studies 3 and 4.

Above all, investigating the bidirectionality of the SNARC and the SSARC effect allows to differentiate between the existing accounts of the two effects. Several theoretical accounts have been proposed in order to explain the structural overlap between numerical/physical size and spatial location, which underlies the SNARC/SSARC effect (Kornblum et al., 1990). Importantly, the existing theoretical accounts of the SNARC/SSARC effect differ in whether they assume symmetrical or asymmetrical associations between numerical/physical size and space. The main objective of this dissertation is thus twofold. First, I seek to investigate the bidirectionality and symmetry of associations between numerical and physical size on the one hand and space on the other hand as they emerge as S-R compatibility effects. Second, in doing so I seek to differentiate between the theories accounting for the effects.

Theoretical accounts and their predictions

In the following, I will outline four theoretical accounts and their predictions about the bidirectionality of the SNARC/SSARC effect: the mental number line, the polarity correspondence principle, the working memory account and the correlations in experience principle. While all four theories can account for the SNARC effect, only the latter three can account for the SSARC effect.

The *mental number line (MNL)* (Dehaene et al., 1993; Dehaene, 2003; Fischer & Shaki, 2014) was one of the first theories to be proposed and was dedicated to account for the SNARC effect specifically. According to the MNL, numbers are mentally represented in an ascending order from left to right on a spatial continuum. While small numbers are located on the left of this continuum, large numbers are located on the right. The activation of a number during number processing simultaneously activates its spatial location on the MNL, which in turn primes a corresponding spatial response (Dehaene et al., 1993; Fischer et al., 2003; Restle, 1970). Many authors assume the MNL to be activated on a central level between stimulus processing and response selection (Dehaene et al., 1993; Ginsburg & Gevers, 2015; Huber et al., 2016; Umiltà et al., 2010) and to be part of long-term memory (Dehaene et al., 1993; Ginsburg & Gevers, 2015; Huber et al., 2016).

Even though the MNL assumes one joint mental representation of number and space (Fischer & Shaki, 2014) – and with that a simultaneous activation of both dimensions – and may therefore account for bidirectional and symmetrical SNARC effects, the MNL may also account for unidirectional or (bidirectional but) asymmetrical SNARC effects. Since the MNL is located between stimulus and response representations as, for instance, assumed by *Dehaene's (1992) Triple-Code Model*, directional asymmetries might arise between stimulus codes and the MNL and/or between the MNL and response codes. Numerical and spatial stimuli might thus activate the MNL to different degrees and/or the activation of the MNL might in turn activate spatial and numerical responses to a different degree. In the same vein, the MNL may account for an effect of stimulus or response mode on the emergence of the regular or reciprocal SSARC effect. Note, however, that the MNL is considered a visuospatial account of spatial-numerical associations (Umiltà et al., 2010), which should thus favor a visuospatial stimulus or response mode.

In contrast to the MNL, the so-called *working memory (WM) account*, which was proposed by van Dijck and colleagues (Abrahamse et al., 2016; Van Dijck & Fias, 2011; Van Dijck et al., 2015), assumes that associations between number and space are formed in working memory. According to the WM account, the elements of a given stimulus set are systematically stored in WM in a canonical order and it is the serial position of an element that corresponds with the spatial response location thus leading to compatibility effects. While early serial positions are associated with left spatial locations, late serial positions are associated with right spatial locations. Importantly, with serial position being the crucial factor, the WM account may account for associations between any ordinal quantity and space (Van Dijck & Fias, 2011; Van Dijck et al., 2015).

The WM account has later been developed into a more general *mental whiteboard hypothesis,* which specifies the coding of serial order in verbal WM (Abrahamse et al., 2014, 2017; De Belder et al., 2015). According to the mental whiteboard hypothesis, the serial position of an element is encoded by connecting this element to a spatial position marker "within an internal, spatially defined system" (Abrahamse et al., 2014, p. 2). This spatial coding of serial order is furthermore assumed to spontaneously "occur[…] from left to right" (Abrahamse et al., 2014, p. 2). In terms of the SNARC/SSARC effect, numerical/physical sizes of a given stimulus set are spontaneously stored in WM in an ascending order from left to right by connecting small numbers/sizes at early serial positions to left position markers and large numbers/sizes at late serial positions to right position markers. While the left position markers then prime left responses, the right position markers in turn prime right responses.

It is unclear if the WM account/mental whiteboard hypothesis predicts or at least can account for a reciprocal SNARC/SSARC effect. In this case, the account would have to assume that spatial stimuli are serially stored from left to right by connecting them to spatial position markers. This assumption alone, however, does not suffice to explain the activation of a response referring to numerical/physical size. Instead, those size-related responses would also have to be serially stored in WM by connecting responses referring to small sizes to left position markers and responses referring to large sizes to right position markers. Corresponding position markers of stimuli and responses could then facilitate performance whereas non-corresponding position markers of stimuli and responses could then impede performance. Because the account does not address the possibility of serial order coding for response sets, the account's predictions remain as unclear as any potential effect of response mode on the emergence of the regular and reciprocal effect. Since the serial order of stimuli is encoded in verbal WM (Abrahamse et al., 2014, 2017; De Belder et al., 2015), the WM account/mental whiteboard hypothesis should, however, favor a verbal stimulus mode.

The *polarity correspondence principle* postulated by Proctor and colleagues (Proctor & Cho, 2006) proposes that in many binary classification tasks, in which stimuli and responses vary on bipolar dimensions, one stimulus and response alternative is assigned negative polarity whereas the other stimulus and response alternative is assigned positive polarity. While corresponding polarities of a given stimulus and the required response facilitate performance in terms of response speed and accuracy, non-corresponding polarities impede performance (Lakens, 2012; Proctor & Cho, 2006; Proctor & Xiong, 2015). According to the polarity correspondence principle, SNARC and SSARC effects thus arise because the categories "(numerically/physically) small" and "left" are given the same negative polarity whereas the categories "(numerically/physically) large" and "right" are given the same positive polarity. Since the categorization of one stimulus/response alternative depends on its opposing stimulus/response alternative, the assignment of polarities occurs spontaneously in a context-dependent manner, furthermore implying that spatial-numerical/size associations emerge as part of the working memory (WM).

Even though Proctor and colleagues do not address the question of bidirectionality, the polarity correspondence principle should predict bidirectional and symmetrical effects because numerical/physical sizes and locations are assigned polarities regardless of being varied as stimulus or response feature. For instance, the categories "left" and "right" are not only assigned negative and positive polarity when they refer to alternative responses as in the regular SNARC/SSARC effect but also when they refer to alternative stimuli as in a reciprocal SNARC/SSARC effect. This has been corroborated by a superior processing of right compared to left stimulus locations due to the saliency of the positive polarity (Just & Carpenter, 1975; Olson & Laxar, 1973). Likewise, the categories "(numerically/physically) small" and "(numerically/physically) large" should not only be assigned negative and positive polarity when they refer to alternative stimuli as in the regular SNARC/SSARC effect but also when they refer to alternative responses as in a reciprocal SNARC/SSARC effect. Since the binary categories of numerical/physical size and location can be presented in various formats and still receive polarity (Proctor & Cho, 2006), regular and reciprocal SNARC/SSARC effects should not be affected by stimulus or response mode.

The *correlations in experience (CORE) principle* proposed by Pitt and Casasanto (2020) assumes that the mental representations of two dimensions become associated because these two dimensions have been experienced to be correlated in the natural or cultural world. In particular, “people spatialize abstract domains in their minds according to the ways those domains are spatialized in their experience” (Pitt & Casasanto, 2020, p. 1048). This ties in with the broader *hierarchical mental metaphors theory (HMMT)* by Casasanto and colleagues (Casasanto, 2017; Casasanto & Bottini, 2014), which assumes a hierarchical structure of mental metaphors that employ a source domain (e.g., space) to mentally represent and structure a target domain (e.g., numerical/physical size). According to CORE, the SNARC effect emerges because of experiences such as finger counting that involve a correlation between number and space, which is then employed to mentally represent the abstract domain of number (Pitt & Casasanto, 2020). Since during finger counting, numerical size and space are both situated on the stimulus as well as response level, the CORE principle should predict bidirectional and symmetrical spatial-numerical associations.

Wühr and colleagues (2024) applied the CORE principle to also account for the SSARC effect. They proposed that grasping habits shape the associations between physical size and space because people typically grasp larger/heavier objects with their stronger dominant hand but smaller/lighter objects with their weaker non-dominant hand. Since during grasping movements, physical size is situated on the stimulus level while spatial location is situated on the response level, the CORE principle should predict unidirectional or at least strongly asymmetrical spatial-size associations. The CORE principle does not necessarily predict an effect of stimulus or response mode on the emergence of a regular/reciprocal SNARC and regular SSARC effect assuming that associations between the mental representations are not restricted to the stimulus or response mode the underlying correlation was originally experienced in. This is in line with the HMMT (Casasanto, 2017; Casasanto & Bottini, 2014) and previous evidence corroborating the modality-independence of mental metaphors (Wühr et al., 2024).

However, since the CORE principle as well as the HMMT remain mute about the reciprocity of compatibility effects, alternative assumptions are conceivable, which lead to different predictions. One could, for example, argue that since correlations do not specify a causal relationship between two variables, the correlations experienced in people's natural or cultural world lead to undirected associations in people's minds without specifying the dimension's situatedness on stimulus or response level. This assumption would predict bidirectional and symmetrical SNARC and SSARC effects. Moreover, it seems also plausible to assume that – according to the HMMT, which proposes the employment of a source domain to mentally represent a target domain (Casasanto, 2017; Casasanto & Bottini, 2014) – an activation of the target domain necessarily activates the employed source domain but an activation of the source domain does not activate any potential target domain employing the source domain. This would predict unidirectional or at least strongly asymmetrical SNARC and SSARC effects in the form of significant regular but non-significant reciprocal effects.

A theory of magnitude (ATOM) by Walsh (2003, 2015) constitutes another theory that has been proposed to account for compatibility effects. However, due to its lack of predictions and its inability to account for compatibility effects involving a metathetic (Sixtus et al., 2023; Stevens, 1958) dimension such as spatial location as in the SNARC/SSARC effect (Casasanto & Pitt, 2019), I refrain from depicting and discussing the question of bidirectionality with regards to ATOM.

Main objectives of Studies 1 and 2 on the bidirectionality of the SNARC effect

To investigate the bidirectionality and symmetry of the SNARC effect, we compared the compatibility effects of two tasks. In a number-location task, participants responded to numerical stimulus size with horizontal location responses, thus resembling a typical SNARC task. Contrarily, in a location-number task, participants responded to horizontal stimulus location with responses referring to numerical size. The location-number task is thus equivalent to a reciprocal SNARC task. In both tasks, participants were asked to respond once according to a compatible and once according to an incompatible mapping.

The main objectives of Study 1 were to investigate the bidirectionality and symmetry of the SNARC effect with manual responses and to test the predictions the different accounts of the SNARC effect make. We chose to employ manual responses since this response mode has been employed in the majority of studies investigating the SNARC effect and thus increases comparability between the experimental designs investigating the regular and the reciprocal SNARC effect. In Exp. 1 of Study 1, participants completed the location-number task by pressing a key once or twice to a left or right stimulus location. In the number-location task, participants responded to one or two dots by pressing a left or right key with two fingers of the same hand. We employed the number of dots as stimuli in the number-location task to achieve a high set-level compatibility (Kornblum et al., 1990) with the number of responses in the location-number task. However, since physical size was confounded with numerical size in Exp. 1, we cannot rule out that the SSARC effect contributed to our results in the number-location task. In Exp. 2 of Study 1, we therefore employed the same experimental set-up but replaced the dot stimuli by the digit stimuli 1 and 2.

The main objectives of Study 2 were to investigate the bidirectionality and symmetry of the SNARC effect with vocal responses and again to test the predictions the different accounts of the SNARC effect make. This time, we chose to employ vocal responses. Even though manual responses have been mainly employed so far, according to Gevers and colleagues (2010) “verbal-spatial coding was the dominant factor in driving the SNARC effect” (p. 187). Results with vocal responses might thus turn out different than with manual responses. In Exp. 1 of Study 2, we employed the same experimental set-up as in Exp. 2 of Study 1, but we replaced the manual by vocal responses. In the number-location task, participants responded to the digit 1 or 2 by saying “left” or “right”. In the location-number task, participants responded to a left or right stimulus location by saying “one” or “two”.

To demonstrate the robustness of our results, we employed a different numerical size set in Exp. 2 of Study 2 and replaced numbers 1 and 2 by numbers 1 and 9. While it is difficult to employ a response set other than 1 and 2 with manual responses, we can easily vary response sets with vocal responses, which allows us to employ numerical values with a more salient distance, such as 1 and 9. Moreover, we can eliminate any potential influence of the so-called *markedness association of response codes (MARC) effect*, which denotes faster and more accurate left responses to odd numbers and faster and more accurate right responses to even numbers, as compared to the reverse assignment (Berch et al., 1999; Cipora et al., 2019; Nuerk et al., 2004). While the SNARC and MARC effects were confounded in Exp. 1 because the smaller number (1) was odd and the larger number (2) was even, the employment of numbers with the same parity (1 and 9) allows to eliminate this confound. In the number-location task, participants therefore responded to the digit 1 or 9 by saying “left” or “right”. In the location-number task, participants responded to a left or right stimulus location by saying “one” or “nine”.

In Exp. 3 of Study 2, we replaced the visuospatial stimuli in the form of physical locations in the location-number task by verbal stimuli in the form of location words (“left” / “right”) to investigate how a consistent use of alphanumeric stimuli and responses would affect the pattern of results[2]. In the former experiments, we used alphanumeric stimuli in the form of digits in the number-location task but visuospatial stimuli in the form of physical locations in the location-number task, rendering both tasks less comparable. First, attention remains fixated at the screen center in the number-location task whereas it gets shifted to the left or right in the location-number task. Second, verbal-spatial coding might be emphasized in the number-location task with alphanumeric stimuli whereas visuospatial coding might be emphasized in location-number task with visuospatial stimuli (Gevers et al., 2010). Importantly, the theoretical accounts of the SNARC effect differ in whether they predict any effect of stimulus or response mode on the emergence of the regular and reciprocal SNARC effect. With Exp. 3 of Study 2 we were able to test the accounts' predictions regarding the effect of stimulus mode on the reciprocity of the SNARC effect. For consistency reasons, we additionally replaced the digits by number words ("one" / "nine") in Exp. 3. Thus, in the number-location task, participants responded to the number words "one" or "nine" by saying "left" or "right" while, in the location-number task, participants responded to the location words "left" or "right" by saying "one" or "nine".

Main objectives of Studies 3 and 4 on the bidirectionality of the SSARC effect

To investigate the bidirectionality and symmetry of the SSARC effect, we employed a similar experimental design and compared the compatibility effects of two tasks. In a size-location task, participants responded to stimulus size with horizontal location responses, thus resembling a typical SSARC task. Contrarily, in a location-size task, participants responded to horizontal stimulus location with responses referring to physical size. The location-size task is

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[2] Please note that all stimuli were presented visually. While I refer to *verbal* stimuli in the sense of written, I refer to *vocal* responses in the sense of spoken.

thus equivalent to a reciprocal SSARC task. In both tasks, participants were asked to respond once according to a compatible and once according to an incompatible mapping.

The main objectives of Study 3 were to investigate the bidirectionality and symmetry of the SSARC effect and to test the predictions the different accounts of the SSARC effect make. We employed vocal responses since, firstly, in the location-size task, responses had to refer to different physical sizes, which is difficult to achieve with manual responses, and secondly, previous studies have shown that regular SSARC effects of similar size emerge with vocal and manual responses (Wühr et al., 2024). In the size-location task, participants therefore responded to a physically small or large stimulus by saying “left” or “right”. In the location-size task, participants responded to a left or right stimulus location by saying “small” or “large”.

Similar to Exp. 3 of Study 2, the first objective of Study 4 was to investigate how a consistent use of alphanumeric stimuli and responses would affect the pattern of results with regards to the regular and reciprocal SSARC effect. We employed the same experimental set-up as in Study 3 but replaced the physical size/location stimuli by verbal size/location stimuli thus allowing attention to remain fixated at the screen center in both tasks and enhancing the set-level compatibility between verbal stimuli and vocal responses for each task (Kornblum et al., 1990). Since the theoretical accounts of the SSARC effect differ in whether they predict any effect of stimulus mode on the emergence of the regular and reciprocal SSARC effect, the second objective of Study 4 was to differentiate between those theories by testing their predictions. In the size-location task, participants responded to the size words “small” or “large” by saying “left” or “right”. In the location-size task, participants responded to the location words “left” or “right” by saying “small” or “large”.

2. Article 1 – Richter, M., & Wühr, P. (2023). Spatial-numerical associations of manual response codes are strongly asymmetrical. *Cognition, 238*, 105538.

Spatial-numerical associations of manual response codes are strongly asymmetrical

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Abstract

The *spatial-numerical association of response codes (SNARC) effect* denotes the observation that humans respond faster and more accurately with a left-side response to smaller numbers and a right-side response to larger numbers, as compared to the opposite mapping. Existing accounts, such as the mental number line hypothesis or the polarity correspondence principle, differ in whether they assume symmetrical associations between numerical and spatial stimulus and response codes or not. In two experiments, we investigated the reciprocity of the SNARC effect in manual choice-response tasks with two conditions. In the number-location task, participants pressed a left or right key to a number stimulus (dots in Experiment 1, digits in Experiment 2). In the location-number task, participants made one or two consecutive keypresses with one hand to a left- or right-side stimulus. Both tasks were performed with a compatible (one-left, two-right; left-one, right-two) and an incompatible (one-right, two-left; left-two, right-one) mapping. In both experiments, results showed a strong compatibility effect in the number-location task, reflecting the typical SNARC effect. In contrast, in both experiments, there was no mapping effect in the location-number task when outliers were excluded. However, when outliers were not excluded, small reciprocal SNARC effects occurred in Experiment 2. Together, the findings suggest that priming of spatial responses by numerical stimuli is much stronger than priming of numerical responses by spatial stimuli. The results are consistent with some accounts of the SNARC effect (e.g., the mental number line hypothesis), but not with others (e.g., the polarity correspondence principle).

Keywords: spatial-numerical associations; SNARC; reciprocity; symmetry; mental number line; polarity correspondence

Introduction

Many empirical studies provide evidence for the existence of associations between numerical size and spatial position. The most established evidence for *spatial-numerical associations* (*SNAs*) is probably the *spatial-numerical association of response codes (SNARC) effect* (see Gevers & Lammertyn, 2005; Fischer & Shaki, 2014 for reviews), which was first demonstrated by Dehaene and colleagues (1990). In their experiment, participants were supposed to decide if two-digit numbers ranging between 31 and 99 were larger or smaller than a given standard of 65. The authors additionally varied the stimulus-response mapping: One group responded by pressing a left key for smaller numbers and a right key for larger numbers, while the second group responded with the opposite mapping. Dehaene et al. (1990) observed faster responses with the mapping "smaller-left/larger-right" than with the mapping "smaller-right/larger-left". Subsequent studies have shown that SNARC effects also arise when number is an irrelevant stimulus feature, which implies that numerical size is automatically processed (e.g., Dehaene et al., 1993; Gevers et al., 2006; Mapelli et al., 2003).

Further studies revealed that the SNARC effect also emerges with different stimulus and response sets. Nuerk and colleagues (2005), for example, observed similar SNARC effects when stimuli were visually presented numbers, verbal numerals, die-faces (number of dots) or auditorily presented numbers. Moreover, SNARC effects do not only occur for bimanual responses but also for unimanual (e.g., Priftis et al., 2006) and verbal responses in two-choice tasks (e.g., Gevers et al., 2010). Hence, the SNARC effect seems to be independent from stimulus and response sets, which suggests that it does not rely on direct associations between stimulus and response codes but is mediated by an intervening representational level. Investigations of spatial-numerical associations without the involvement of response codes have shown that SNAs also occur in single response tasks such as number detection tasks or Go/No-Go-tasks, revealing that number and space are also intrinsically linked at a conceptual level (Aulet et al., 2021; Fischer & Shaki, 2016; Thevenot et al., 2018).

The SNARC effect describes the phenomenon that numerical stimuli influence the selection and execution of spatial responses. More specific, the effect illustrates that small numbers facilitate the selection and execution of left responses whereas large numbers facilitate the selection and execution of right responses. The present study investigates if this effect can also occur in a reciprocal[3] manner, that is, if spatial positions as stimuli can influence the selection and execution of "numerical" responses. In a nutshell, this paper addresses the question if the typical SNARC effect is bidirectional or not. In fact, several theories accounting for the SNARC effect assume symmetrical associations between spatial and numerical representations, which should result in bidirectional response priming effects.

The most popular account of the SNARC effect is the *mental number line* (*MNL*) (e.g., Dehaene et al., 1993; Dehaene, 2003; Fischer & Shaki, 2014). According to the MNL, numbers are mentally represented from left to right in an ascending order and the activation of a number simultaneously activates the corresponding position on the MNL. Many authors assume that the MNL is part of *long-term memory (LTM)*, which is activated between stimulus processing and response selection (e.g., Feldman et al., 2019; Ginsburg & Gevers, 2015; Huber et al., 2016; Umiltà et al., 2010). According to this assumption, numerical stimuli activate spatial positions on the MNL, which in turn prime corresponding responses (Restle, 1970; Dehaene et al., 1993; Fischer et al., 2003). Many authors expect the MNL to be indicative of bidirectional effects due to the simultaneous activation of spatial and numerical information

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[3] In previous literature, the term "reverse" SNARC effect has been employed to denote superior performance of right responses to small stimuli and left responses to large stimuli as compared to the opposite mapping. To avoid ambiguity, we decided to use the term "reciprocal" SNARC effect for denoting compatibility effects with location stimuli and number responses.

(e.g., Aulet et al., 2021; Fischer & Shaki, 2015; Hartmann et al., 2012; Kramer et al., 2011; Lugli et al., 2013; Shaki & Fischer, 2014; Stoianov et al., 2008).

Another theoretical account of the SNARC effect is *a theory of magnitude* (*ATOM*). In ATOM, Walsh (2003, 2015) postulates the existence of a module in the parietal cortex that processes and integrates information of various dimensions such as quantity, size, space, and time (see also Bueti & Walsh, 2009). Evidence for the existence of such a module stems from neuropsychological, neurophysiological, and behavioral studies. ATOM, for example, predicts interferences and priming effects between different dimensions such as quantity, size, space and time, which behavioral studies have shown (Bueti & Walsh, 2009; Walsh, 2003).

Given the assumption of a common metric, one could presume that ATOM predicts bidirectional interactions between different dimensions. This is, however, not the case. According to Walsh (2015), some dimensions might not interfere as their processing abilities develop at different times and thus might form hierarchies. Yet, ATOM does not make any prediction which dimensions do or do not interact. According to Casasanto and Pitt (2019), ATOM cannot even explain SNARC-like effects involving spatial position as the crucial response variable since ATOM was explicitly postulated to account for interferences between prothetic[4] variables (e.g., Walsh, 2003, 2015). Unlike numerical size, spatial position is not a prothetic but a metathetic variable and as such cannot be measured, resulting in the incommensurability of both dimensions.

While some theoretical accounts assume long-term associations between numerical size and space such as the MNL or ATOM, other accounts assume that the SNARC effect rests upon

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[4] According to Stevens (1958), dimensions that require judgments of quantity or magnitude (e.g., size, intensity) are called *prothetic* dimensions. In contrast, dimensions that require judgments of “what” and “where” (e.g., positions or locations) are called *metathetic* dimensions. See Sixtus et al. (2023) for a receptor-based distinction between prothetic and metathetic variables.

short-term associations, which are established for or while performing a particular task. The latter include the *polarity correspondence principle* by Proctor and colleagues (e.g., Proctor & Cho, 2006) as well as the *working memory (WM) account* by van Dijck and colleagues (e.g., van Dijck & Fias, 2011). In the polarity correspondence principle, Proctor and colleagues postulate that in many binary classification tasks with stimuli and responses varying on bipolar dimensions (e.g., size, quantity, position, etc.), one stimulus and response category is assigned a positive polarity while the opposite stimulus and response category is assigned a negative polarity. The authors exemplify that in a typical SNARC task, the categories “small” and “left” are given negative polarity, whereas the categories “large” and “right” are given positive polarity (Proctor & Cho, 2006). Tasks in which the polarities of stimuli and responses correspond lead to faster reactions and fewer errors than tasks in which the polarities do not correspond (Lakens, 2012; Proctor & Cho, 2006; Proctor & Xiong, 2015). The associations between stimulus and response alternatives on the one hand and between polarities on the other hand are short-termed as they depend on the given stimulus and response set (Nathan et al., 2009; Gevers et al., 2006; Wühr & Richter, 2022). The polarity correspondence principle implies the existence of bidirectional SNARC effects because polarities are assigned to category labels regardless of whether these categories contain stimuli or responses.

More recently, van Dijck and colleagues proposed that the SNARC effect depends on the serial order in which the elements of a stimulus set are stored in WM (e.g., van Dijck & Fias, 2011; van Dijck et al., 2015). Van Dijck and Fias (2011) investigated the SNARC effect in a dual-task in which participants were to respond to the parity of a target digit while memorizing a set of digits in random order. The authors observed a significant interaction between the serial position of the target stimulus in the memory set and response position, which indicated faster left-hand responses to numbers in early serial positions and faster right-hand responses to numbers in late serial positions. The absolute size of the target stimulus, however, did not exert any influence. The results suggest that the SNARC effect depends on spontaneous associations between the serial position of stimuli in working memory and spatial position. Early serial positions therefore seem to be associated with left responses and late serial positions seem to be associated with right responses.

The proponents of the WM account do not address the issue of reciprocity, but it is possible to consider whether this account allows for bidirectional SNARC effects or not. Imagine a task in which participants have to press a key once when responding to a left stimulus and twice when responding to a right stimulus (or opposite mapping). If participants memorize the (positions of) stimuli in a canonical order (i.e., from left to right) and the serial positions of stimuli in WM in turn activate corresponding numerical responses, a (reciprocal) SNARC effect could occur in this task. This effect would materialize as shorter RTs in the compatible (left S – one R; right S – two R) than in the incompatible mapping (left S – two R; right S – one R).

Several studies have already aimed at demonstrating the influence of spatial information processing onto the processing of numbers. However, these studies did not employ a variation of the typical SNARC task with spatial stimuli and numerical responses but investigated the influence of spatial actions on the generation of random numbers (*random number generation*, *RNG*). In a study by Loetscher and colleagues (2008), participants were asked to move their heads alternately to the left and right and spontaneously generate a random number between 1 and 30 at each turning point. The results revealed that leftward movements produced more small numbers (<16) than rightward movements. In a following study by Loetscher and colleagues (2010), participants were asked to randomly produce numbers (between 1 and 30) in time to a metronome while their eye movements were measured. The results indicated that eye movements to the bottom left corresponded with the production of rather small numbers while eye movements to the top right corresponded with the production of larger numbers. The findings of Loetscher et al. (2008, 2010) corroborate the close connection between the processing of spatial and numerical information. Yet, since the results are merely correlative, they cannot prove any causal effect the processing of spatial information might have on the processing of numerical information.

Results of a study by Shaki and Fischer (2014) further suggest an impact of spatial actions on number processing. In their experiment 2, participants were instructed to walk a few steps straight ahead and then make a prescribed turn to the left or right. Additionally, participants were asked to say a random number (between 1 and 9) with each step. Participants on average generated smaller numbers prior to a leftward turn compared to a rightward turn. These results underpin the influence of spatial information processing on numerical information processing. However, it is still ambiguous which exact processing levels are involved. It is, for instance, plausible that the given instruction (turn to the left) or the planning of the spatial action might be driving the effect, constituting a stimulus-response (S-R) or a response-response (R-R) priming effect. Therefore, it remains unclear if a spatial stimulus can facilitate or impede the selection of a numerical response.

In a similar vein, Stoinanov et al. (2008) explicitly addressed the possibility that spatial information can (also) affect numerical processing on a central stage of processing (i.e., the MNL). They presented a spatial prime stimulus while participants had to make numerical judgments. The spatial primes affected the numerical judgments when they followed the numerical stimuli but not when the preceded them, which was attributed to the fact that spatial information is processed faster than numerical information (see also Kramer et al., 2011). Note, however, that these authors explicitly excluded the possibility of S-R priming effects by requiring “neutral” vocal responses. In summary, the studies show that spatial information can affect numerical processing at a central stage of processing, but it remains unclear whether spatial information can also prime numerical responses.

We conducted two experiments to investigate the reciprocity of response priming effects in SNARC tasks. In both experiments, we compared the compatibility effects in two tasks. In the *number-location task*, participants responded to a numerical stimulus (one and two dots in Experiment 1; digits 1 and 2 in Experiment 2) with left/right responses, resembling a typical SNARC task. Contrarily, in the *location-number task*, horizontally aligned positions (left/right) served as stimuli, to which participants responded by pressing a key once or twice. The location-number task is thus equivalent to a reciprocal SNARC task. In both tasks, participants were asked to respond with a compatible (one S – left R, two S – right R; left S – one R, right S – two R) and an incompatible mapping (one S – right R, two S – left R; left S – two R, right S – one R). Taking the size of the compatibility effect as a measure for the strength of associations between stimulus and response, three patterns of results are conceivable. Significant compatibility effects of equal size would point to bidirectional and symmetrical associations. Significant compatibility effects in both directions which differ in size would indicate bidirectional but asymmetrical associations. If compatibility effects, however, occur only in the typical number-location task and not in the location-number task, this pattern of results would suggest unidirectional associations.

Experiment 1

In Experiment 1, we investigated the reciprocity of stimulus-response priming between number and space. In particular, we compared S-R compatibility effects in a number-location task, requiring a left or right keypress to one or two dots, to S-R compatibility effects in a location-number task, requiring one or two keypresses to a left or right stimulus location. Hence, the number-location task resembles a typical SNARC task, in which numerical stimulus information can prime a spatial response. In contrast, the location-number task constitutes a reciprocal SNARC task, in which spatial stimulus information could prime a "number" response. We are aware that the most common stimuli in SNARC tasks are digits rather than the number of stimulus items (i.e., numerosity). However, since the manual responses in the location-number task varied in the number of keypresses (i.e., numerosity), we decided to use equivalent stimuli in the number-location task, and thus create equal levels of set-level compatibility (Kornblum et al., 1990) in both tasks.

Methods[5]

Participants

A meta-analysis on the SNARC effect (Wood et al., 2008) reported very strong regular SNARC effects for unimanual responses with an average effect size of $d = 1.69$, which corresponds to partial $\eta^2 = 0.42$. Since we aimed at investigating a so far unknown reciprocal SNARC effect, which might have smaller effect sizes, we decided to cut the effect size estimate by half and use an effect size of partial $\eta^2 = 0.2$ for a power analysis. We used the software MorePower (Campbell & Thompson, 2012) to conduct the power analysis, which revealed that a sample size of 54 participants would be required to detect an effect of this size with high power ($1-\beta = 0.95$) at the standard alpha-error probability of 0.05.

Sixty-four volunteer students (53 female, 11 male) with a mean age of 24.813 years (*SD* = 25.190) participated in our experiment and received either course credit or a payment of 10 Euro in exchange. All participants reported normal or corrected-to-normal vision. Moreover,

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[5] The experiment was preregistered on the website OpenScienceFramework (OSF) (https://osf.io/g3e25).

55 participants described themselves as right-handers, whereas 8 participants described themselves as left-handers and one participant reported to be ambidextrous. Prior to participation, volunteers gave their informed consent. The local Ethics Committee at TU Dortmund University approved the experimental protocol for our study (GEKTUDO_2022_36).

Apparatus and Stimuli

With a viewing distance of approximately 50 cm, participants sat in front of a customary 19-inch color monitor. We used EPrime 3.0 (Psychology Software Tools; Sharpsburg, PA, USA) to control the presentation of stimuli and to register responses (i.e., key pressed, reaction time (RT)). At the beginning of each trial, a small plus sign (Courier font, size 18 pt) at the screen center served as a fixation point. All imperative stimuli were presented in black on a white background. In the number-location task, the imperative stimulus was either one black dot or two black dots, presented at screen center. Each dot had a diameter of 15 mm. Two dots were shown in a diagonal configuration (one dot placed to the top right of the other dot), which was 30 mm in width and height. Participants responded to the stimuli by pressing the “left arrow” key with the index finger and the “right arrow” key with the middle finger of their right hand. In the location-number task, the imperative stimulus was a black square with a side length of 20 mm, which appeared at the center of the left or the right screen half. Participants responded by pressing the “down arrow” key one or two times with their right hand’s index finger. We decided to use the arrow keys of a German standard keyboard as they allowed for unimanual responses in both tasks with three adjacent keys of similar size. The keyboard was centrally aligned to the participant’s body midline, and the responding hand was in a comfortable position to the right of the body midline. In studies of spatial S-R compatibility, the position of the hand (left or right of body midline) did not affect the spatial coding of two adjacent fingers of the same hand (e.g., Heister et al., 1987).

Procedure

Each participant completed four conditions, which resulted from combining two tasks (number-location task, location-number task) and two S-R mappings (compatible, incompatible). In the regular number-location task, participants had to respond to the number of dots presented (one or two) by pressing a left or right key with the index and middle finger of their right hand according to a compatible mapping (one S – left R, two S – right R) or an incompatible mapping (one S – right R, two S – left R). In the location-number task, participants had to respond to stimulus location (left or right) by pressing a key with the index finger of their right hand once or twice according to a compatible mapping (left S – one R, right S – two R) or an incompatible mapping (left S – two R, right S – one R).

At the beginning of each condition, instructions presented at the screen informed participants about the content and the procedure of the following task. Each condition consisted of one training block and two experimental blocks. Each training block consisted of 10 trials and each experimental block consisted of 40 trials. Trials were randomized within blocks. At the beginning of each trial, a fixation point was presented for 400 or 600 ms with both durations occurring equally often within each block. Then, the imperative stimulus was presented until a response was made or for a maximum of 2,000 ms. In case of a correct response, an inter-trial interval with an empty screen was presented for 1,000 ms. In case of an error or missing response, a corresponding error message was presented during the inter-trial interval. Task and S-R mapping instructions were repeated at the beginning of each experimental block. Between blocks, participants were able to take a break or to continue with the subsequent block.

The experiment took about 30-40 min. While the experimenter stayed in the laboratory for the practice blocks, she left the laboratory for the experimental blocks. Participants completed both S-R mapping conditions of the two tasks consecutively. The order of tasks (number-location or location-number first) and the order of mappings (compatible or incompatible mapping first) was counterbalanced between participants. The order of mappings between tasks was the same within one participant.

Design and Data Analysis

We planned two sets of analyses. The first analysis, a two-way ANOVA, investigated the impact of two independent variables (i.e., Task, Mapping) on the dependent variables (i.e., RTs, error percentages). The factor *Task* contained two levels: the number-location task with number (one vs. two dots) as the critical stimulus feature and location (left vs. right keypress) as the critical response feature and the location-number task with location (left vs. right stimulus) as the critical stimulus feature and number (one vs. two keypresses) as the critical response feature. The second independent variable *S-R Mapping* also had two levels, a compatible mapping condition (one S – left R, two S – right R in the number-location task; left S – one R, right S – two R in the location-number task), and an incompatible mapping condition (one S – right R, two S – left R in the number-location task; left S – two R, right S – one R in the location-number task). Both variables were manipulated within subjects, in different blocks of trials, which were counterbalanced between participants. Reaction Times (RTs) of correct unimanual keypress responses and error percentages served as dependent variables. However, in conditions where two keypresses were required, the program measured RTs of the second keypress only and failed to record RTs of the first keypress or inter-response times. In the location-number task, the mean RT thus consisted of a mixture of first and second keypress responses. Nevertheless, the program recorded the number of keypress responses which were made by participants, which ensured an appropriate monitoring for the presence/absence of a second keypress and thus checked response accuracy.

In case the ANOVA's two-way interaction was significant, we planned to use *t* tests to determine the source of interaction. Although error percentages are typically not normally distributed, we preferred using *t* tests over non-parametric tests, such as the Wilcoxon test, because error percentages often contain a large number of ties, which represent evidence for H0, but are excluded from the non-parametric test. Since the hypothesis of unidirectional associations predicts a null effect in the location-number task, but evaluating null effects as evidence for the null hypothesis is difficult in the framework of null-hypothesis significance testing, we also report the Bayes Factor (BF) for each pair-wise comparison (Rouder et al., 2009). The BF allows to evaluate how strongly the data support either H0 or H1. To interpret the BF values, we refer to the evidence categories provided by Jeffreys (1961, as cited in Lee & Wagenmakers, 2014).

The second analysis investigated the time course of mapping effects on RTs in the two tasks. This analysis was motivated by the results of previous studies showing that the size of SNARC effects, like other compatibility or congruency effects, depends on response speed (i.e., RT; see Proctor et al., 2011, for a review). In particular, it has been reported that the SNARC effect in number-location tasks increases when RT increases (e.g., Gevers et al., 2006; Mapelli et al., 2003). Hence, a first objective of our analysis is to check whether the time course of the mapping effects in our number-location task is similar to the well-known time course of SNARC effects. A second aim of our analysis is to investigate whether a small mapping effect might have occurred for a particular RT level in the location-number tasks, which did not achieve statistical significance in the omnibus analysis.

In our preregistration, we planned to apply the Tukey (1977) criterion for identifying and excluding outliers. In particular, according to this method, observations are considered outliers when they are located more than 1.5 *IQR*s below the second quartile of the distribution, or more than 1.5 *IQR*s above the third quartile of the distribution. However, we also analyzed our data with the complete sample, and we report the results in the appendix to allow for comparisons between the results with and without outliers.

Results

Data trimming

As preregistered, we applied the Tukey (1977) criterion for identifying and excluding outliers in dependent variables, which led to the exclusion of three participants[6]. For determining outliers, we collapsed data across the mapping variable, and considered four variables (i.e., mean RT and mean error percentage in number-location task, mean RT and mean error percentage in location-number task). The same participants would have been excluded with a different, often used criterion for outlier identification (i.e., *M* +/- 2.5 *SD*). Our remaining sample thus consisted of 61 participants. However, to allow readers to check how exclusion of participants affected the results, we decided to report the results for the complete sample in **Appendix A**.

There were less than 1% of trials with too fast responses (i.e., RT < 100 ms) in both the number-location task (*M* < 0.01%, *SD* < 0.01) and in the location-number task (*M* < 0.01%, *SD* < 0.01). Similarly, there were less than 1% of trials with too slow responses (i.e., RT > 1,500 ms) in both the number-location task (*M* = 0.042%, *SD* = 0.231) and in the location-number task (*M* = 0.042%, *SD* = 0.282). These trials were eliminated before further analysis.

Reaction Times (RTs)

RTs from trials with correct responses were subjected to a two-factorial Analysis Of

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[6] Participant numbers 6, 32 and 44 were excluded from the dataset of Experiment 1. Note that participant numbers range from 1 to 65 instead of 64 because participant number 30 is non-existent due to an error in the data collection.

Variance (ANOVA) with *Task* (number-location task vs. location-number task) and *Mapping* (compatible vs. incompatible mapping) as within-subjects factors. Both main effects and the two-way interaction were significant. The significant main effect of *Task*, *F*(1, 60) = 75.941, *MSE* = 1748.656, $p < .001$, partial $\eta^2 = 0.559$, reflected shorter RTs in the number-location task (*M* = 387 ms, *SD* = 53) than in the location-number task (*M* = 434 ms, *SD* = 50). The significant main effect of *Mapping*, *F*(1, 60) = 19.649, *MSE* = 661.925, $p < .001$, partial $\eta^2 = 0.247$, reflected shorter RTs with the compatible mapping (*M* = 403 ms, *SD* = 54) than with the incompatible mapping (*M* = 418 ms, *SD* = 58). The most important finding, however, was the significant two-way interaction, *F*(1, 60) = 16.954, *MSE* = 525.989, $p < .001$, partial $\eta^2 = 0.220$, indicating different mapping effects in the two tasks.

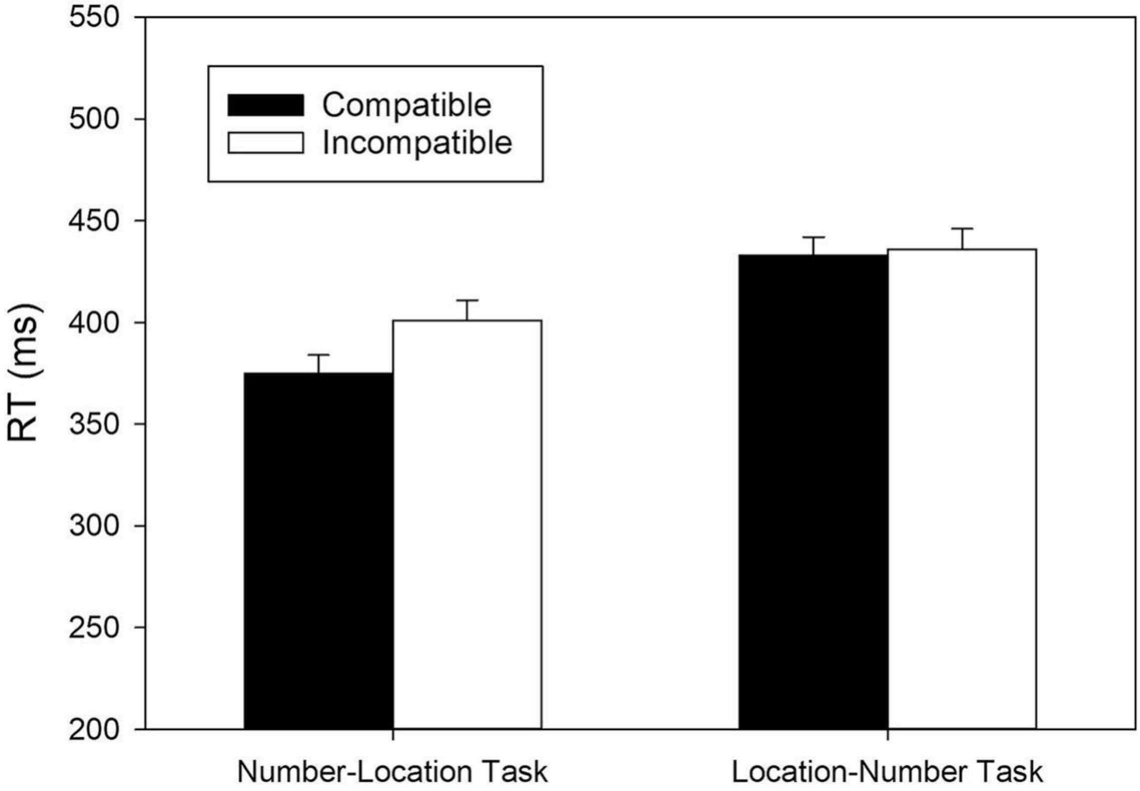

Figure 1. RTs of correct responses observed in Experiment 1 as a function of Task and S-R Mapping. Error bars reflect 95% confidence intervals for within-subjects designs (Cousineau, 2017). In the number-location task, we measured RT of a single keypress in all conditions. In

the location-number task, we measured RT of a single keypress or RT of the second keypress in a sequence of two.

To uncover the source of the two-way interaction, we compared compatible and incompatible mapping conditions separately for the two tasks. In the number-location task, RTs were significantly shorter in compatible than in incompatible conditions, $t(60) = 6.372$, $p < .001$, $d = 0.816$, $BF_{+0} = 442{,}851.156$, indicating a regular SNARC effect of 27 ms (see **Figure 1**) and extreme evidence for H1. In contrast, in the location-number task, RTs did not differ between the two mapping conditions, $t(60) = 0.543$, $p = .589$, $d = 0.069$, $BF_{+0} = 0.161$, indicating moderate evidence for H0.

Error Percentages

Error percentages were also subjected to a two-factorial ANOVA with *Task* (number-location task vs. location-number task) and *Mapping* (compatible vs. incompatible mapping) as within-subjects factors. Again, both main effects and the two-way interaction were significant. The significant main effect of *Task*, $F(1, 60) = 8.227$, $MSE = 4.863$, $p = .006$, partial $\eta^2 = 0.121$, reflected more errors in the number-location task ($M = 2.463$, $SD = 2.664$) than in the location-number task ($M = 1.653$, $SD = 1.731$). The significant main effect of *Mapping*, $F(1, 60) = 13.667$, $MSE = 4.320$, $p < .001$, partial $\eta^2 = 0.186$, reflected less errors with the compatible mapping ($M = 1.566$, $SD = 1.771$) than with the incompatible mapping ($M = 2.550$, $SD = 2.607$). Again, however, the most important finding was the significant two-way interaction, $F(1, 60) = 6.018$, $MSE = 2.922$, $p = .017$, partial $\eta^2 = 0.091$, indicating different mapping effects in the two tasks.

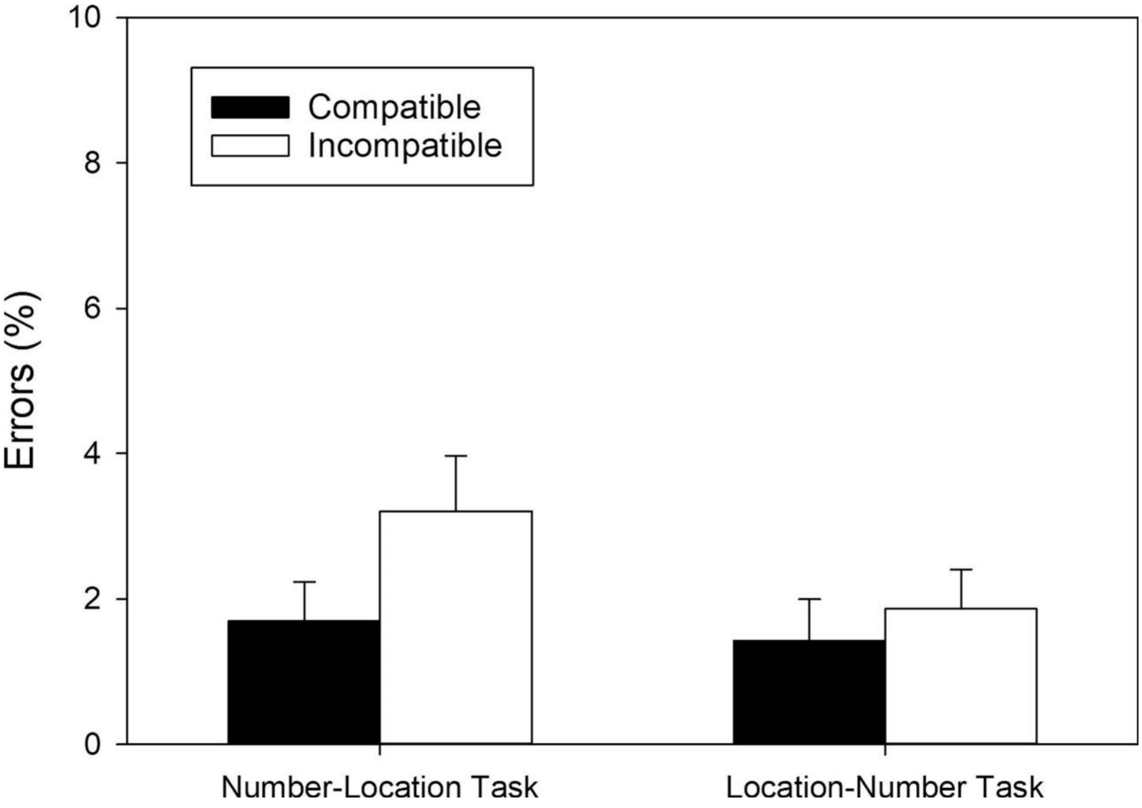

Figure 2. Error percentages observed in Experiment 1 as a function of Task and S-R Mapping. Error bars reflect 95% confidence intervals for within-subjects designs (Cousineau, 2017).

To uncover the source of the two-way interaction, we again compared compatible and incompatible mapping conditions separately for the two tasks. In the number-location task, errors were significantly less frequent in compatible than in incompatible conditions, $t(60) = 3.893$, $p < .001$, $d = 0.498$, $BF_{+0} = 93.154$ (see **Figure 2**), indicating very strong evidence for H1. In contrast, in the location-number task, error percentages did not differ between the two mapping conditions, $t(60) = 1.534$, $p = .130$, $d = 0.196$, $BF_{+0} = 0.424$, indicating anecdotal evidence for H0.

Time course analysis of RTs

For this analysis, we used the method of vincentizing (Ratcliff, 1979). Therefore, we rank-ordered RTs separately for each participant and condition. Then, we divided each rank-ordered set of RTs into four equally-sized quartiles, and computed the mean for each quartile.

The means of the quartiles were then subjected to a three-factorial ANOVA with *Task* (number-location task, location-number task), *Mapping* (compatible, incompatible) and *Quartile* (1-4) as within-subject variables. The corresponding means are shown in **Figure 3**. When reporting the results, we will concentrate on the interactions between *Quartile* and the other variables.

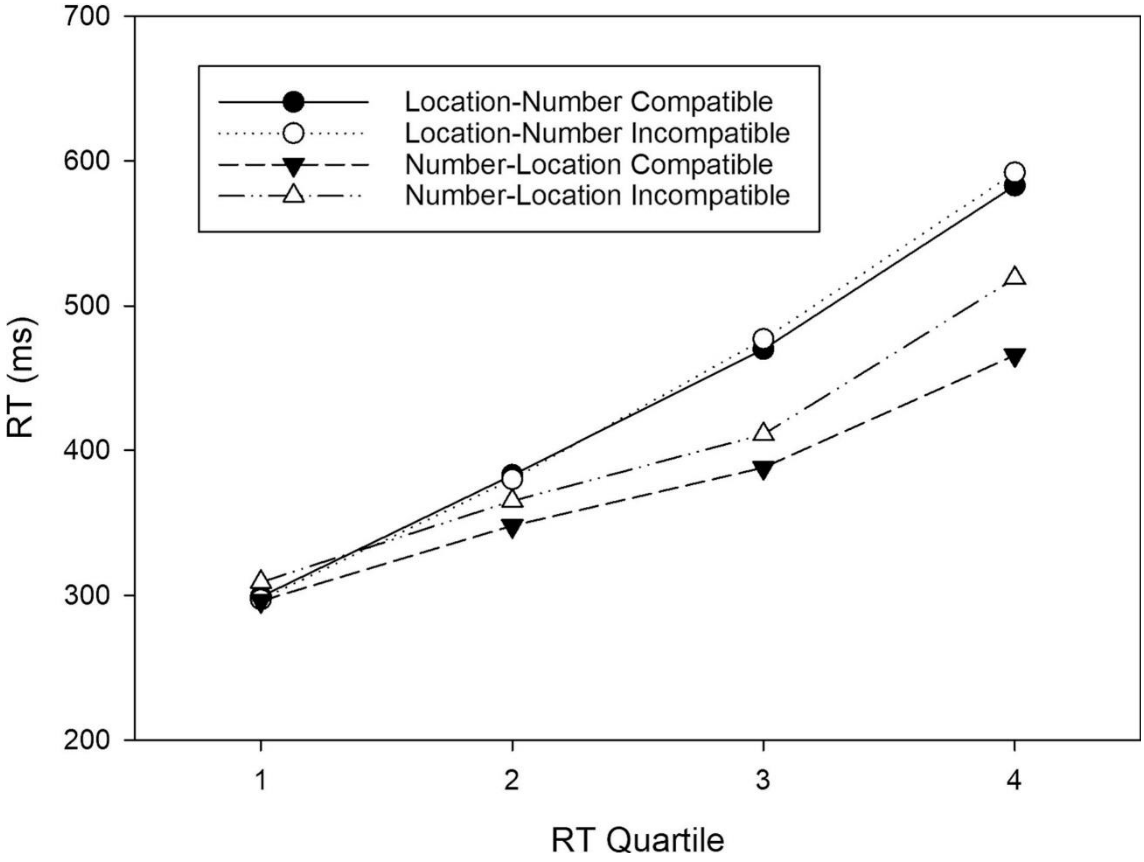

Figure 3. RTs of correct responses observed in Experiment 1 as a function of Task, S-R Mapping and RT Quartile.

The two-way interactions of *Quartile* with *Task* and *Mapping*, and the three-way interaction were all significant. The significant *Task* × *Quartile* interaction, *F*(3, 180) = 156.750, *MSE* = 800.255, *p* < .001, partial η² = 0.723, reflected the finding that mean RTs in the location-number task became increasingly slower, as compared to the number-location task, when RTs increased. In other words, the range of RTs was much larger in the former task than in the latter. The significant *Mapping* × *Quartile* interaction, *F*(3, 180) = 12.358, *MSE* = 693.167, $p < .001$, partial $\eta^2 = 0.171$, reflected the finding that mapping effects increased with RT level. Importantly, however, the latter finding was further qualified by the significant three-way interaction, *F*(3, 180) = 8.023, *MSE* = 379.620, $p < .001$, partial $\eta^2 = 0.118$, that showed that both the mapping effect and the increase of the mapping effect with RT level were restricted to the number-location task.

In order to uncover the source of the significant three-way interaction, we conducted 2x4 ANOVAs, with *Mapping* and *Quartile* as within-subject variables, separately for each task. In the number-location task, both the main effect of *Mapping*, *F*(1, 60) = 40.722, *MSE* = 2,119.943, $p < .001$, partial $\eta^2 = 0.404$, and the *Mapping* x *Quartile* interaction, *F*(3, 180) = 24.697, *MSE* = 427.230, $p < .001$, partial $\eta^2 = 0.292$, were significant. The two-way interaction reflected the finding that the mapping effect increased with increasing RT level. In particular, the mapping effect was 13 ms in the first quartile, 17 ms in the second quartile, 23 ms in the third quartile, and 54 ms in the fourth quartile. In contrast, in the location-number task, neither the main effect of *Mapping*, *F*(1, 60) = 0.346, *MSE* = 2,639.809, $p = .559$, partial $\eta^2 = 0.006$, nor the *Mapping* x *Quartile* interaction, *F*(3, 180) = 1.643, *MSE* = 645.557, $p = .181$, partial $\eta^2 = 0.027$, were significant.

Discussion

Experiment 1 investigated the reciprocity of number-space associations by comparing compatibility effects in a number-location task to those in a location-number task. As expected, we found a regular SNARC effect in the number-location task: Responses were faster and more accurate in the compatible condition (one S – left R; two S – right R) as compared to the incompatible condition (one S – right R, two S – left R). Further analysis revealed that the time course of the mapping effect in the number-location task conformed to the well-known time course of the SNARC effect which increases with increasing response time (e.g., Gevers et al., 2006; Mapelli et al., 2003). In contrast, we did not find a reciprocal SNARC effect in the location-number task, where responses did not differ in speed or accuracy between the compatible (left S – one R; right S – two R) and the incompatible (left S – two R, right S – one R) condition. An additional time course analysis corroborated this observation by showing that mapping effects were absent across the entire RT range. The results of Experiment 1 therefore suggest that numerical stimuli can prime spatial response codes whereas spatial stimuli cannot prime numerical response codes. However, Experiment 1 had two shortcomings that constrain the validity of the results. The first problem is that the dot stimuli did not only vary in numerosity, but also in size. Hence, it is not clear whether the compatibility effects in the number-location task are actually number-location effects or size-location effects (e.g., Ren et al., 2011). The second problem is that we did not record both keypresses in the two-keypress condition, preventing a separate analysis of these keypresses.

Experiment 2

Experiment 2 served three aims. The first aim was to replicate the pattern of results of Experiment 1 with a different sample and two methodological improvements. The second aim of Experiment 2 was to test whether the compatibility effects observed in the number-location task of Experiment 1 were actually number-location (i.e., SNARC) effects or size-location (i.e., SSARC[7]) effects (e.g., Vellan & Leth-Steensen, 2022). In the number-location task of Experiment 1, we employed one or two dots as imperative stimuli to which participants responded by pressing a left or right key with the index and middle finger of their right hand.

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[7] The acronym SSARC stands for *spatial-size association of response codes* (e.g., Weis et al., 2018).

In our stimulus material, however, stimulus numerosity co-varied with stimulus size because the one-dot stimulus was smaller than the two-dot stimulus. Since previous studies have demonstrated compatibility effects between stimulus size and left/right responses (e.g., Ren et al., 2011; Vellan & Leth-Steensen, 2022; Wühr & Seegelke, 2018), we cannot infer whether the compatibility effect observed in the number-location task of Experiment 1 was caused by stimulus number and/or stimulus size. We avoided this problem by using digit stimuli instead of dot patterns in Experiment 2.

The third aim of Experiment 2 was to improve the sensitivity for detecting compatibility effects in the location-number task by measuring both keypresses when two were required. In Experiment 1, the program only measured the last keypress in each condition, which was a single keypress when one response was required and the second keypress when two were required. Hence, the RT analysis for the location-number task included a mixture of first and second keypresses. One might argue that the second keypress is more informative than the first because, in the location-number task, participants might make the first keypress before deciding whether a second keypress was required or not. Nevertheless, we felt it more appropriate to measure both keypresses when two were required in the location-number task, and to perform separate analyses of first and second keypress responses.

Methods

Participants

We applied the same rationale as in Experiment 1 to determine the sample size of Experiment 2. Accordingly, 54 participants would be required to detect an effect with an effect size of *partial* $\eta^2 = 0.2$ with high power ($1-\beta = 0.95$) at the standard alpha-error probability of 0.05.

Fifty-five volunteer students (38 female, 17 male) with a mean age of 23.636 years (*SD*

= 3.324) participated in our experiment and received either course credit or a payment of 10 Euro in exchange. All participants reported normal or corrected-to-normal vision. Moreover, 45 participants reported to be right-handed, whereas 9 participants reported to be left-handed and one participant reported to be ambidextrous. Prior to participation, volunteers gave their informed consent. The local Ethics Committee at TU Dortmund University approved the experimental protocol for our study (GEKTUDO_2022_36).

Apparatus and Stimuli

The apparatus and stimuli were the same as in Experiment 1, except that in the number-location task, the Arabic numerals 1 and 2[8] (Times New Roman font, size 40 pt) served as imperative stimuli to which participants responded by pressing a left or right key with the index and middle finger of their right hand. Moreover, in the location-number task, in which participants had to respond to stimulus location (left or right) by pressing a key with the index finger of their right hand once or twice, the first and, if required, the second responses were recorded.

Procedure

The procedure was the same as in Experiment 1 with the only exception that participants responded to the Arabic numerals 1 and 2 in the number-location task.

Design and Data Analysis

The design and data analysis were similar to Experiment 1. Again, we conducted two sets of analyses. We used a two-way ANOVA, with *Task* (number-location vs. location-number) and *S-R Mapping* (compatible, incompatible) as within-subjects factors, to investigate the impact of the two independent variables (i.e., Task, Mapping) on the dependent variables (i.e.,

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[8] It is possible that the digit 2 contained more pixels than the digit 1 and thus might have covered a slightly larger area.

RTs, error percentages). In case the two-way interaction was significant, we again planned to use *t* tests to determine the source of interaction. However, this time, we measured RTs of the first and the second keypress in conditions where two keypresses were required. This allowed us to analyze the first and second keypress response separately. We therefore analyzed six dependent variables: mean RT and mean error percentage entailing all trials in the number-location task; mean RT and mean error percentage of the first keypress entailing all trials in the location-number task; mean RT and mean error percentage of the second keypress entailing only those trials which required a two-keypress response in the location-number task. As for Experiment 1, we also report the BF for each pair-wise comparison, which we interpret according to the evidence categories provided by Jeffreys, 1961 (as cited in Lee & Wagenmakers, 2014).

As in Experiment 1, the second analysis investigated the time course of mapping effects in RTs in the two tasks. Firstly, we aimed to compare the time course of the mapping effects in our number-location task to the well-known time course of SNARC effects. Secondly, we aimed to investigate whether a small mapping effect might have occurred for a particular RT level in the location-number task, which did not achieve statistical significance in the omnibus analysis.

Results

Data trimming

Similar to Experiment 1, we applied the Tukey (1977) criterion for identifying and excluding outliers in dependent variables, which led to the exclusion of five participants[9]. For determining outliers, we collapsed data across the mapping variable, and considered six variables (i.e., mean RT and mean error percentage in number-location task, mean RT and

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[9] Participant numbers 1, 5, 19, 41 and 54 were excluded from the dataset of Experiment 2.

mean error percentage of the first keypress in location-number task, mean RT and mean error percentage of the second keypress in location-number task). The same five participants would have been excluded with a different, often used criterion for outlier identification (i.e., *M* +/- 2.5 *SD*). Our remaining sample thus consisted of 50 participants. However, because excluding the five participants affected the pattern of results, we decided to additionally report the results for the complete sample in the **Appendix B**.

There were less than 1% of trials with too fast responses (i.e., RT < 100 ms) in both the number-location task (*M* = 0.026%, *SD* = 0.182) and in the location-number task (*M* = 0.103%, *SD* = 0.350). Similarly, there were less than 1% of trials with too slow responses (i.e., RT > 1,500 ms) in both the number-location task (*M* = 0.064%, *SD* = 0.282) and in the location-number task (*M* < 0.01%, *SD* < 0.01). These trials were eliminated before further analysis.

Reaction Times (RTs)

RTs from trials with correct responses were subjected to a two-factorial Analysis Of Variance (ANOVA) with *Task* (number-location task vs. location-number task) and *Mapping* (compatible vs. incompatible mapping) as within-subjects factors. Note this analysis involved RTs from single keypresses in the number-location task, and RTs from first keypresses in the location-number task. Both main effects and the two-way interaction were significant. The significant main effect of *Task*, *F*(1, 49) = 229.488, *MSE* = 692.372, *p* < .001, partial η^2 = 0.824, reflected shorter RTs in the location-number task (*M* = 322 ms, *SD* = 38) than in the number-location task (*M* = 378 ms, *SD* = 39). The significant main effect of *Mapping*, *F*(1, 49) = 19.412, *MSE* = 653.369, *p* < .001, partial η^2 = 0.284, reflected shorter RTs with the compatible mapping (*M* = 342 ms, *SD* = 40) than with the incompatible mapping (*M* = 358 ms, *SD* = 54). The most important finding, however, was the significant two-way interaction, *F*(1, 49) = 19.968, *MSE* = 362.305, *p* < .001, partial η^2 = 0.290, indicating different mapping effects in the two tasks.

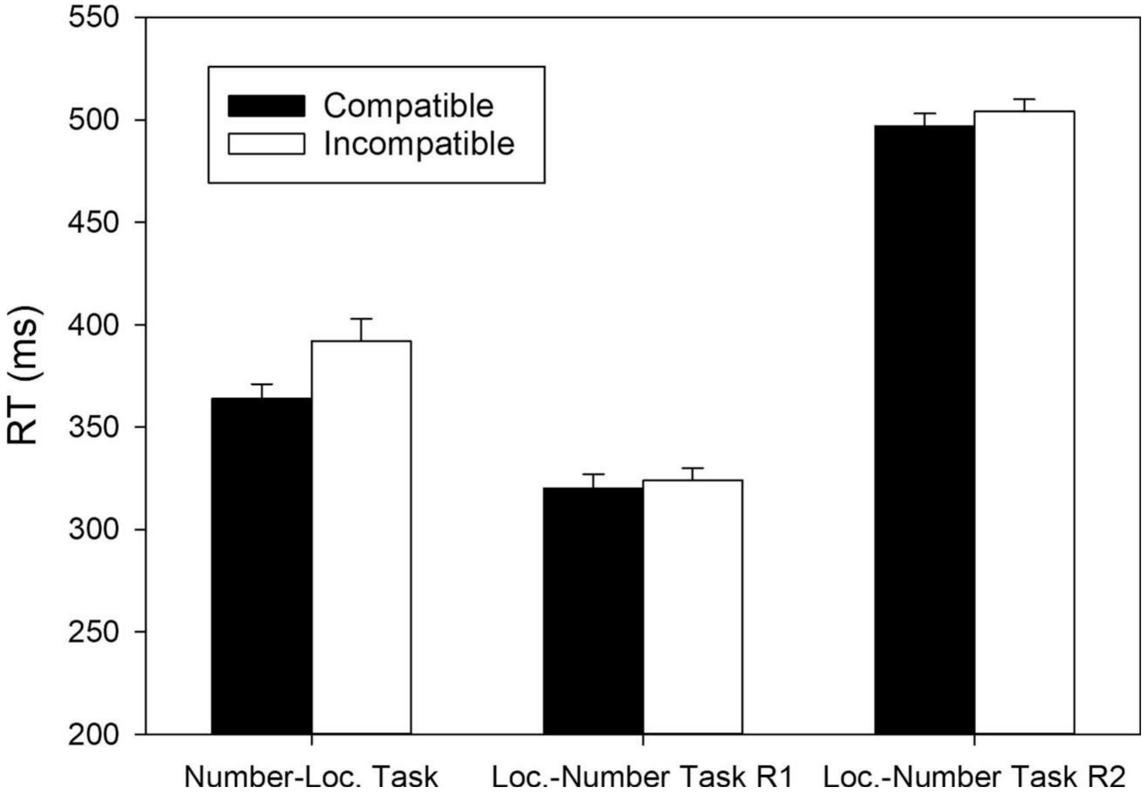

Figure 4. RTs of correct responses observed in Experiment 2 as a function of Task and S-R Mapping. Error bars reflect 95% confidence intervals for within-subjects designs (Cousineau, 2017). R1 denotes a single keypress or the first keypress in a sequence; R2 denotes the second keypress in a sequence of two.

To uncover the source of the two-way interaction, we compared compatible and incompatible mapping conditions separately for the two tasks. In the number-location task, RTs were significantly shorter in compatible than in incompatible conditions, $t(49) = 4.990$, $p < .001$, $d = 0.706$, $BF_{+0} = 2{,}354.342$, indicating a regular SNARC effect of 28 ms (see **Figure 4**) and extreme evidence for H1. In contrast, in the location-number task, RTs did not differ between the two mapping conditions, $t(49) = 1.282$, $p = .206$, $d = 0.181$, $BF_{+0} = 0.332$, indicating moderate evidence for H0.

Error Percentages

Error percentages were also subjected to a two-factorial ANOVA with *Task* (number-location task vs. location-number task) and *Mapping* (compatible vs. incompatible mapping) as within-subjects factors. Again, both main effects and the two-way interaction were significant. The significant main effect of *Task*, $F(1, 49) = 41.190$, $MSE = 2.839$, $p < .001$, partial $\eta^2 = 0.457$, reflected more errors in the number-location task ($M = 2.609$, $SD = 2.506$) than in the location-number task ($M = 1.080$, $SD = 1.390$). The significant main effect of *Mapping*, $F(1, 49) = 18.822$, $MSE = 3.641$, $p < .001$, partial $\eta^2 = 0.278$, reflected less errors with the compatible mapping ($M = 1.259$, $SD = 1.404$) than with the incompatible mapping ($M = 2.430$, $SD = 2.594$). Again, however, the most important finding was the significant two-way interaction, $F(1, 49) = 24.044$, $MSE = 2.610$, $p < .001$, partial $\eta^2 = 0.329$, indicating different mapping effects in the two tasks.

To uncover the source of the two-way interaction, we again compared compatible and incompatible mapping conditions separately for the two tasks. In the number-location task, errors were significantly less frequent in compatible than in incompatible conditions, $t(49) = 5.466$, $p < .001$, $d = 0.773$, $BF_{+0} = 10,948.541$ (see **Figure 5**), indicating extreme evidence for H1. In contrast, in the location-number task, error percentages did not differ between the two mapping conditions, $t(49) = 0.184$, $p = .855$, $d = 0.026$, $BF_{+0} = 0.156$, indicating moderate evidence for H0.

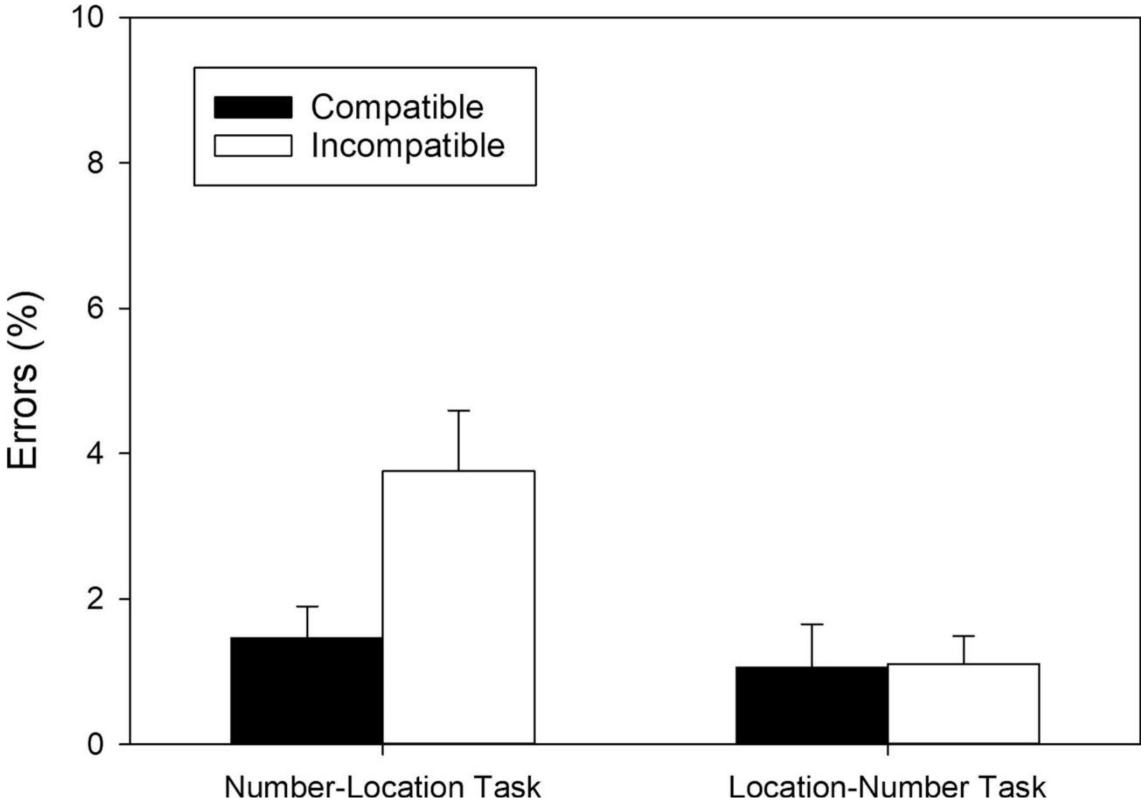

Figure 5. Error percentages observed in Experiment 2 as a function of Task and S-R Mapping. Error bars reflect 95% confidence intervals for within-subjects designs (Cousineau, 2017).

RTs and Error Percentages of the Second Response

We additionally analyzed the mean RT and mean error percentage of the second keypress response in the location-number task by comparing the compatible and incompatible mapping condition. Also for the second keypress response, neither RTs, $t(49) = 1.813$, $p = .076$, $d = 0.256$, $BF_{+0} = 0.700$, nor error percentages, $t(49) = -0.498$, $p = .621$, $d = -0.070$, $BF_{+0} = 0.173$, differed between the two mapping conditions, indicating anecdotal evidence for H0 in RTs and moderate evidence for H0 in error percentages. This corroborates the pattern of results we found for the first keypress response.

Time course analysis of RTs

We used the same method as in Experiment 1 and subjected the means of the RT quartiles to a three-factorial ANOVA with *Task* (number-location task, location-number task), *Mapping* (compatible, incompatible) and *Quartile* (1-4) as within-subject variables. Again, this analysis involved RTs from single keypresses in the number-location task, and RTs from first keypresses in the location-number task. The corresponding means are shown in **Figure 6**. When reporting the results, we will concentrate on the interactions between *Quartile* and the other variables.

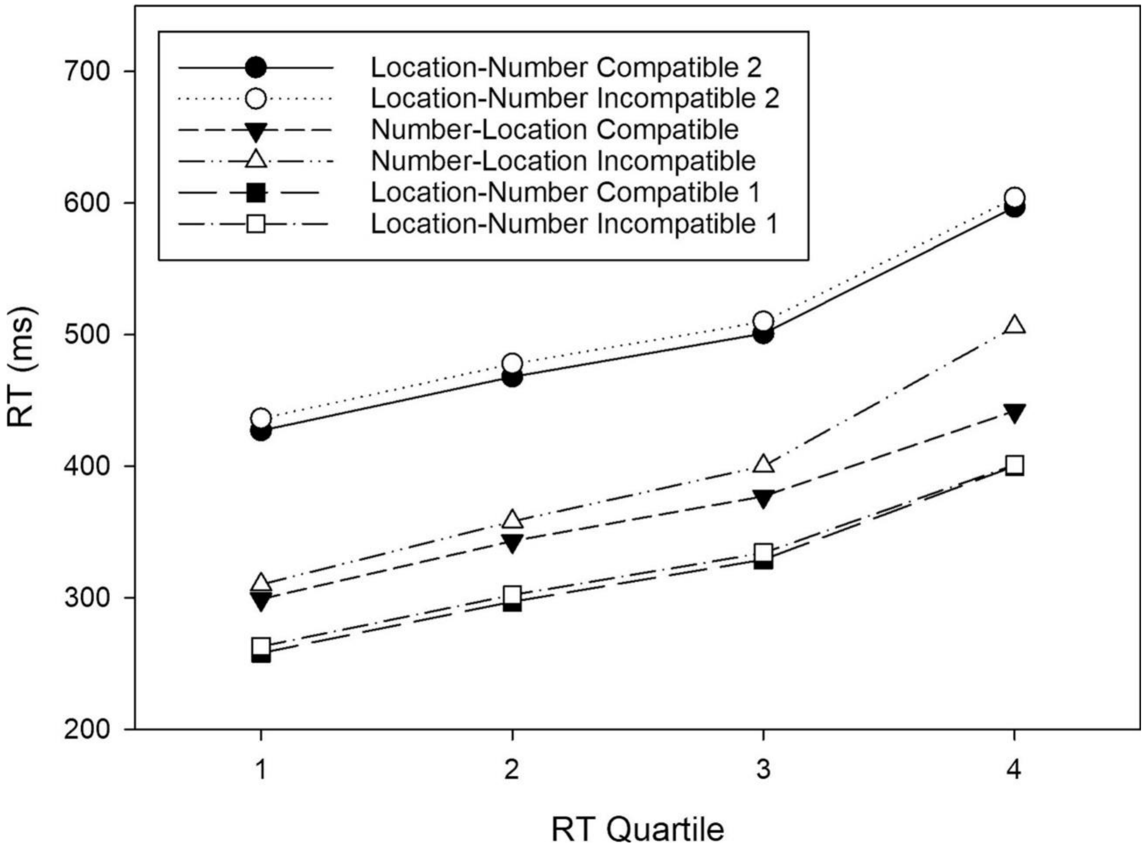

Figure 6. RTs of correct responses observed in Experiment 2 as a function of Task, S-R Mapping and RT Quartile. The numbers 1 and 2 (in the box) denote the first and second keypress, respectively, in two-keypress conditions.

The two-way interactions of *Quartile* with *Task* and *Mapping*, and the three-way interaction were all significant. The significant *Task* × *Quartile* interaction, $F(3, 147) = 15.488$, $MSE = 521.860$, $p < .001$, partial $\eta^2 = 0.240$, reflected the finding that mean RTs in the number-location task became increasingly slower, as compared to the location-number task, when RTs increased. In other words, the range of RTs was larger in the former task than in the latter. The significant *Mapping* × *Quartile* interaction, *F*(3, 147) = 16.492, *MSE* = 386.523, *p* < .001, partial η^2 = 0.252, reflected the finding that mapping effects increased with RT level. Importantly, however, the latter finding was further qualified by the significant three-way interaction, *F*(3, 147) = 25.793, *MSE* = 335.419, *p* < .001, partial η^2 = 0.345, that showed that both the mapping effect and the increase of the mapping effect with RT level were restricted to the number-location task.

In order to uncover the source of the significant three-way interaction, we conducted 2x4 ANOVAs, with *Mapping* and *Quartile* as within-subject variables, separately for each task. In the number-location task, both the main effect of *Mapping*, *F*(1, 49) = 25.584, *MSE* = 3,122.975, *p* < .001, partial η^2 = 0.343, and the *Mapping* x *Quartile* interaction, *F*(3, 147) = 31.695, *MSE* = 471.292, *p* < .001, partial η^2 = 0.393, were significant. The two-way interaction reflected the finding that the mapping effect increased with increasing RT level. In particular, the mapping effect was 11 ms in the first quartile, 15 ms in the second quartile, 23 ms in the third quartile, and 64 ms in the fourth quartile. In contrast, for the first keypress in the location-number task, neither the main effect of *Mapping*, *F*(1, 49) = 1.562, *MSE* = 935.853, *p* = .217, partial η^2 = 0.031, nor the *Mapping* x *Quartile* interaction, *F*(3, 147) = 0.352, *MSE* = 250.650, *p* = .788, partial η^2 = 0.007, were significant.

A similar pattern of results emerged for RTs of the second keypress response in the location-number task. After vincentizing (Ratcliff, 1979), we subjected the means of the RT quartiles of the second keypress to a two-factorial ANOVA with *Mapping* (compatible, incompatible) and *Quartile* (1-4) as within-subject variables. Similar to the first keypress response, neither the main effect of *Mapping*, *F*(1, 49) = 3.299, *MSE* = 1,992.278, *p* = .075, partial $\eta^2 = 0.063$, nor the *Mapping* x *Quartile* interaction, $F(3, 147) = 0.055$, $MSE = 516.531$, $p = .983$, partial $\eta^2 = 0.001$, were significant.

Discussion

Experiment 2 replicated the results of Experiment 1 with a different sample, and some methodological changes. As expected, we found a regular SNARC effect in the number-location task: Responses were faster and more accurate in the compatible mapping (1 – left R, 2 – right R) compared to the incompatible mapping (1 – right R, 2 – left R). Again, additional analysis showed the typical time course of the SNARC effect (e.g., Gevers et al., 2006; Mapelli et al., 2003). On the contrary, we failed to observe a reciprocal SNARC effect in the location-number task: Responses differed neither in RTs nor in error percentages between the compatible mapping (left S – one R, right S – two R) and the incompatible mapping (right S – one R, left S – two R). Notably, these results were observed for the first as well as the second keypress response. Additionally, the time course analysis showed the absence of a mapping effect in the location-number task for the entire RT range. However, we also observed that excluding outliers affected our pattern of results. In fact, when outliers were not excluded, the two-way ANOVA as well as the time course analysis revealed a significant reciprocal SNARC effect (see **Appendix B**). This additional finding implies that bidirectional SNARC effects occurred in a subsample of the participants who showed extreme RTs and/or error percentages. Nevertheless, spatial-numerical associations of manual response codes seem to be at least strongly asymmetrical.

Experiment 2 also served two further aims: By employing Arabic digits (1 vs. 2) instead of numerosity (one vs. two dots) as stimuli in the number-location task, we were able to replicate the results with a different stimulus set, and to largely reduce the confound between number and size in the stimulus set of Experiment 1. We thus demonstrated that the mapping effect in the number-location task occurred due to spatial-numerical associations of response codes (SNARC) with negligible influence of spatial-size associations of response codes (SSARC). Moreover, by analyzing the first and second keypress responses separately we avoided comparisons between responses which require motor programs of different complexities (Henry & Rogers, 1960). The fact that the analysis of the second keypress response is in line with the results of the first keypress response corroborates our findings and controls for the possibility that the absence of associations in the reciprocal direction can be attributed to non-informative one-keypress responses.

General Discussion

This paper addresses the question whether the SNARC effect relies on bidirectional associations between stimulus and response codes. The typical SNARC effect describes the phenomenon that numerical stimuli can automatically activate spatial responses. In our experiment, we investigated if, on the contrary, spatial stimuli can also activate numerical responses. Participants completed two different tasks. In the number-location task, which resembled the typical SNARC task, participants responded to stimulus number with left or right keypresses. In the location-number task, participants responded to stimulus position with one or two keypresses. In Experiment 1, the numerical stimuli in the number-location task were one or two dots, whereas digits (1 and 2) served as the numerical stimuli in Experiment 2.

As expected, we found a regular SNARC effect in the number-location task of both experiments: Responses were faster and more accurate in the compatible mapping (one – left R, two – right R) compared to the incompatible mapping (one – right R, two – left R). Moreover, this compatibility effect showed the typical time course of the SNARC effect, which increases with increasing response time (e.g., Gevers et al., 2006; Mapelli et al., 2003). In the location-number task of both experiments, however, no SNARC effect occurred for the opposite direction: Neither RTs nor error percentages differed between both mapping conditions. Additional time course analyses did not reveal any compatibility effect in this task.

The usual exclusion of data sets with long RTs or high error percentages (outliers) did not affect the results of Experiment 1. A reciprocal SNARC effect neither occurred with or without three outlier data sets in the location-number task of Experiment 1. However, the exclusion of outlier data sets affected the results of Experiment 2. When five outlier data sets were included in the analysis of Experiment 2, we observed a small, but significant, reciprocal SNARC effect in the location-number task of Experiment 2 (see **Appendix B**). This effect disappeared when these data sets were removed from the analysis. These observations suggest that reciprocal SNARC effects might be obtained in participants that have longer RTs and/or higher error percentages than the majority of participants, and therefore we do not want to claim that reciprocal SNARC effects do not exist. But even when the complete samples of both experiments are considered, and the occurrence of small reciprocal SNARC effects in the location-number tasks of Experiment 2 is acknowledged, these reciprocal SNARC effects were much smaller than the regular SNARC effects in the number-location task of both experiments. Hence, our results demonstrate that S-R priming effects between the numerical and the spatial domain are strongly asymmetrical. In the following section, we first discuss to what extend our results do or do not correspond with the given theoretical accounts of the SNARC effect before discussing alternative explanations.

Implications for theoretical accounts of the SNARC effect

The most prominent explanation of the SNARC effect is the MNL (e.g., Dehaene et al., 1993; Dehaene, 2003; Fischer & Shaki, 2014) which assumes the spatial representation of numerical size in an ascending order from left to right. Since numbers and positions are integrated into one mental representation, the account of the MNL implies the existence of bidirectional associations between both dimensions (Fischer & Shaki, 2015; Hartmann et al., 2012; Lugli et al., 2013; Shaki & Fischer, 2014; Stoianov et al., 2008). Nevertheless, the MNL account is compatible with our results if one assumes that the MNL is located between stimulus and response representations, on an intermediate (semantic) level (Ginsburg & Gevers, 2015; Huber et al., 2016; Umiltà et al., 2010). This assumption has already been included in Dehaene's (1992) *Triple-Code Model*. To explain the asymmetrical pattern of priming effects, one has to assume that numerical stimuli activate the MNL more strongly than spatial stimuli. Alternatively, one might also assume that numerical and spatial stimuli activate the MNL with comparable strength, but the subsequent activation of the corresponding spatial response is stronger than the subsequent activation of the corresponding numerical response. Future research might address the question of whether the asymmetry occurs between stimuli and the MNL, or between the MNL and responses.

Another prominent account for cross-dimensional compatibility effects is ATOM (Walsh, 2003, 2015). ATOM postulates the existence of a shared representation of action-relevant features such as quantity, space and time in the parietal cortex (Walsh, 2003, 2015). The assumption of a common representation suggests interference and compatibility effects between the processing of several dimensions such as quantity, physical size, space and time. However, according to Walsh (2015), this does not imply that interference or compatibility effects necessarily have to be symmetrical or bidirectional. Dimensions do not only differ in the effort which is required to learn them but also in their level of awareness and their linguistic integration. A dimension which is explicitly learned and emphasized in language (such as physical size) should interfere with another dimension to a greater extent compared to a dimension which is learned rather implicitly and which is little emphasized in language (such as time).

Unfortunately, Walsh (2003, 2015) does not make any prediction concerning the relation between numerical size and space. According to this logic, the results of our experiment would indicate a dominance of number over space. However, ATOM was criticized for being postulated for prothetic dimensions only (such as time, quantity, weight), even though space (spatial position) constitutes a metathetic dimension (Casasanto & Pitt, 2019). ATOM therefore could not even account for the typical SNARC effect, which relies on the interaction between a prothetic and a metathetic dimension.

While the MNL and ATOM accounts assume long-term associations between size and space, other accounts assume that short-term associations between both dimensions underlie the SNARC effect. The polarity correspondence principle, for example, suggests that in many binary classification tasks, positive and negative polarities are assigned to stimuli and responses varying on bipolar dimensions (e.g., Proctor & Cho, 2006; Proctor & Xiong, 2015). In SNARC tasks, “left” and “small” as stimulus or response alternatives are tagged as “negative”, whereas “large” and “right” as stimulus or response alternatives are tagged as “positive” (Proctor & Cho, 2006). The polarity correspondence principle predicts symmetrical compatibility effects since “small” and “left”/ “large” and “right” are consistently given the same negative/positive polarity regardless of being a stimulus or response feature. Thus, our findings are at odds with the polarity correspondence principle (Santiago & Lakens, 2015).

Finally, the working memory account assumes that the SNARC effect depends on the serial order in which stimuli are stored in WM (e.g., van Dijck & Fias, 2011). According to the WM account, numerical stimuli in a SNARC task are typically represented in an ascending order and early serial positions are associated with left responses whereas late serial positions are associated with right responses. In our opinion, the WM account would be in line with bidirectional SNARC effects assuming that also stimulus spatial positions are spontaneously represented in a canonical order (from left to right) in WM. Stimuli in early serial positions (left) would then be associated with small numbers while stimuli in late serial positions (right) would be associated with large numbers. However, this effect appeared only in a small subset of participants in Experiment 2, suggesting that only these participants represented spatial stimuli in a canonical order from left to right.

Possible conditions for the emergence of reciprocal SNARC effects

The results of Experiment 2 showed small, but significant, reciprocal SNARC effects in the location-number task, when five participants with suspiciously long RTs or suspiciously high error percentages were included in the analysis (see **Appendix B**). When these outlier data sets were excluded from the analysis, the remaining sample (*N* = 50) – that is, the majority of participants – did not show such reciprocal SNARC effects. What can these observations tell us about the conditions that foster the occurrence of reciprocal SNARC effects? At first sight, one might assume that slower responses foster the occurrence of reciprocal SNARC effects because the outlier participants had, on average, longer RTs. The results of the time course analyses, however, contradict this hypothesis. For the large majority of participants in both experiments, the reciprocal SNARC effects did not increase when RTs increased. Hence, the occurrence of reciprocal SNARC effects seems to depend on some inter-individual differences between the majority of participants, who do not show reciprocal SNARC effects, and a minority of participants, who do show reciprocal SNARC effects. To uncover those features of participants and tasks that might foster the occurrence of reciprocal SNARC effects could, thus, remain an issue of future research.

Conclusion

The present study indicates that number stimuli can activate spatial responses much more strongly as compared to the reciprocal activation of number responses by spatial stimuli. In other words: The associations between stimulus and (manual) response codes which are responsible for the SNARC effect appear to be strongly asymmetrical. These findings are incompatible with some theoretical accounts of the SNARC effect (e.g., the polarity correspondence principle) whereas they are compatible with other accounts (e.g., the MNL) if some additional assumptions are made.

Additional information

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Availability of data and materials

The datasets of Experiment 1 and 2 have been published on the "Mendeley Data" repository (https://doi.org/10.17632/h4n8r72c7h.1). All other materials can be obtained from both authors upon request. The experiments' programs (E-Prime 3.0) and the R code can be obtained from both authors upon request.

Declaration of interest

The authors have no competing interests to declare.

Informed consent

Before the experiment, all participants gave written informed consent to participate.

Ethics approval

The local Ethics Committee at TU Dortmund University had approved the experimental protocol for our study (approval no. GEKTUDO_2022_36).

CRediT Author Statement

M. R.: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - Original Draft, Writing - Review and Editing.

P. W.: Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing - Original draft, Writing - Review and Editing, Visualization, Project administration.

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Appendix A: Analysis of Experiment 1

In this section, we report the results of the analyses for Experiment 1 for the complete sample (*N* = 64), that is, including three outlier data sets.

Reaction Times (RTs)

RTs from trials with correct responses were subjected to a two-factorial Analysis Of Variance (ANOVA) with *Task* (number-location task vs. location-number task) and *Mapping* (compatible vs. incompatible mapping) as within-subjects factors. Both main effects and the two-way interaction were significant. The significant main effect of *Task*, *F*(1, 63) = 76.450, *MSE* = 2,141.312, *p* < .001, partial η^2 = 0.548, reflected shorter RTs in the number-location task (*M* = 392 ms, *SD* = 57) than in the location-number task (*M* = 442 ms, *SD* = 63). The significant main effect of *Mapping*, *F*(1, 63) = 15.874, *MSE* = 815.440, *p* < .001, partial η^2 = 0.201, reflected shorter RTs with the compatible mapping (*M* = 410 ms, *SD* = 64) than with the incompatible mapping (*M* = 424 ms, *SD* = 66). The most important finding, however, was the significant two-way interaction, *F*(1, 63) = 15.063, *MSE* = 528.147, *p* < .001, partial η^2 = 0.193, indicating different mapping effects in the two tasks.

To uncover the source of the two-way interaction, we compared compatible and incompatible mapping conditions separately for the two tasks. In the number-location task, RTs were significantly shorter in compatible than in incompatible conditions, *t*(63) = 5.654, *p* < .001, *d* = 0.707, BF_{+0} = 36,152.549, indicating a regular SNARC effect of 25 ms and extreme evidence for H1. In contrast, in the location-number task, RTs did not differ between the two mapping conditions, *t*(63) = 0.657, *p* = .513, *d* = 0.082, BF_{+0} = 0.168, indicating moderate evidence for H0.

Error Percentages

Error percentages were also subjected to a two-factorial ANOVA with *Task* (number-location task vs. location-number task) and *Mapping* (compatible vs. incompatible mapping) as within-subjects factors. Again, both main effects and the two-way interaction were significant. The significant main effect of *Task*, *F*(1, 63) = 8.528, *MSE* = 4.694, *p* = .005, partial η^2 = 0.119, reflected more errors in the number-location task (*M* = 2.518, *SD* = 2.648) than in the location-number task (*M* = 1.727, *SD* = 1.750). The significant main effect of *Mapping*, *F*(1, 63) = 13.656, *MSE* = 4.310, *p* < .001, partial η^2 = 0.178, reflected less errors with the compatible mapping (*M* = 1.643, *SD* = 1.841) than with the incompatible mapping (*M* = 2.602, *SD* = 2.558). Again, however, the most important finding was the significant two-way interaction, *F*(1, 63) = 4.717, *MSE* = 3.009, *p* = .034, partial η^2 = 0.070, indicating different mapping effects in the two tasks.

To uncover the source of the two-way interaction, we again compared compatible and incompatible mapping conditions separately for the two tasks. In the number-location task, errors were significantly less frequent in compatible than in incompatible conditions, *t*(63) = 3.708, *p* < .001, *d* = 0.463, BF_{+0} = 54.661, indicating very strong evidence for H1. In contrast, in the location-number task, error percentages did not differ between the two mapping conditions, *t*(63) = 1.726, *p* = .089, *d* = 0.216, BF_{+0} = 0.555, indicating anecdotal evidence for H0.

Time course analysis of RTs

The means of the RT quartiles (see also **Table A1**) were subjected to a three-factorial ANOVA with *Task* (number-location task, location-number task), *Mapping* (compatible, incompatible) and *Quartile* (1-4) as within-subject variables. When reporting the results, we will concentrate on the interactions between *Quartile* and the other variables. The two-way interactions of *Quartile* with *Task* and *Mapping*, and the three-way interaction were all significant. The significant *Task* × *Quartile* interaction, *F*(3, 189) = 155.624, *MSE* = 900.698, *p* <

.001, partial η² = 0.712, reflected the finding that mean RTs in the location-number task became increasingly slower, as compared to the number-location task, when RTs increased. In other words, the range of RTs was much larger in the former task than in the latter. The significant *Mapping* × *Quartile* interaction, *F*(3, 189) = 9.122, *MSE* = 867.406, *p* < .001, partial η² = 0.126, reflected the finding that mapping effects increased with RT level. Importantly, however, the latter finding was further qualified by the significant three-way interaction, *F*(3, 189) = 8.713, *MSE* = 386.432, *p* < .001, partial η² = 0.121, that showed that both the mapping effect and the increase of the mapping effect with RT level were restricted to number-location task.

Table A1. Mean RTs observed in Experiment 1 as a function of Task, S-R Mapping and RT quartile (*N* = 64; all participants included).

		RT Quartile			
		1	2	3	4
Number-Location Task	Compatible	299	352	394	476
	Incompatible	311	368	415	527
Location-Number Task	Compatible	303	389	478	598
	Incompatible	301	388	486	606

In order to uncover the source of the significant three-way interaction, we conducted 2x4 ANOVAs, with *Mapping* and *Quartile* as within-subject variables, separately for each task. In the number-location task, both the main effect of *Mapping*, *F*(1, 63) = 31.646, *MSE* = 2,575.304, *p* < .001, partial η² = 0.334, and the *Mapping* x *Quartile* interaction, *F*(3, 189) = 18.302, *MSE* = 564.787, *p* < .001, partial η² = 0.225, were significant. The two-way interaction reflected the finding that the mapping effect increased with increasing RT level. In particular, the mapping effect was 12 ms in the first quartile, 16 ms in the second quartile, 21 ms in the third quartile, and 52 ms in the fourth quartile. In contrast, in the location-number task, neither the main effect of *Mapping*, $F(1, 63) = 0.497$, $MSE = 2{,}805.631$, $p = .483$, partial $\eta^2 = 0.008$, nor the *Mapping* x *Quartile* interaction, $F(3, 189) = 1.368$, $MSE = 689.052$, $p = .254$, partial $\eta^2 = 0.021$, were significant.

Appendix B: Analysis of Experiment 2

In this section, we report the results of the analyses for Experiment 2 for the complete sample ($N = 55$), that is, including five outlier data sets.

Reaction Times (RTs)

RTs from trials with correct responses were subjected to a two-factorial Analysis Of Variance (ANOVA) with *Task* (number-location task vs. location-number task) and *Mapping* (compatible vs. incompatible mapping) as within-subjects factors. Both main effects and the two-way interaction were significant. The significant main effect of *Task*, $F(1, 54) = 203.442$, $MSE = 849.689$, $p < .001$, partial $\eta^2 = 0.790$, reflected shorter RTs in the location-number task ($M = 332$ ms, $SD = 53$) than in the number-location task ($M = 388$ ms, $SD = 57$). The significant main effect of *Mapping*, $F(1, 54) = 22.486$, $MSE = 1049.117$, $p < .001$, partial $\eta^2 = 0.294$, reflected shorter RTs with the compatible mapping ($M = 350$ ms, $SD = 49$) than with the incompatible mapping ($M = 370$ ms, $SD = 71$). The most important finding, however, was the significant two-way interaction, $F(1, 54) = 17.911$, $MSE = 546.110$, $p < .001$, partial $\eta^2 = 0.249$, indicating different mapping effects in the two tasks.

To uncover the source of the two-way interaction, we compared compatible and incompatible mapping conditions separately for the two tasks. In the number-location task, RTs were significantly shorter in compatible than in incompatible conditions, *t*(54) = 4.923, *p* < .001, *d* = 0.664, BF_{+0} = 2,198.909, indicating a regular SNARC effect of 34 ms and extreme evidence for H1. In the location-number task, RTs were also significantly shorter in compatible than in incompatible conditions, *t*(54) = 2.311, *p* = .025, *d* = 0.312, BF_{+0} = 1.680, indicating a reciprocal SNARC effect of 7 ms and anecdotal evidence for H1.

Error Percentages

Error percentages were also subjected to a two-factorial ANOVA with *Task* (number-location task vs. location-number task) and *Mapping* (compatible vs. incompatible mapping) as within-subjects factors. Again, both main effects and the two-way interaction were significant. The significant main effect of *Task*, *F*(1, 54) = 34.305, *MSE* = 3.826, *p* < .001, partial η^2 = 0.388, reflected more errors in the number-location task (*M* = 2.964, *SD* = 3.006) than in the location-number task (*M* = 1.419, *SD* = 1.997). The significant main effect of *Mapping*, *F*(1, 54) = 24.501, *MSE* = 4.960, *p* < .001, partial η^2 = 0.312, reflected less errors with the compatible mapping (*M* = 1.448, *SD* = 1.670) than with the incompatible mapping (*M* = 2.935, *SD* = 3.213). Again, however, the most important finding was the significant two-way interaction, *F*(1, 54) = 26.733, *MSE* = 2.612, *p* < .001, partial η^2 = 0.331, indicating different mapping effects in the two tasks.

To uncover the source of the two-way interaction, we again compared compatible and incompatible mapping conditions separately for the two tasks. In the number-location task, errors were significantly less frequent in compatible than in incompatible conditions, *t*(54) = 5.999, *p* < .001, *d* = 0.809, BF_{+0} = 84,514.556, indicating extreme evidence for H1. In contrast, in the location-number task, error percentages did not differ between the two mapping conditions, *t*(54) = 1.230, *p* = .224, *d* = 0.166, BF_{+0} = 0.300, indicating moderate evidence for H0.

RTs and Error Percentages of the Second Response

We additionally analyzed the mean RT and mean error percentage of the second keypress response in the location-number task by comparing the compatible and incompatible mapping condition. Similar to the first keypress, RTs for the second keypress were also significantly shorter in compatible than in incompatible conditions, *t*(54) = 2.615, *p* = .012, *d* = 0.353, BF_{+0} = 3.207, indicating a reciprocal SNARC effect of 12 ms and moderate evidence for H1. Error percentages, however, again did not differ between the two mapping conditions, *t*(54) = 0.673, *p* = .504, *d* = 0.091, BF_{+0} = 0.183, indicating moderate evidence for H0.

Time course analysis of RTs

The means of the RT quartiles (see also **Table B1**) were subjected to a three-factorial ANOVA with *Task* (number-location task, location-number task), *Mapping* (compatible, incompatible) and *Quartile* (1-4) as within-subject variables. When reporting the results, we will concentrate on the interactions between *Quartile* and the other variables.

Table B1. Mean RTs observed in Experiment 2 as a function of Task, S-R Mapping and RT quartile (*N* = 55; all participants included).

		RT Quartile			
		1	2	3	4
Number-Location Task	Compatible	303	349	384	453
	Incompatible	316	368	413	528
Location-Number Task R1	Compatible	262	304	339	412
	Incompatible	268	311	346	421
Number-Location Task R2	Compatible	432	477	513	612
	Incompatible	443	486	525	628

The two-way interactions of *Quartile* with *Task* and *Mapping*, and the three-way interaction were all significant. The significant *Task* × *Quartile* interaction, *F*(3, 162) = 15.998, *MSE* = 567.437, *p* < .001, partial η² = 0.229, reflected the finding that mean RTs in the number-location task became increasingly slower, as compared to the location-number task, when RTs increased. In other words, the range of RTs was larger in the former task than in the latter. The significant *Mapping* × *Quartile* interaction, *F*(3, 162) = 22.151, *MSE* = 517.205, *p* < .001, partial η² = 0.291, reflected the finding that mapping effects increased with RT level. Importantly, however, the latter finding was further qualified by the significant three-way interaction, *F*(3, 162) = 27.344, *MSE* = 368.456, *p* < .001, partial η² = 0.336, that showed that mapping effects occurred for both tasks but that the increase of the mapping effect with RT level was restricted to the number-location task.

In order to uncover the source of the significant three-way interaction, we conducted 2x4 ANOVAs, with *Mapping* and *Quartile* as within-subject variables, separately for each task. In the number-location task, both the main effect of *Mapping*, *F*(1, 54) = 24.665, *MSE* = 5,211.601, *p* < .001, partial η² = 0.314, and the *Mapping* x *Quartile* interaction, *F*(3, 162) = 36.264, *MSE* = 593.117, *p* < .001, partial η² = 0.402, were significant. The two-way interaction reflected the finding that the mapping effect increased with increasing RT level. In particular, the mapping effect was 13 ms in the first quartile, 19 ms in the second quartile, 29 ms in the third quartile, and 75 ms in the fourth quartile. In the location-number task, the main effect of *Mapping*, *F*(1, 54) = 5.151, *MSE* = 1,129.041, *p* = .027, partial η² = 0.087, was also significant. However, the *Mapping* x *Quartile* interaction, *F*(3, 162) = 0.079, *MSE* = 292.545, *p* = .971, partial η² = 0.001, was not significant, indicating that the mapping effect did not differ between RT levels.

A similar pattern of results emerged for RTs of the second keypress response in the location-number task. After vincentizing (Ratcliff, 1979), we subjected the means of the RT quartiles of the second keypress to a two-factorial ANOVA with *Mapping* (compatible, incompatible) and *Quartile* (1-4) as within-subject variables. Similar to the first keypress response, the main effect of *Mapping*, *F*(1, 54) = 6.976, *MSE* = 2,290.604, *p* = .011, partial η^2 = 0.114, was significant, but the *Mapping* x *Quartile* interaction, *F*(3, 162) = 0.372, *MSE* = 622.052, *p* = .773, partial η^2 = 0.007, was not.

3. Article 2 – Richter, M., & Wühr, P. (2024). The reciprocity of spatial-numerical associations of vocal response codes depends on stimulus mode. *Memory & Cognition*, *52*, 944-964.

The reciprocity of spatial-numerical associations of vocal response codes depends on stimulus mode

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Abstract

Individuals make faster left responses to small/er numbers and faster right responses to large/r numbers than vice versa. This “spatial-numerical association of response codes” (SNARC) effect represents evidence for an overlap between the cognitive representations of number and space. Theories of the SNARC effect differ in whether they predict bidirectional S-R associations between number and space or not. We investigated the reciprocity of S-R priming effects between number and location in three experiments with vocal responses. In Experiments 1 and 2, participants completed a number-location task with digits as stimuli and location words as responses, and a location-number task with physical locations as stimuli and number words as responses. In addition, we varied the S-R mapping in each task. Results revealed a strong SNARC effect in the number-location task, but no reciprocal SNARC effect in the location-number task. In Experiment 3, we replaced physical location stimuli by location words and digit stimuli by number words. Results revealed a regular and a reciprocal SNARC effect of similar size. Reciprocal SNARC effects thus seem to emerge with verbal location stimuli and vocal responses, but not with physical location stimuli and vocal responses. The S-R associations underlying the SNARC effect with vocal responses thus appear bidirectional and symmetrical for some combinations of stimulus and response sets, but not for others. This has implications for theoretical accounts of the SNARC effect which need to explain how stimulus mode affects the emergence of reciprocal but not regular SNARC effects.

Keywords: SNARC; number; location; reciprocity; vocal responses

Introduction

A few decades ago, Dehaene and colleagues (1990) made the observation that a left keypress response (with the left hand) is faster and more accurate to smaller numbers compared to larger numbers, whereas a right keypress response (with the right hand) is faster and more accurate to larger numbers compared to smaller numbers. Numerical size can thus influence the selection and execution of spatial responses. This phenomenon, which has been termed the *spatial-numerical association of response codes (SNARC)* effect, implies the existence of associations, or even overlap, between the cognitive representations of number and space, the so-called *spatial-numerical associations*. Since the observation by Dehaene and colleagues (1990), much effort has been dedicated to the investigation of spatial-numerical associations, originally focusing on the SNARC effect and its determinants, before expanding to the study of other forms of spatial-numerical associations, for example, in line bisection or random number generation tasks. Research thereby testified to the ubiquity of spatial-numerical associations (Fischer & Shaki, 2014; Gevers & Lammertyn, 2005).

The studies investigating the SNARC effect as prominent evidence of spatial-numerical associations were able to determine several characteristics of the effect. First, the effect also emerges with number as an irrelevant stimulus feature, implying that numerical size is automatically processed even if it is not relevant for task completion (e.g., Dehaene et al., 1993; Gevers et al., 2006; Mapelli et al., 2003). Second, the SNARC effect is context-dependent: The number 5 is, for instance, associated with a right response in a number set ranging from 1-5 whereas it is associated with a left response in a number set ranging from 5-9 (Dehaene et al., 1993; Fias, 1996). Ben Nathan et al. (2009) even demonstrated that “the effect is instantaneous: What matters is the relative magnitude that a number happens to carry at any given moment” (p. 582). Third, the SNARC effect can also be observed with various stimulus and response sets. If numerical size is visually presented in the form of numbers, number words, or die-faces (number of dots, i.e., numerosity), or even auditorily presented, SNARC effects of similar sizes occur (Nuerk et al., 2005). SNARC effects also emerge with different response modes such as unimanual (e.g., Wood et al., 2008) or vocal responses (e.g., Gevers et al., 2010). The independence of the SNARC effect from stimulus and response modes implies that instead of relying on direct connections between specific stimulus and response codes, the associations between number and space rather seem to rest upon an intervening representational level (e.g., Hubbard et al., 2005; Nuerk et al., 2005).

With their observation that the SNARC effect also arises with vocal responses, Gevers et al. (2010) challenged the prevalent view that *visuospatial coding* – that is, the “correspondence between the position of a number on a continuous left-to-right-oriented representational medium (the mental number line) and the spatial position of the response” – is responsible for the effect (Gevers et al., 2010, p. 181). Instead, the authors were able to show that the SNARC effect at least partly relies on a verbal coding of space in the form of the categorical labels “left” and “right”, which they termed *verbal-spatial coding*. Moreover, Gevers and colleagues (2010) demonstrated that a pure verbal encoding of spatial information is sufficient to induce the SNARC effect, emphasizing the role of verbal labeling when spatial locations are encoded and mentally represented.

When investigating the SNARC effect the question of reciprocity arises. Are the associations between numerical size and spatial location, which underlie the SNARC effect, bidirectional in such a way that spatial stimuli can also activate numerical responses similar to how numerical stimuli can activate spatial responses? Or are they unidirectional in such a way that numerical stimuli can activate spatial responses but spatial stimuli cannot activate numerical responses? So far, some studies have investigated the influence of spatial information onto the processing of numbers but have merely focused on the bidirectionality of spatial-numerical associations in general, that is, without the involvement of response codes. For example, Stoianov et al. (2008) observed that spatial primes can affect performance in a numerical judgement task with “neutral” vocal responses, showing that spatial information affects numerical processing on a central processing stage (i.e., the mental number line; see also Kramer et al., 2011).

Other studies have addressed reciprocal effects between spatial and numerical processing by employing *random number generation* tasks. Loetscher and colleagues (2008), for instance, observed that when attempting to generate random numbers while turning one’s head alternately to the left and right, participants were more likely to produce smaller numbers during leftward movements, but larger numbers during rightward movements. Similarly, Loetscher and colleagues (2010) reported that participants were more likely to produce smaller numbers when moving their eyes to the bottom-left, but more likely to produce larger numbers when moving their eyes to the upper-right. These correlational results were extended by Shaki and Fischer (2014), who demonstrated an effect of spatial information processing onto numerical information processing by showing that participants generated smaller numbers before they made a prescribed leftward turn compared to a rightward turn. Nevertheless, it remains unclear if the effect occurred due to the given instruction of the prescribed turn in the form of a stimulus-response (S-R) priming effect, or due to the planning of the spatial action in the form of a response-response (R-R) priming effect. Even though the bidirectionality of spatial-numerical associations could thus be demonstrated, the bidirectionality of true S-R priming effects of spatial-numerical associations such as the SNARC effect have rarely been addressed so far.

Together with a previous study (Richter & Wühr, 2023), this paper tries to close this gap by investigating the reciprocity of the SNARC effect. In doing that, we are the first to directly compare the regular[10] SNARC effect in a number-location task, which employs numerical stimuli (e.g., 1 and 2) and spatial (i.e., left and right) responses, to a "reciprocal"[11] SNARC effect in a location-number task, which employs spatial (i.e., left and right) stimuli and numerical responses (e.g., 1 and 2). The regular SNARC effect describes the phenomenon that numerical stimuli influence the selection and execution of spatial responses in such a manner that small numbers prime left responses and large numbers prime right responses. If the SNARC effect is bidirectional, spatial stimuli should also influence the selection and execution of numerical responses in the form of a reciprocal SNARC effect. So far, several theories that have been proposed to account for SNARC effects differ in whether they assume bi- or unidirectional associations between number and space and thus in whether they predict reciprocal SNARC effects or not.

The *mental number line (MNL)* was the first theory proposed in order to account for the SNARC effect (e.g., Dehaene, 2003; Dehaene et al., 1993; Fischer & Shaki, 2014). The MNL assumes that numbers are mentally represented from left to right in an ascending order with small numbers located on the left and large numbers located on the right. When processing numerical sizes, the number activated simultaneously activates the corresponding position on the MNL. The MNL is assumed to be situated between stimulus processing and response selection and to be part of long-term memory (e.g., Dehaene et al., 1993; Ginsburg & Gevers, 2015; Huber et al., 2016; Umiltà et al., 2010). That means, a numerical stimulus activates a

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[10] Even though we use the term *regular SNARC effect* to denote the compatibility effect between numerical stimuli and spatial responses as employed in a typical SNARC task, we do not mean to characterize the effect in the opposite direction as *irregular*.

[11] We use the term *reciprocal SNARC effect* to denote a compatibility effect between spatial stimuli and numerical responses.

number code together with its spatial position on the MNL, which then primes a corresponding spatial response (Dehaene et al., 1993; Fischer et al., 2003; Restle, 1970). Note, however, that the representational overlap of number and space on the MNL does not necessarily imply reciprocal, or even symmetrical, SNARC effects. Rather, it is possible that asymmetries arise either between different stimulus codes and the MNL, or between the MNL and different response codes. For example, it is possible that numerical and spatial stimuli activate the MNL to different degrees.

The *polarity correspondence principle* postulated by Proctor and colleagues (e.g., Proctor & Cho, 2006) constitutes a second account of the SNARC effect. According to this principle, in many binary classification tasks positive polarity is assigned to one stimulus and response alternative, whereas negative polarity is assigned to the opposite stimulus and response alternative. In a typical SNARC task, the stimuli vary on the bipolar dimension of numerical size (small-large) while the responses vary on the bipolar dimension of spatial location (left-right). The polarity correspondence principle assumes that negative polarity is assigned to the categories “small” and “left”, whereas positive polarity is assigned to the categories “large” and “right” (Proctor & Cho, 2006). In case the polarities of stimuli and responses match, faster and more accurate responses are made compared to when they do not match (see Lakens, 2012; Proctor & Cho, 2006; Proctor & Xiong, 2015). In contrast to the MNL, the polarity correspondence principle implies that the associations between number and space are part of working memory (WM) as stimulus and response alternatives are given positive and negative polarities in relation to the opposing alternatives and thus depend on the given stimulus and response set (see Ben Nathan et al., 2009; Gevers et al., 2006; Wühr & Richter, 2022).

In our view, the polarity correspondence principle should predict bidirectional SNARC effects because both numbers and locations are assigned polarities regardless of whether they occur as stimulus or response features. In particular, if participants code “left” and “right” responses as negative and positive polarity, respectively, then “left” and “right” should also be coded as negative and positive, respectively, when they refer to alternative stimuli. The latter assumption is supported by findings demonstrating superior processing of right locations as compared to left locations, a finding that has been attributed to different polarities (e.g., Just & Carpenter, 1975; Olson & Laxar, 1973). Similarly, if participants code “small” and “large” stimuli as negative and positive polarity, respectively, then “small” and “large” should also be coded as negative and positive, respectively, when they refer to alternative responses.

A third account which emphasizes the role of short-term associations between number and space as underlying the SNARC effect is the *working memory (WM) account* by van Dijck and colleagues (e.g., Abrahamse et al., 2016; van Dijck & Fias, 2011; van Dijck et al., 2015). According to this account, the crucial variable is the serial order in which the elements of a stimulus set are stored in WM, with earlier serial positions being associated with left spatial locations, and later serial positions being associated with right spatial locations. The WM account of the SNARC effect has later been extended to a more general theory of serial-order coding in WM, called the *mental whiteboard hypothesis* (Abrahamse et al., 2014, 2017). According to this hypothesis, coding the serial order of items in (verbal) WM is achieved by connecting the items to spatial position markers. These spatial position markers are conceived as “coordinates within an internal, spatially defined system” (Abrahamse et al., 2014, p. 2). Moreover, it is assumed “that [the spatial coding of serial order] spontaneously occurs from left to right” (Abrahamse et al., 2014, p. 2), which provides an account for the SNARC effect with number stimuli and spatial responses (e.g., Abrahamse et al., 2014). In particular, the authors assume that participants spontaneously store the stimulus numbers of a typical SNARC experiment in ascending order, which implies that smaller numbers are tagged to left-side position markers and larger numbers are tagged to right-side position markers, and the position markers subsequently affect the selection of a (congruent or incongruent) spatial response to a stimulus (Abrahamse et al., 2014, 2016). In contrast to the MNL, which assumes that spatial-numerical associations are stored in long-term memory (Dehaene et al., 1993; Ginsburg & Gevers, 2015; Huber et al., 2016), the mental whiteboard hypothesis assumes that they are stored in WM. Moreover, while the MNL accounts for spatial-numerical associations only, the mental whiteboard hypothesis accounts for associations between any ordinal quantity and space (Abrahamse et al., 2014).

Importantly, proponents of the mental whiteboard hypothesis assume a bidirectional relationship between spatial processing and (verbal) serial order memory (e.g., De Belder et al., 2015). Accordingly, retrieval from serial order memory should not only modulate spatial processing, as reflected in the regular SNARC effect, but spatial processing should also modulate retrieval from serial order memory. The authors provided evidence for this assumption by showing that the location of (irrelevant) spatial cues affected the retrieval of letters depending on the serial position of the letter within a to-be-stored list. In particular, left-side cues facilitated retrieval of letters at early list positions, whereas right-side cues facilitated retrieval of letters at later list positions (De Belder et al., 2015). Despite assuming a bidirectional relation between spatial processing and (verbal) serial order memory, it is not immediately clear whether the WM account, or the mental whiteboard hypothesis, would predict a reciprocal SNARC effect. Assume a task in which participants respond to a left or right location stimulus by pressing a key once or twice, and the S-R mapping is varied. Even if participants spontaneously store the stimuli in a canonical order (i.e., from left to right), and spatial tags would be used for coding serial position, it is not clear why these spatial tags should differently prime the one- or two-keypress responses. Moreover, the mental whiteboard hypothesis explicitly assumes spatial position markers for coding serial positions in *verbal* WM. Verbal WM is clearly implicated in the typical SNARC task with alphanumeric stimuli, but not in the reciprocal SNARC task with spatial stimuli. In fact, it is unclear whether spatial position markers are also involved in representing serial order of spatial stimuli (e.g., De Belder et al., 2015; Ginsburg et al., 2017).

In a previous study (Richter & Wühr, 2023), we have already begun to investigate whether SNARC effects are reciprocal or not. More specifically, in two experiments we investigated if the processing of spatial stimuli can influence the selection and execution of numerical responses, which would lead to the occurrence of a reciprocal SNARC effect. To do so, we compared the compatibility effect of a number-location task, resembling the typical SNARC task, with the compatibility effect of a location-number task, resembling a reciprocal SNARC task. In the number-location task, one and two dots (Exp. 1) or the digits 1 and 2 (Exp. 2) served as stimuli to which participants responded by pressing a left or right key with two fingers of their dominant hand. In the location-number task, a black square presented in a left/right location served as a stimulus to which participants responded by pressing a key once or twice with the index finger of their dominant hand. Participants completed both tasks twice, once according to a compatible mapping (one-left, two-right; left-one, right-two) and once according to an incompatible mapping (one-right, two-left; left-two, right-one).

As expected, we found a regular SNARC effect in the number-location task of both experiments: Participants responded faster and more accurately in the compatible compared to the incompatible mapping. However, we did not find a reciprocal SNARC effect: In the location-number task, participants' performance was similar across both mapping conditions.

Those results suggest that numerical stimuli can influence spatial responses whereas spatial stimuli cannot influence numerical responses. However, excluding outlier data affected the pattern of results in Experiment 2, where we used digit stimuli: Including outliers in the analysis led to a small, but significant, reciprocal SNARC effect. While reciprocal SNARC effects seemed absent for the majority of participants, small effects emerged in a subsample which showed extreme reaction times and/or error percentages. Thus, the associations between number and space, which underlie the SNARC effect, seem to be at least strongly asymmetrical.

The major aim of the present study was to further investigate the reciprocity of the SNARC effect in three experiments with vocal responses, and to replicate and extend the results of our previous experiments (Richter & Wühr, 2023). In particular, the present experiments differed in three important aspects from the previous experiments. Firstly, we changed the response mode. In the experiments reported in this paper, participants responded vocally, instead of manually, by saying a location word ("left"[12] or "right") in the number-location task, and by saying a number word in the location-number task ("one" or "two" in Experiment 1, "one" or "nine" in Experiments 2 and 3). Crucially, Gevers et al. (2010) have shown that SNARC effects of similar size can be obtained with manual as well as with vocal responses. Moreover, Gevers and colleagues concluded that "verbal-spatial coding was the dominant factor in driving the SNARC effect" (Gevers et al., 2010, p. 187) in their experiments, emphasizing the role of verbal rather than visual encoding of spatial information which is then associated with numerical size. We therefore predicted that the results with vocal responses should be similar to the results we obtained with manual responses in the

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[12] Participants responded with the German words for "left", "right", "one", "two" and "nine" in our experiments, but we are using the English words in the text for clarity.

previous study (Richter & Wühr, 2023).

Secondly, in our previous experiments with manual keypress responses, we used the numerical values 1 and 2 both as stimulus and as (manual) response values. To foster a comparison between the results, we used the same stimulus and response values in the present Experiment 1. However, we found it important to investigate the reciprocity of S-R compatibility effects between number and space with different stimulus and response sets to demonstrate the robustness of our results. We therefore used different numerical values (i.e., 1 and 9) in Experiments 2 and 3. A similar increase in the number of sequential keypress responses is less practical for obvious reasons, and would introduce other problems such as differences in the complexity of response alternatives (e.g., Henry & Rogers, 1960; Sternberg et al., 1978).

Thirdly, while we used visuospatial stimuli (left and right physical locations) in the location-number task of our previous experiments, we wanted to investigate whether a consistent use of alphanumeric stimuli would affect the pattern of results. In Experiments 1 and 2 of our present paper, we merely changed the response mode by using alphanumeric responses (“left” / “right” in the number-location task; “one” / “two” or “nine” in the location-number task). In Experiment 3, we also changed the stimulus presentation by using alphanumeric stimuli in the form of number words (“one” / “nine” in the number-location task) and location words (“left” / “right” in the location-number task). Note that while responses in all three experiments were given vocally, stimuli in all three experiments were presented visually in the form of digits or number words in the number-location task and in the form of physical locations or location words in the location-number task. Therefore, we differentiate between vocal responses (in the sense of spoken) and verbal stimuli (in the sense of written).

Experiment 1

The purpose of Experiment 1 was to investigate the reciprocity of the SNARC effect with vocal responses. Therefore, we compared the compatibility effect of a number-location task (SNARC task) with the compatibility effect of a location-number task (reciprocal SNARC task). In the number-location task, participants responded to the digit 1 or 2 with the vocal response "left" or "right". Conversely, in the location-number task, participants responded to a left or right stimulus location with the vocal response "one" or "two". Participants completed both tasks twice, once according to a compatible mapping (1-left, 2-right; left-1, right-2) and once according to an incompatible mapping (1-right, 2-left; left-2, right-1). The compatibility effect served as a measure for the strength of the associations between stimuli and responses which could form three possible patterns. Significant compatibility effects of equal size would suggest bidirectional and symmetrical associations. Significant compatibility effects of different sizes would suggest bidirectional, but asymmetrical associations. A significant compatibility effect in the typical number-location task and a non-significant compatibility effect in the reciprocal location-number task would, contrarily, indicate unidirectional associations. Note that the terms reciprocity and uni-/bidirectionality thus refer to the direction of effects whereas the terms symmetry and asymmetry refer to the magnitude of effects.

Methods

Participants

Similar SNARC effects can be obtained with manual as well as with vocal responses in a typical SNARC task, that is, employing numerical stimuli and spatial responses. Gevers et al. (2010, Experiment 1), for example, reported a vocal SNARC effect of $\eta^2_p = .33$, which was not statistically different from a SNARC effect with manual responses. Since we were interested in a so far unknown reciprocal SNARC effect with vocal responses, which might have smaller effect sizes, we decided to reduce the effect size estimate and use an effect size of $\eta^2_p = 0.2$ for a power analysis. We conducted the power analysis with the software MorePower (Campbell & Thompson, 2012) revealing that a sample size of 54 participants would be required to detect an effect of this size with high power ($1-\beta = .95$) at the standard alpha-error probability of .05.

Sixty students (53 female, 7 male) with a mean age of 20.633 years (*SD* = 3.551) voluntarily participated in our experiment. According to self-report, 57 participants were right-handed, whereas 3 participants were left-handed. All participants reported normal (*N* = 30) or corrected-to-normal vision (*N* = 30). Prior to participation, all volunteers gave their informed consent. They were compensated by receiving either course credit or a payment of 10 Euro in exchange for participation. The local Ethics Committee at TU Dortmund University approved the experimental protocol for our study (GEKTUDO_2022_36).

Apparatus and Stimuli

Participants sat in front of a 19-inch color monitor with a viewing distance of approximately 50 cm. The software EPrime 3.0 (Psychology Software Tools; Sharpsburg, PA, USA) controlled the presentation of stimuli and registered responses (i.e., vocal responses, reaction times). A small plus sign (Courier font, size 18 pt) served as a fixation point and was presented at the screen center at the beginning of each trial. All stimuli were presented in black on a white background. In the number-location task, the Arabic digits 1 and 2 (Times New Roman, size 40 pt) served as stimuli and were presented at screen center. Participants responded vocally to the stimuli by saying “left” or “right” into a microphone, which was aligned to the participants’ midline and stood directly in front of them. The microphone was connected to the voice-key of the Chronos console (Psychology Software Tools; Sharpsburg, PA, USA), which registered reaction times and recorded the participants' vocal responses. Each vocal response was stored in a separate audio-file and later checked in terms of accuracy. In the location-number task, a black square with a side length of 20 mm served as the stimulus and was presented 12 cm to the left or the right of the screen center. Participants responded vocally by saying “one” or “two”.

Procedure

Combining two tasks (number-location task, location-number task) and two S-R mappings (compatible, incompatible) resulted in four conditions which were completed by each participant. In the number-location task, participants responded vocally to the Arabic digits 1 or 2 by saying “left” or “right” according to a compatible mapping (1 - “left”, 2 - “right”) or an incompatible mapping (1 - “right”, 2 - “left”). In the location-number task, participants responded vocally to the left or right stimulus location by saying “one” or “two” according to a compatible mapping (left - “one”, right - “two”) or an incompatible mapping (left - “two”, right - “one”). The time course and sample stimuli of the number-location task and the location-number task are depicted in **Figure 1**.

Instructions presented at the beginning of each condition informed participants about the content and the procedure of the task. Each condition consisted of one training block with 10 trials and two experimental blocks with 40 trials each. Within each block, trials were randomized. A fixation point was presented at the beginning of each trial for 400 or 600 ms, with both durations occurring equally often within each block. The stimulus was then presented until a response was registered or for a maximum of 2,000 ms. If the voice key registered a response, an inter-trial interval showing an empty screen was presented for 1,000 ms. If the voice key did not register a response, a corresponding error message indicating a missing response was presented during the inter-trial interval. Trials with a missing response were not repeated. Since the program could not identify the correctness of vocal responses, participants were not provided feedback about response accuracy. At the beginning of each experimental block, the instructions informing the participants about the task and S-R mapping were again presented. Participants were allowed to take a break between blocks or to continue with the subsequent one.

Both factors (i.e., task and S-R mapping) were varied within-subjects but between different blocks of trials. Both the order of tasks (number-location or location-number task first) and the order of mappings (compatible or incompatible mapping first) were counterbalanced between participants. Both S-R mapping conditions were completed consecutively within one task and the order of mappings was consistent between the two tasks for one participant. The whole experiment took about 30 min. The experimenter stayed in the laboratory during the practice blocks but left the room before the participants continued with the experimental blocks.

Design and Data Analysis

Before the statistical analysis, the vocal responses recorded during the experiment were checked in terms of accuracy for each participant. Response errors were manually entered into each data file. A response was counted as erroneous when the first sound could be ascribed to the wrong response despite potentially switching to the correct response subsequently. The design of the experiment was a two-factorial (*Task* × *Mapping*) within-subjects design. The first independent variable *Task* had two levels: the number-location task and the location-number task. The second factor S-R *Mapping* also contained two levels: the compatible mapping condition and the incompatible mapping condition.

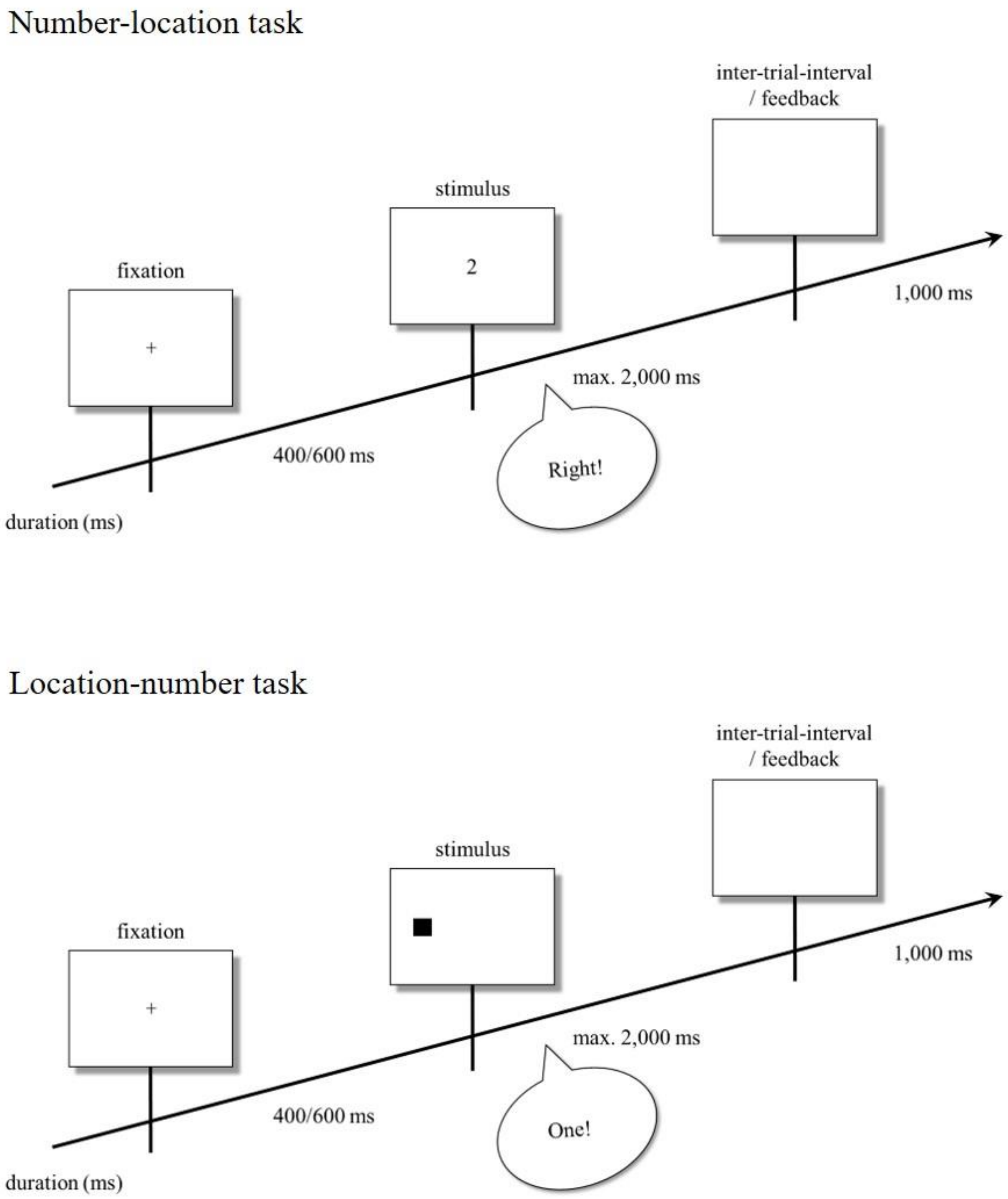

Figure 1. Time course of events in typical trials of the number-location task (upper panel), and the location-number task (lower panel) according to compatible mappings. Feedback was only provided after a missing response. The rectangles represent stimulus displays; the speech bubble represents a vocal response to the stimulus.

We measured Reaction Times (RTs) of correct vocal responses and error percentages as dependent variables. We planned to analyze our data with a two-factorial Analysis Of Variance (ANOVA), with *Task* (number-location, location-number) and S-R *Mapping* (compatible, incompatible) as within-subjects variables. In case of a significant two-way interaction, we planned to conduct *t*-tests to determine the source of the interaction. Even though error percentages are usually not normally distributed which would indicate the use of non-parametric tests, we preferred using *t*-tests due to the large number of ties in error percentages which are excluded from non-parametric tests and thus bias the results towards H1. For both directions, we use the label H1 (experimental hypothesis) to denote a significant effect and H0 (null hypothesis) to denote a non-significant effect. Moreover, we report the Bayes Factor (BF) for each pairwise comparison (Rouder et al., 2009), which allows to evaluate the evidence for H1 and H0. Assuming unidirectional associations between number and space implies a null effect in the location-number task. However, since absence of evidence is not evidence of absence, the null-hypothesis significance testing falls short in evaluating evidence for H0. We interpret the BF values according to the evidence categories provided by Jeffreys, 1961 (as cited in Lee & Wagenmakers, 2014).

Previous studies have shown that the size of compatibility or congruency effects such as the SNARC effect depends on response speed (i.e., RT; see Proctor et al., 2011, for a review). Regarding the regular SNARC effect in number-location tasks, it has been observed that the effect increases with increasing RTs (e.g., Gevers et al., 2006; Mapelli et al., 2003). We therefore conducted additional distributional analyses[13] investigating the time course of the mapping effects in both the number-location task as well as the location-number task. With that we were able to check if the time course of the regular SNARC effect in our number-

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[13] Please note that, even though referred to within the discussion sections of the main manuscript, the distributional analyses of Exp. 1-3 (before and after the exclusion of outliers) are reported in the **Appendix**.

location task conforms to the time course of the SNARC effect which has been empirically established so far. Moreover, we wanted to rule out the possibility that a small mapping effect occurred for a specific RT level in the location-number task, which did not reach significance in the primary analysis.

Results

Data trimming

On an overall level, we excluded one participant from data analysis (number 34 in our data set) because her mean error percentage in the number-location task was 20% or higher. After removing this dataset, the highest error percentages were 13.5% in the number-location task, and 6.1% in the location-number task. On a trial level, the first trial in each block and trials with RTs below 100 ms or above 1,500 ms were excluded from data analysis. Participants' responses were too fast (i.e., RT < 100 ms) in less than 1% of trials in both the number-location task (*M* = 0.078%, *SD* = 0.311) and in the location-number task (*M* = 0.157%, *SD* = 0.585). Similarly, participants' responses were too slow (i.e., RT > 1,500 ms) in less than 1% of trials in both the number-location task (*M* = 0.275%, *SD* = 0.817) and in the location-number task (*M* = 0.278%, *SD* = 1.114).

Reaction Times (RTs)

We conducted a two-factorial ANOVA with *Task* and *Mapping* as within-subjects factors and RTs from trials with correct responses as a dependent variable. Both main effects and the two-way interaction were significant. The significant main effect of *Task*, $F(1, 58) = 71.367$, $MSE = 1,252.917$, $p < .001$, $\eta^2_p = .552$, indicated shorter RTs in the location-number task (*M* = 429 ms, *SD* = 66) than in the number-location task (*M* = 468 ms, *SD* = 74). The significant main effect of *Mapping*, $F(1, 58) = 44.778$, $MSE = 817.958$, $p < .001$, $\eta^2_p = .436$, reflected shorter RTs with the compatible mapping (*M* = 436 ms, *SD* = 68) than with the incompatible mapping (*M*

= 461 ms, *SD* = 76). Most interestingly, however, the two-way interaction, *F*(1, 58) = 20.311, *MSE* = 1,061.135, $p < .001$, $\eta^2_p = .259$, was significant, revealing different mapping effects in the two tasks.

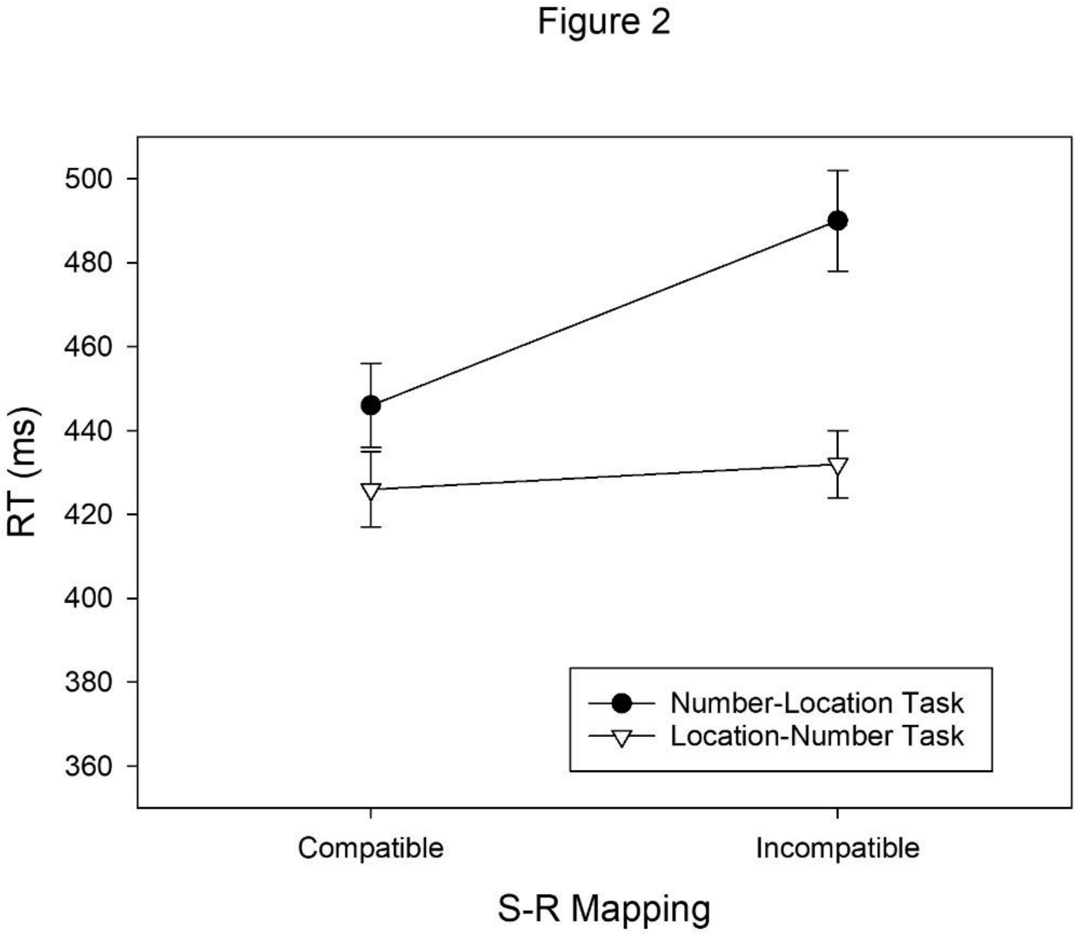

Figure 2. RTs of correct responses as a function of Task and S-R Mapping observed in Exp. 1. Error bars reflect 95% confidence intervals for within-subjects designs (Cousineau, 2017).

By means of pairwise comparisons between the compatible and incompatible mapping condition for each task we aimed to determine the source of the two-way interaction. In the number-location task, significantly shorter RTs in the compatible than in the incompatible condition, $t(58) = 6.410$, $p < .001$, $d = 0.834$, $BF_{+0} = 454{,}889.170$, revealed a regular SNARC effect of 44 ms (cf. **Figure 2**) and extreme evidence for H1. Contrarily, in the location-number task, RTs did not differ significantly between both mapping conditions, *t*(58) = 1.428, *p* = .159, *d* = 0.186, BF_{+0} = 0.372, indicating anecdotal evidence against the presence of a reciprocal SNARC effect.

Error Percentages

Even though error percentages were very low and the results of the statistical analysis should thus be interpreted with caution, we decided to report the analysis of error percentages for the sake of completeness. Importantly, error percentages were the highest in conditions in which RTs were the slowest, ruling out a potential speed-accuracy trade-off.

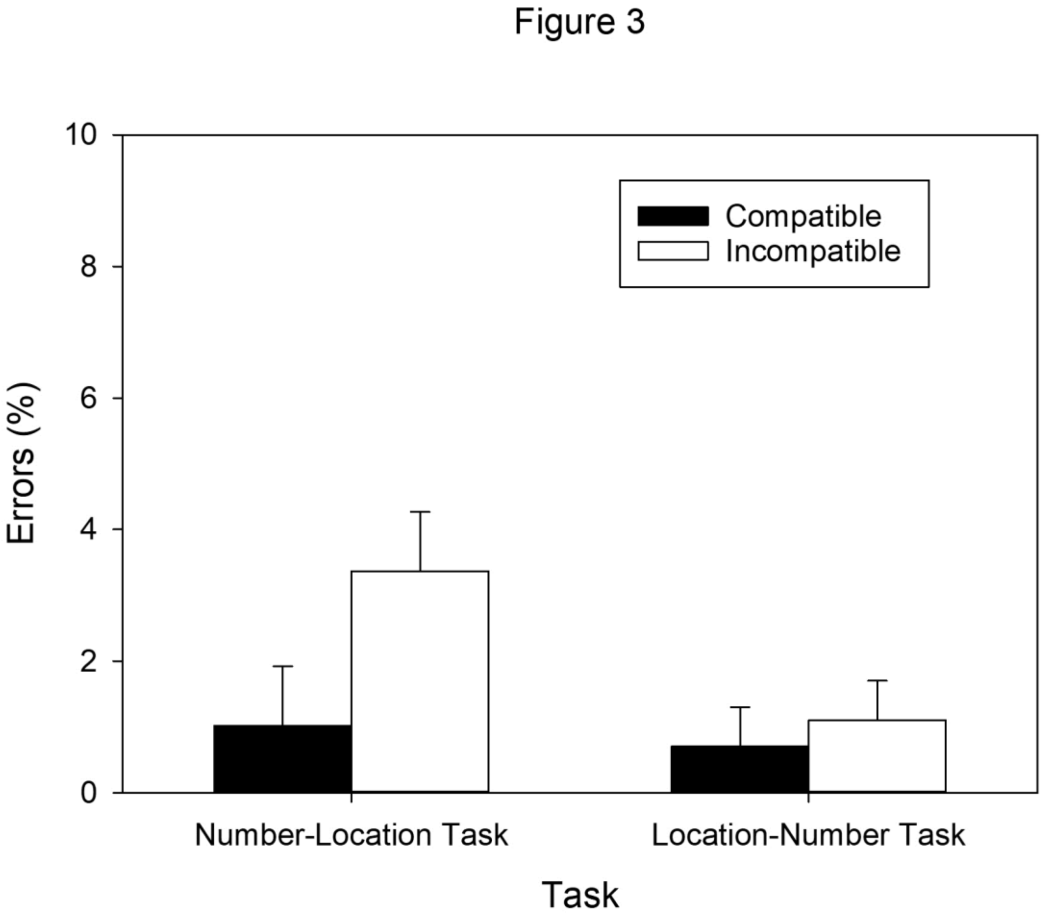

Figure 3. Error percentages as a function of Task and S-R Mapping observed in Exp. 1. Error bars reflect 95% confidence intervals for within-subjects designs (Cousineau, 2017).

Error percentages were also subjected to a two-factorial ANOVA with *Task* and *Mapping* as within-subjects variables. Both main effects and the two-way interaction again reached significance. The main effect of *Task*, $F(1, 58) = 17.388$, $MSE = 5.679$, $p < .001$, $\eta^2_p = .231$, indicated significantly more errors in the number-location task ($M = 2.200$, $SD = 3.252$) than in the location-number task ($M = 0.906$, $SD = 1.696$). The significant main effect of *Mapping*, $F(1, 58) = 19.175$, $MSE = 6.050$, $p < .001$, $\eta^2_p = .248$, reflected more errors with the incompatible mapping ($M = 2.254$, $SD = 2.901$) than with the compatible mapping ($M = 0.852$, $SD = 2.211$). Again, the most interesting finding was the significant two-way interaction, $F(1, 58) = 11.448$, $MSE = 4.712$, $p = .001$, $\eta^2_p = .165$, which revealed different mapping effects in the two tasks.

To uncover the source of the two-way interaction, we again computed pairwise comparisons between the compatible and incompatible mapping condition for each task separately. In the number-location task, significantly fewer errors were made in the compatible than in the incompatible condition, $t(58) = 4.423$, $p < .001$, $d = 0.576$, $BF_{+0} = 471.626$, revealing a regular SNARC effect of 2.358% (cf. **Figure 3**) and extreme evidence for H1. In contrast, in the location-number task, error percentages did not differ between the two mapping conditions, $t(58) = 1.572$, $p = .121$, $d = 0.205$, $BF_{+0} = 0.454$, revealing anecdotal evidence against the presence of a reciprocal SNARC effect.

Exclusion of outliers

Reciprocal SNARC effects did not reach significance in the omnibus analysis or the distributional analysis (for the latter see **Appendix**). Nevertheless, small numerical trends of up to 17 ms (in the fourth quartile of the distributional analysis) emerged in the location-number task. Since a previous study has shown that outliers might be driving these small reciprocal SNARC effects (Richter & Wühr, 2023), we decided to run the same set of analysis after excluding outlier participants according to the Tukey (1977) criterion, which identifies observations below Q_{25} – 1,5×IQR or above Q_{75} + 1,5×IQR as outliers. We collapsed data across the mapping variable and applied the criterion to four variables (mean RT and error percentage in the number-location and location-number task, respectively), which led to the exclusion of eight further participants and a remaining sample of *N* = 51. By removing outliers, the numerical trends of small reciprocal SNARC effects in RTs decreased from 6 ms (*d* = 0.186) to 3 ms (*d* = 0.111) in the pairwise comparisons, while evidence for the null hypothesis increased from anecdotal (BF_{+0} = 0.372) to moderate (BF_{+0} = 0.206). The same pattern was observable for numerical trends in error percentages, which decreased from 0.446% (*d* = 0.205) to 0.104% (*d* = 0.078), while evidence for the null hypothesis increased from anecdotal (BF_{+0} = 0.454) to moderate (BF_{+0} = 0.117).

Discussion

The purpose of Experiment 1 was to investigate the reciprocity of the SNARC effect. Therefore, we compared the compatibility effect of a number-location task (SNARC task) with the compatibility effect of a location-number task (reciprocal SNARC task). As expected, we found a regular SNARC effect in the number-location task. Participants' vocal responses were faster and more accurate in the compatible mapping condition (1 - “left”, 2 - “right”) than in the incompatible mapping condition (1 - “right”, 2 - “left”). Moreover, the SNARC effect in RTs showed the typical time course as it increased with increasing RTs (e.g., Gevers et al., 2006; Mapelli et al., 2003). In contrast, we did not find a reciprocal SNARC effect in the location-number task. An additional distributional analysis (see **Appendix**) corroborated this finding: although the two-way interaction of Mapping and Quartile was significant for this task, suggesting a numerical increase of reciprocal SNARC effects with increasing RTs, post-hoc tests could not detect a significant mapping effect for any quartile. Our results thus indicate that digit stimuli activated vocal location responses, whereas spatial stimuli did not activate vocal number responses with the same strength. The finding that small numerical trends of reciprocal SNARC effects increased with increasing RTs might at first glance suggest that long RTs are required for reciprocal SNARC effects to emerge. However, excluding outliers eliminated this interaction implying that small reciprocal SNARC effects were mainly driven by a small subset of participants who showed extreme RTs and/or error percentages. Nevertheless, spatial-numerical associations of vocal response codes seem to be at least strongly asymmetrical.

Experiment 2

Experiment 2 served two aims. The first aim was to replicate the pattern of results of Experiment 1 with a different stimulus set and a different sample. Therefore, we used the numerical values 1 and 9 as digit stimuli in the number-location task, and as (vocal) number responses in the location-number task. The second aim was to test how removing a possible influence of the so-called *markedness association of response codes* (MARC) effect from the design would affect the pattern of results. The MARC effect refers to faster left-hand responses to odd digit stimuli, and faster right-hand responses to even digit stimuli, when compared to the reverse combinations (e.g., Berch et al., 1999; Cipora et al., 2019; Nuerk et al., 2004). In Experiment 1, MARC compatibility and SNARC compatibility were confounded because the small number (1) was odd, and the larger number (2) was even. Therefore, we cannot exclude that the mapping effect observed in the number-location task reflected a combination of both SNARC and MARC effects. Similarly, the small compatibility effects in the location-number task, which were observed for longer RTs, might either reflect reciprocal SNARC effects, reciprocal MARC effects, or both. In Experiment 2, we wanted to isolate the asymmetrical pattern for the SNARC effect by excluding any contribution of the MARC effect. This was achieved by using two odd numbers (1 and 9) as the small and the large number.

Methods[14]

Participants

We applied the same rationale as in Experiment 1 to estimate the effect size and conduct a power analysis. Therefore, again, a sample size of 54 participants would be required to detect an effect of $\eta^2_p = 0.2$ with high power ($1-\beta = .95$) at the standard alpha-error probability of .05.

Sixty-one students (42 female, 19 male) with a mean age of 23.262 years (*SD* = 3.723) volunteered in our experiment. According to self-report, 54 participants were right-handed and 7 participants were left-handed. All participants reported to have normal (*N* = 40) or corrected-to-normal (*N* = 21) vision. All volunteers gave their informed consent prior to participation and received either course credit or a payment of 10 Euro in exchange. Again, the local Ethics Committee at TU Dortmund University approved the experimental protocol for our study (GEKTUDO_2022_36).

Apparatus and Stimuli

The apparatus and stimuli were the same as in Experiment 1, with the only exception that we replaced the digit stimuli 1 / 2 and the corresponding number responses “one” / “two”, which were used in Experiment 1, by the digit stimuli 1 / 9 and the number responses “one” / “nine”. Thus, in the number-location task, the Arabic digits 1 or 9 served as stimuli to which participants responded vocally by saying “left” or “right”, whereas in the location-number task, a black square occurred to the left or right of fixation, and participants responded vocally to stimulus location by saying “one” or “nine”.

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[14] The experiment was pre-registered at OSF (https://osf.io/7kt4y).

Procedure

The procedure in Experiment 2 was the same as in Experiment 1 with the only exception that different numerical stimuli and responses were employed. In the number-location task, the compatible mapping thus contained the assignments 1 - “left” / 9 - “right” and the incompatible mapping contained the assignments 1 - “right” / 9 - “left”. In the location-number task, the compatible mapping consisted of the assignments left - “one” / right - “nine” and the incompatible mapping consisted of the assignments left - “nine” / right - “one”.

Design and Data Analysis

The design and data analysis were the same as in Experiment 1.

Results

Data trimming

On an overall level, we excluded three participants due to technical difficulties[15]. On a trial level, the first trial in each block and trials with RTs below 100 ms or above 1,500 ms were excluded from data analysis. Participants’ responses were too fast (i.e., RT < 100 ms) in less than 1% of trials in both the number-location task (*M* = 0.079%, *SD* = 0.399) and in the location-number task (*M* = 0.078%, *SD* = 0.351). Similarly, participants’ responses were too slow (i.e., RT > 1,500 ms) in less than 1% of trials in both the number-location task (*M* = 0.236%, *SD* = 0.807) and in the location-number task (*M* = 0.236%, *SD* = 0.876).

Reaction Times (RTs)

We conducted a two-factorial ANOVA with *Task* and *Mapping* as within-subjects factors and RTs from trials with correct responses as a dependent variable. Both main effects and the

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[15] In fact, the recordings of several vocal responses from these participants had poor quality, making it impossible to determine the accuracy of these responses. Note that we removed these participants (numbers 35, 36, 37) from the dataset.

two-way interaction were significant. The significant main effect of *Task*, *F*(1, 57) = 228.505, *MSE* = 860.703, *p* < .001, η^2_p = .800, reflected shorter RTs in the location-number task (*M* = 387 ms, *SD* = 59) than in the number-location task (*M* = 445 ms, *SD* = 68). The significant main effect of *Mapping*, *F*(1, 57) = 11.355, *MSE* = 1,080.322, *p* = .001, η^2_p = .166, indicated shorter RTs with the compatible mapping (*M* = 409 ms, *SD* = 59) than with the incompatible mapping (*M* = 423 ms, *SD* = 79). Most interestingly, however, the two-way interaction, *F*(1, 57) = 6.208, *MSE* = 841.351, *p* = .016, η^2_p = .098, was significant, indicating different mapping effects in the two tasks.

Figure 4

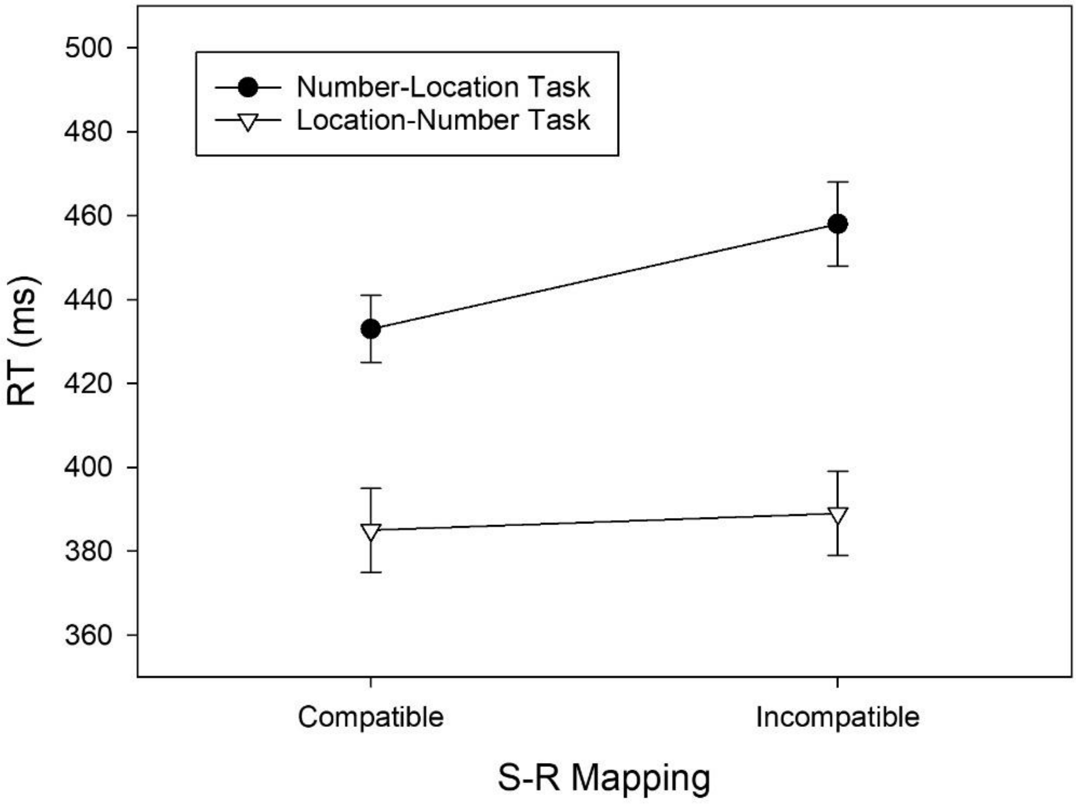

Figure 4. RTs of correct responses as a function of Task and S-R Mapping observed in Exp. 2. Error bars reflect 95% confidence intervals for within-subjects designs (Cousineau, 2017).

In the number-location task, significantly shorter RTs in the compatible than in the incompatible condition, *t*(57) = 4.416, *p* < .001, *d* = 0.580, BF_{+0} = 454.621, revealed a regular SNARC effect of 24 ms (cf. **Figure 4**) and extreme evidence for H1. Contrarily, in the location-number task, RTs did not differ significantly between both mapping conditions, *t*(57) = 0.835, *p* = .407, *d* = 0.110, BF_{+0} = 0.200, indicating moderate evidence against the presence of a reciprocal SNARC effect.

Error Percentages

We again decided to report the analysis of error percentages, even though error percentages were very low and the results of the statistical analysis should thus be interpreted with caution. Similar to Experiment 1, error percentages were the highest in conditions in which RTs were the slowest, ruling out a potential speed-accuracy trade-off.

Error percentages were subjected to a two-factorial ANOVA with *Task* and *Mapping* as within-subjects variables. Both main effects and the two-way interaction were again significant. The main effect of *Task*, *F*(1, 57) = 24.011, *MSE* = 1.796, *p* < .001, η^2_p = .296, indicated significantly more errors in the number-location task (*M* = 1.538, *SD* = 2.251) than in the location-number task (*M* = 0.676, *SD* = 1.212). The significant main effect of *Mapping*, *F*(1, 57) = 9.283, *MSE* = 3.455, *p* = .004, η^2_p = .140, reflected more errors with the incompatible mapping (*M* = 1.479, *SD* = 2.306) than with the compatible mapping (*M* = 0.735, *SD* = 1.148). Again, the most interesting finding was the significant two-way interaction, *F*(1, 57) = 16.051, *MSE* = 1.924, *p* < .001, η^2_p = .220, which revealed different mapping effects in the two tasks.

In the number-location task, significantly fewer errors were made in the compatible than in the incompatible condition, *t*(57) = 3.843, *p* < .001, *d* = 0.505, BF_{+0} = 78.679, revealing a regular SNARC effect of 1.473% (cf. **Figure 5**) and very strong evidence for H1. In contrast, in the location-number task, error percentages did not differ between the two mapping conditions, $t(57) = 0.071$, $p = .944$, $d = 0.009$, $BF_{+0} = 0.144$, indicating moderate evidence against the presence of a reciprocal SNARC effect.

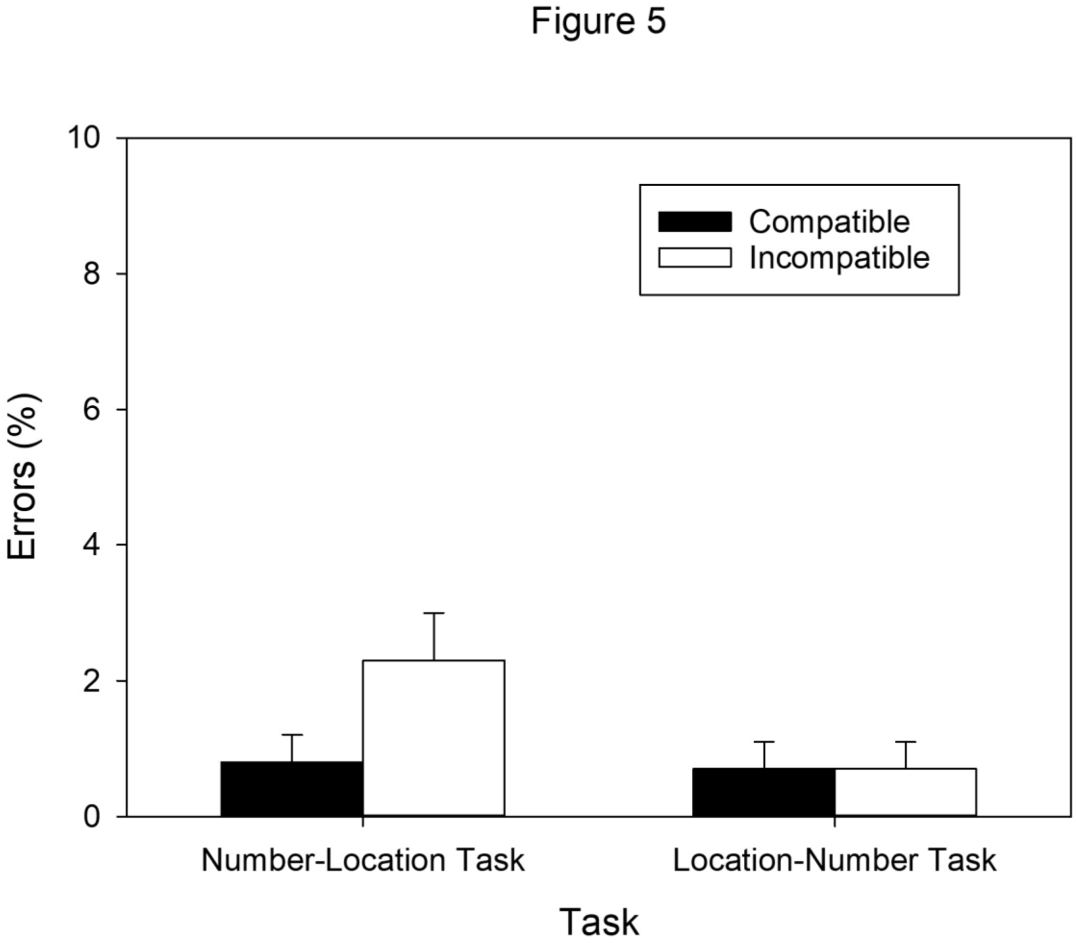

Figure 5. Error percentages as a function of Task and S-R Mapping observed in Exp. 2. Error bars reflect 95% confidence intervals for within-subjects designs (Cousineau, 2017).

Exclusion of outliers

Again, we conducted the same set of analysis after excluding outlier participants. Applying the Tukey (1977) criterion led to the exclusion of four participants and a remaining sample of $N = 54$. By removing outliers, the numerical trends of small reciprocal SNARC effects in RTs decreased from 5 ms ($d = 0.110$) to < 1 ms ($d = 0.004$) in the pairwise comparisons, consistently providing moderate evidence against the presence of a reciprocal SNARC effect (BF_{+0} = 0.148).

Discussion

The results of Experiment 2 replicated the main findings of Experiment 1 with a different stimulus and response set. We found a regular SNARC effect in the number-location task of Experiment 2, and no reciprocal SNARC effect in the location-number task. The time course pattern of the regular SNARC effect was again congruent with the one reported before (e.g., Gevers et al., 2006; Mapelli et al., 2003; see **Appendix**). Numerically small trends of reciprocal SNARC effects disappeared completely after excluding outliers, which thus supports the hypothesis that bidirectional SNARC effects might occur for a small subsample showing extreme RTs and/or error percentages. Since two odd numbers (1, 9) were used as stimuli and responses in Experiment 2, we excluded a potential impact of the MARC effect on our results, and the mapping effects observed can be interpreted as pure SNARC effects. The result that a regular but no reciprocal SNARC effect occurred despite the absence of a MARC effect strengthens the finding of Experiment 1 that the spatial-numerical associations, which underlie SNARC effects, are strongly asymmetrical for the vocal response mode.

Experiment 3

The major aim of Experiment 3 was to test how a consistent use of alphanumeric stimuli and responses would affect the pattern of results. In Experiments 1 and 2, we used alphanumeric stimuli (1 / 2 or 9) and responses (“left” / “right”) in the number-location task. In the reciprocal location-number task, we also used alphanumeric responses (“one” / “two” or “nine”), but we used visuospatial stimuli (left and right physical locations). The change of the stimulus presentation mode from alphanumeric to visuospatial makes the location-number task less comparable to the number-location task for two reasons. Firstly, while attention remains concentrated on the fixation point in the number-location task, it is allocated to the left or right in the location-number task. Secondly, the visuospatial instead of the verbal-spatial coding (cf. Gevers et al., 2010) might be emphasized in the location-number task but not in the number-location task. The asymmetry of spatial-size associations which we found in Experiments 1 and 2 could therefore also be attributed to asymmetrical associations of stimulus codes instead of response codes. In Experiment 3, we replaced the visuospatial stimuli in the location-number task by alphanumeric stimuli in the form of location words (“left” / “right”). For consistency reasons, we also replaced the digits, which we employed as stimuli in the number-location task, by number words (“one” / “nine”).

Methods

Participants

We aimed to attain a similar power as in Experiments 1 and 2. Fifty-two students (35 female, 17 male) with a mean age of 23.712 years (*SD* = 3.177) volunteered in our experiment. According to self-report, 45 participants were right-handed and 7 participants were left-handed. All participants reported to have normal (*N* = 27) or corrected-to-normal (*N* = 25) vision. All volunteers gave their informed consent prior to participation and received either course credit or a payment of 10 Euro in exchange. Again, the local Ethics Committee at TU Dortmund University approved the experimental protocol for our study (GEKTUDO_2022_36).

Apparatus and Stimuli

The apparatus and stimuli were the same as in Experiment 2, with the only exception that we replaced the numerical digits 1 / 9 by the number words “one” / “nine” in the number-location task and the left/right square stimuli by the centrally presented location words “left” / “right” in the location-number task. All stimuli were presented in 40 pt in Times New Roman.

Thus, in the number-location task, the words “one” or “nine” served as stimuli to which participants responded vocally by saying “left” or “right”, whereas in the location-number task, the words “left” or “right” served as stimuli to which participants responded by saying “one” or “nine”.

Procedure

The procedure in Experiment 3 was the same as in Experiment 2 with the only exception that different stimuli were employed. In the number-location task, the compatible mapping thus contained the assignments “one” - “left” / “nine” - “right” and the incompatible mapping contained the assignments “one” - “right” / “nine” - “left”. In the location-number task, the compatible mapping consisted of the assignments “left” - “one” / “right” - “nine” and the incompatible mapping consisted of the assignments “left” - “nine” / “right” - “one”.

Design and Data Analysis

The design and data analysis were the same as in Experiments 1 and 2. Moreover, we conducted a comparison of mapping effects between experiments[16] to investigate in how far the changes between experiments affected the regular and the reciprocal SNARC effects, respectively.

Results

Data trimming

On an overall level, we excluded two participants (21 and 48 in our dataset) because their mean error percentage in the location-number task was 20% or higher. On a trial level, the first trial in each block and trials with RTs below 100 ms or above 1,500 ms were excluded from data analysis. Participants’ responses were too fast (i.e., RT < 100 ms) in less than 1% of

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[16] Please note that, even though referred to within the discussion sections of the main manuscript, the comparison of mapping effects between experiments is reported in the **Appendix**.

trials in both the number-location task (*M* = 0.077%, *SD* = 0.307) and in the location-number task (*M* = 0.130%, *SD* = 0.632). Similarly, participants' responses were too slow (i.e., RT > 1,500 ms) in less than 1% of trials in both the number-location task (*M* = 0.237%, *SD* = 1.179) and in the location-number task (*M* = 0.180%, *SD* = 0.709).

Figure 6

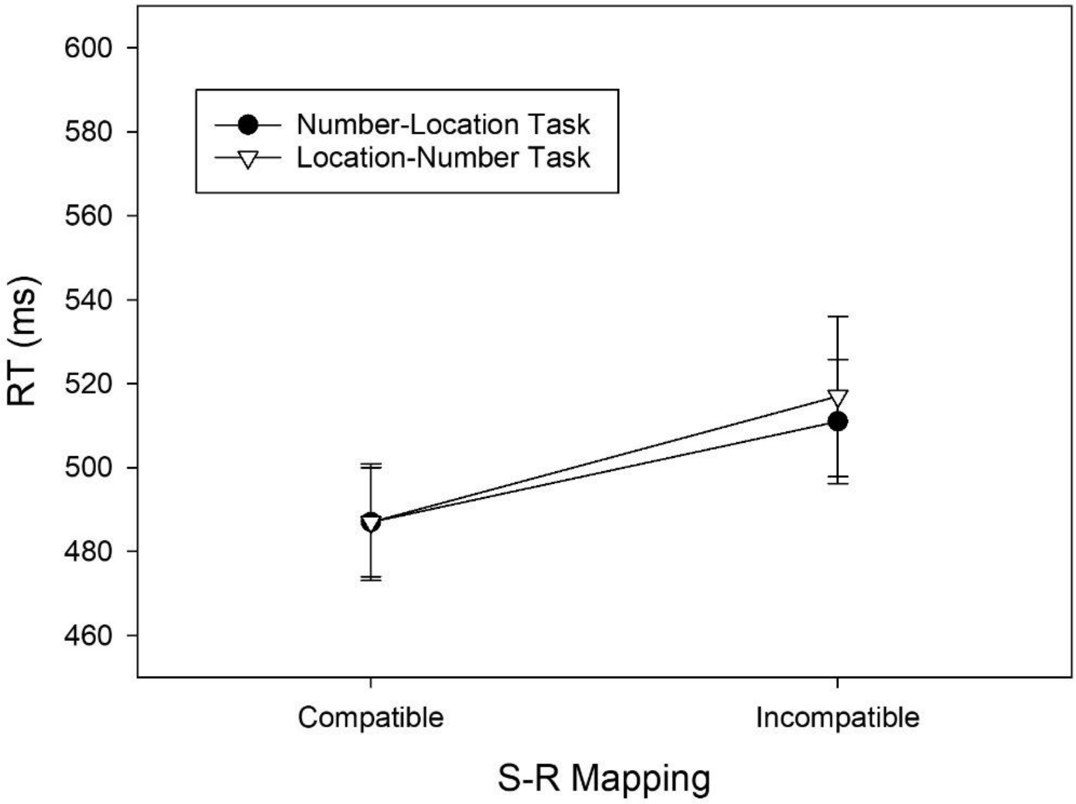

Figure 6. RTs of correct responses as a function of Task and S-R Mapping observed in Exp. 3. Error bars reflect 95% confidence intervals for within-subjects designs (Cousineau, 2017).

Reaction Times (RTs)

We conducted a two-factorial ANOVA with *Task* and *Mapping* as within-subjects factors and RTs from trials with correct responses as a dependent variable. Only the main effect of *Mapping*, *F*(1, 49) = 11.532, *MSE* = 2,807.828, *p* = .001, η^2_p = .191, was significant indicating shorter RTs with the compatible mapping (*M* = 486 ms, *SD* = 62) than with the incompatible mapping (*M* = 512 ms, *SD* = 80). The main effect of *Task*, *F*(1, 49) = 0.651, *MSE* = 1,897.706, *p* = .424, η^2_p = .013, and the two-way interaction, *F*(1, 49) = 0.382, *MSE* = 1,427.844, *p* = .539, η^2_p = .008, were non-significant, indicating similar RT levels and similar mapping effects in the two tasks.

In the number-location task, significantly shorter RTs in the compatible than in the incompatible condition, *t*(49) = 2.673, *p* = .01, *d* = 0.378, BF_{+0} = 3.700, revealed a regular SNARC effect of 22 ms (cf. **Figure 6**) and moderate evidence for H1. In the location-number task, significantly shorter RTs in the compatible than in the incompatible condition, *t*(49) = 2.864, *p* = .006, *d* = 0.405, BF_{+0} = 5.723, revealed a reciprocal SNARC effect of 29 ms and moderate evidence for H1.

Error Percentages

Error percentages were subjected to a two-factorial ANOVA with *Task* and *Mapping* as within-subjects variables. The main effect of *Task*, *F*(1, 49) = 2.781, *MSE* = 3.869, *p* = .102, η^2_p = .054, was non-significant. The main effect of mapping and the two-way interaction were significant. The significant main effect of *Mapping*, *F*(1, 49) = 12.776, *MSE* = 10.094, *p* < .001, η^2_p = .207, reflected more errors with the incompatible mapping (*M* = 4.303, *SD* = 3.245) than with the compatible mapping (*M* = 2.697, *SD* = 2.931). The significant two-way interaction, *F*(1, 49) = 4.501, *MSE* = 2.710, *p* = .039, η^2_p = .084, revealed differences in the mapping effects between the two tasks.

In the number-location task, significantly fewer errors were made in the compatible than in the incompatible condition, *t*(49) = 2.129, *p* = .038, *d* = 0.301, BF_{+0} = 1.214, revealing a regular SNARC effect of 1.112% (cf. **Figure 7**) and anecdotal evidence for H1. In the location-number task, significantly fewer errors were made in the compatible than in the incompatible condition, $t(49) = 4.292$, $p < .001$, $d = 0.607$, $BF_{+0} = 271.313$, indicating a reciprocal SNARC effect of 2.1% (cf. **Figure 7**) and extreme evidence for H1.

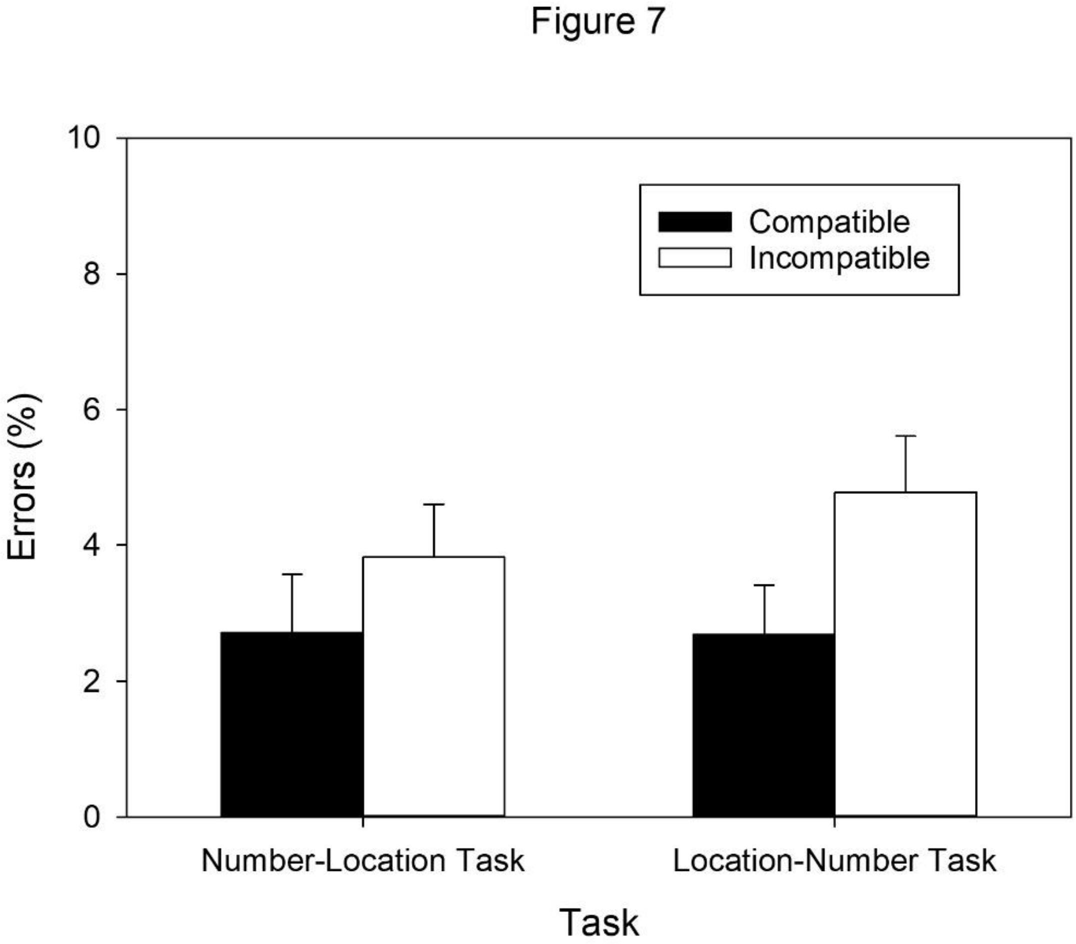

Figure 7. Error percentages as a function of Task and S-R Mapping observed in Exp. 3. Error bars reflect 95% confidence intervals for within-subjects designs (Cousineau, 2017).

Exclusion of outliers

Again, we conducted the same set of analysis after excluding outlier participants. Applying the Tukey (1977) criterion led to the exclusion of four participants and a remaining sample of $N = 46$. In the omnibus analysis of error percentages without outliers, the two-way interaction *Mapping* x *Task*, $F(1, 45) = 3.015$, $MSE = 2.769$, $p = .089$, $\eta^2_p = .063$, became non-significant indicating similar mapping effects in the two tasks.

Discussion

The results of Experiment 3 were quite different from the results of Experiments 1 and 2. We again obtained a regular SNARC effect in the number-location task, but this time we also obtained a reciprocal SNARC effect in the location-number task: Participants' responses were faster and more accurate when they responded to the location word "left" by saying "one" and to the location word "right" by saying "nine" as compared to the reverse assignment. In terms of size, the reciprocal SNARC effect was similar to the regular SNARC effect for RTs and larger than the regular SNARC effect for error percentages. The distributional analyses (see **Appendix**) revealed similar time courses for the regular and reciprocal SNARC effect, which both increased with increasing RTs. Excluding outliers merely affected the differences between the regular and reciprocal SNARC effect, which vanished for error percentages and emerged for the time courses, but did not affect the emergence of a reciprocal SNARC effect itself. Hence, we observed a reciprocal SNARC effect when verbal stimuli and vocal responses were used in the location-number task, which was absent when visuospatial stimuli (i.e., locations) were used in combination with manual responses (Richter & Wühr, 2023) or in combination with vocal responses (Experiments 1 and 2). Alphanumeric stimuli thus seem to foster the occurrence of a reciprocal SNARC effect. The finding that regular and reciprocal SNARC effects were of similar size with alphanumeric stimuli suggests that the spatial-numerical associations, which underlie the SNARC effects in these tasks, are bidirectional and symmetrical in this particular case.

A comparison of mapping effects between experiments (see **Appendix**), moreover, revealed that the regular SNARC effect decreased from Experiment 1 to Experiments 2 and 3, which can be attributed to the employment of the numerical values 1 and 9 in both latter experiments and the employment of numerical 1 and 2 in the former experiment. Contrarily, the reciprocal SNARC effect increased from Experiments 1 and 2 to Experiment 3, which can be attributed to the employment of verbal compared to visuospatial stimuli.

General Discussion

We conducted three experiments that directly compared SNARC effects in a number-location task to reciprocal SNARC effects in a location-number task with vocal responses in both tasks. In all three experiments, we found a regular SNARC effect in the number-location task with alphanumeric stimuli and responses. Participants' responses were faster and more accurate when they responded to a small number by saying "left" and to a large number by saying "right" as compared to the reverse assignment. This pattern emerged regardless of using digits (Exp. 1 and 2) or number words (Exp. 3) as stimuli. Additional distributional analysis revealed that the SNARC effect increased with increasing RTs, resembling the typical time course pattern of SNARC effects (e.g., Gevers et al., 2006; Mapelli et al., 2003).

In contrast, we did not find a reciprocal SNARC effect in the location-number task of Experiments 1 and 2, in which we used visuospatial stimuli (left/right physical locations). Regardless of RT level, response times and error percentages did not differ significantly between the compatible and the incompatible mapping condition. In contrast, we did find a reciprocal SNARC effect in the location-number task of Experiment 3, in which we used verbal stimuli (i.e., location words "left" / "right") and vocal responses. Participants' responses were faster and more accurate when they responded to the location word "left" by saying "one" and to the location word "right" by saying "nine" as compared to the reverse assignment. When using alphanumeric stimuli and responses, regular and reciprocal SNARC effects were of similar size. Thus, location words but not physical locations can influence the selection and execution of vocal number responses to a similar extent as number words can influence the selection and execution of vocal location responses.

Together with the results of a previous study with manual responses (Richter & Wühr, 2023), the following empirical picture emerges. The regular SNARC effect occurred for all different combinations of stimulus and response sets: We observed the regular SNARC effect with numerosity stimuli and manual keypress responses, digit stimuli and manual keypress responses, digit stimuli and vocal responses, and with number word stimuli and vocal responses. These results confirm previous studies that have demonstrated regular SNARC effects of similar size with different stimulus modes (e.g., Nuerk et al., 2005) and different response modes (i.e., manual and vocal; Gevers et al., 2010).

The reciprocal SNARC effect, in contrast, varied considerably with different stimulus and response modes. With visuospatial stimuli and manual number responses (Richter & Wühr, 2023), and visuospatial stimuli and vocal number responses (present Experiments 1 and 2), we observed very weak reciprocal SNARC effects that disappeared when outlier data sets were excluded. Hence, for these combinations of stimulus and response sets, regular SNARC effects were much stronger than reciprocal SNARC effects suggesting asymmetrical S-R associations. Only with verbal stimuli and vocal responses we observed regular and reciprocal SNARC effects of similar size (Experiment 3).

Some studies suggest that the symmetry or asymmetry of spatial-numerical associations might depend on response mode: While spatiomotor responses tend to cause much interference between space and number (Cona et al., 2021; Decarli et al., 2022; Lindemann et al., 2007) thus potentially fostering symmetrical associations, vocal tasks on the contrary might foster asymmetrical associations (Walsh, 2013). Our observation of symmetrical SNARC effects with alphanumeric stimuli and responses but asymmetrical SNARC effects with nonalphanumeric stimuli and responses, however, points towards the opposite hypothesis. To further investigate potential asymmetries between patterns of data using motor vs. vocal responses, we compared the results of Experiment 2 of our previous work (Richter & Wühr, 2023), where we used manual responses, to the results of Experiment 1 of our present work where we used the same stimuli but vocal responses. Importantly, there were no differences in the regular SNARC effect between response modes. Moreover, there were no differences in the reciprocal SNARC effect between response modes. Response mode therefore did not affect regular or reciprocal SNARC effects in our experiments.

The finding of bidirectional and symmetrical associations between number and space in S-R priming tasks employing alphanumeric stimuli and responses is in line with spatial-numerical associations in general for which reciprocity has already been demonstrated. While bidirectional spatial-numerical associations have already been observed as Stimulus-Stimulus (S-S) congruency effects in priming tasks (Kramer et al., 2011; Stoianov et al., 2008) or as Response-Response (R-R) effects in random number generation tasks (Loetscher et al., 2008; Loetscher et al., 2010; Shaki & Fischer, 2014), the current experiments extend those findings by demonstrating that bidirectional spatial-numerical associations may under certain circumstances also emerge as Stimulus-Response (S-R) effects, that is, in the form of reciprocal SNARC effects.

Possible sources for the occurrence of reciprocal SNARC effects

Several methodological aspects might have contributed to the observed variation in the occurrence of the reciprocal SNARC effect in our experiments. First, one might argue that set-level compatibility (e.g., Kornblum et al., 1990) was higher between verbal stimuli and vocal responses than for other combinations of stimulus and response sets, and higher set-level compatibility might have contributed to the occurrence of a reciprocal SNARC effect in

Experiment 3. The findings that overall RTs were longer in Experiment 3 than in Experiment 2, and that the regular SNARC effect was of comparable size in the two experiments, however, provides evidence against an important role of set-level compatibility. Second, using verbal stimuli might have induced verbal-spatial coding, rather than visuospatial coding, and verbal coding of space might foster the occurrence of the reciprocal SNARC effect (cf. Gevers et al., 2010, for discussing the role of verbal-spatial coding for the regular SNARC effect). Third, the overall RT level was much higher with verbal than with visuospatial stimuli. Mean RTs in the location-number task increased from 387 ms in Experiment 2 (429 ms in Exp. 1) to 502 ms in Experiment 3. In line with the finding that reciprocal SNARC effects increase with increasing RTs, the emergence of reciprocal SNARC effects with verbal location stimuli might be mediated by higher RTs. Future research should address which factors are responsible for the emergence of reciprocal SNARC effects.

Nevertheless, small numerical trends of a reciprocal SNARC effect emerged for visuospatial stimuli, which significantly increased with increasing RTs. Even though the exclusion of outlier data eliminated those trends, we thus cannot exclude that reciprocal SNARC effects might occur for visuospatial stimuli under certain circumstances, in particular for participants who show high RTs and/or error percentages. This finding is consistent with the results of our previous study with manual responses (Richter & Wühr, 2023).

Theoretical accounts of the SNARC effect

The theoretical accounts which have been proposed to explain SNARC effects differ in whether they predict bidirectional associations between number and space or not. Moreover, they differ in whether they can explain that stimulus mode affects the emergence of reciprocal but not regular SNARC effects. The results of our experiments are thus only in line with some of those accounts.

MNL

As one of the most prominent accounts of the SNARC effect, the MNL (e.g., Dehaene, 2003; Dehaene et al., 1993; Fischer & Shaki, 2014) assumes that numbers are spatially represented in ascending order from left to right. The MNL proposes a shared representation of number and space and thus the simultaneous activation of spatial and numerical information (e.g., Fischer & Shaki, 2015; Hartmann et al., 2012; Lugli et al., 2013; Shaki & Fischer, 2014; Stoianov et al., 2008). Yet, the MNL account also assumes that this shared representation is located on an intermediate (semantic) level between stimulus processing and response selection (Ginsburg & Gevers, 2015; Huber et al., 2016; Umiltà et al., 2010). The asymmetry we observed in Experiments 1 and 2, and in our previous study (Richter & Wühr, 2023), could have thus occurred either between stimuli and the MNL, or between the MNL and responses. The observation that employing verbal location stimuli instead of visuospatial stimuli in the location-number task leads to symmetrical associations meanwhile suggests that stimulus mode is responsible for the asymmetry formerly observed. Verbal location stimuli thus seem to activate the MNL more strongly than visuospatial stimuli. This, however, seems to be at odds with the fact that the MNL itself constitutes a visuospatial account of spatial-numerical associations (Umiltà et al., 2010). In conclusion, the MNL account is flexible enough to account for symmetrical or asymmetrical patterns of SNARC and reciprocal SNARC effects, although it does not provide a direct answer for the observed impact of stimulus mode on the reciprocal SNARC effect.

Polarity correspondence principle

The polarity correspondence account of the SNARC effect assumes that negative polarities are assigned to “left” and “small”, whereas positive polarities are assigned to “large” and “right” (e.g., Proctor & Cho, 2006). Since polarities are attributes of dimensions, polarity coding of left-right and small-large should occur regardless of whether these dimensions vary on the stimulus or on the response side. Therefore, polarity coding should not only occur in our number-location task, which resembles the typical SNARC task, but also in our location-number task. In other words, according to our interpretation of the polarity correspondence account, it should predict reciprocal and symmetrical compatibility effects in the two tasks.

The predictions of the polarity correspondence account are consistent with the results of Experiment 3, where we observed similar SNARC and reciprocal SNARC effects with verbal (number or location) stimuli and vocal (location or number) responses. In contrast, the polarity correspondence account is not consistent with the results of the present Experiments 1 and 2, where we failed to observe reciprocal SNARC effects with physical location stimuli and vocal number responses. Similarly, the results of our previous experiments (Richter & Wühr, 2023), where we failed to observe a reciprocal SNARC effect with physical location stimuli and manual number responses, are also at odds with polarity correspondence. To account for the absence of reciprocal SNARC effects in these experiments, the polarity correspondence account would have to claim that, in these experiments, polarity coding did not occur for either the physical location stimuli or for the number responses. The fact that (vocal) number responses produced reciprocal SNARC effects in the present Experiment 3 falsifies the latter hypothesis. Hence, the polarity correspondence account must attribute the failure to obtain reciprocal SNARC effects in all the other experiments to the absence of polarity coding for physical location stimuli. This account, however, is implausible because polarity coding of location stimuli has been invoked in previous studies of picture-word verification (e.g., Just & Carpenter, 1975; Olson & Laxar, 1973) and orthogonal S-R correspondence effects (e.g., Cho & Proctor, 2003; Weeks & Proctor, 1990).

WM account

Lastly, the WM account proposes that the association between the serial position of a numerical stimulus stored in WM and the spatial location of the response leads to the (regular) SNARC effect (e.g., van Dijck & Fias, 2011; van Dijck et al., 2015). This account was later extended to, or incorporated into, a theory of coding the serial order of items in verbal WM, called the mental whiteboard hypothesis (e.g., Abrahamse et al., 2014, 2017; De Belder et al., 2015). According to this hypothesis, coding the serial order of items in (verbal) WM is achieved by connecting the items to spatial position markers. Since the spatial coding of serial order is assumed to occur from left to right, it allows to account for the SNARC effect with number stimuli and spatial responses (e.g., Abrahamse et al., 2016). In order to explain the regular SNARC effect in our task, proponents of the WM account would assume that participants (i) spontaneously represent the two number stimuli in an ascending order, which (ii) is achieved by connecting the smaller number (e.g., 1) to a left position marker and the larger number (e.g., 2) to a right position marker. The congruency, or incongruency, between the spatial position markers and the spatial responses then produces the observed SNARC effect (cf. Abrahamse et al., 2014).

Although the mental whiteboard hypothesis assumes bidirectional effects between WM retrieval and spatial processing (e.g., De Belder et al., 2015), it is not clear whether this account would predict (or explain) reciprocal SNARC effects. If we adapt the WM account of regular SNARC effects to our reciprocal SNARC task, we would have to assume that participants (i) spontaneously represent the two location stimuli in a canonical (i.e., left-to-right) order, and (ii) connect the two stimuli to spatial position markers. But how should these position markers then prime the (manual or vocal) number responses that are required in this task? To our knowledge, the WM account does not consider the possibility that responses are also (spontaneously) represented in a canonical (ascending) order, and therefore connected to spatial position markers, which could provide a basis for the reciprocal SNARC effect. Hence, on these assumptions, the WM account does not readily appear to predict reciprocal SNARC effects, and therefore seems to face problems when attempting to explain the reciprocal SNARC effect observed in our Experiment 3.

Conclusion

The results of the present study demonstrate a dissociation between regular SNARC effects (in number-location tasks) and reciprocal SNARC effects (in location-number tasks) with vocal responses. While regular SNARC effects occurred in our experiments with different stimulus sets (digits, number words), reciprocal SNARC effects only occurred with location word stimuli and vocal number responses, but not with physical location stimuli and vocal number responses. These findings suggest that the associations between numerical and spatial information, which are responsible for regular and reciprocal SNARC effects, are completely bidirectional, and create symmetrical S-R compatibility effects, only for particular combinations of stimulus and response sets. For other combinations of stimulus and response sets, the associations are unidirectional (i.e., number → space) and allow for regular SNARC effects only. The present results complement our previous findings of SNARC effects in the absence of reciprocal SNARC effects with manual responses. Together, the findings have implications for existing theoretical accounts of the SNARC effect which need to explain that stimulus mode affects the emergence of reciprocal but not regular SNARC effects.

Additional information

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Availability of data and materials

The datasets for the experiments reported here are available at the Mendeley repository https://doi.org/10.17632/dvpwx4634t.1. All other materials can be obtained from both authors upon request. The experiments' programs (E-Prime 3.0) and the R code can be obtained from both authors upon request.

Declaration of interest

The authors have no competing interests to declare.

Informed consent

Before the experiments, all participants gave written informed consent to participate.

Ethics approval

The local Ethics Committee at TU Dortmund University had approved the experimental protocol for our study (approval no. GEKTUDO_2022_36).

CRediT Author Statement

M. R.: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing

P. W.: Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing - Original Draft, Writing - Review & Editing, Visualization, Project administration

Open Practices

We report how we determined our sample size, all data exclusions (if any), all manipulations, and all measures in the study. The data sets for the experiments reported here are available at the Mendeley repository https://doi.org/10.17632/dvpwx4634t.1. Programs for running the experiments, which were written in E-Prime 3.0, can be obtained from both authors upon request. Data were analyzed using *R* (version 4.2.2), and *Jamovi* (version 2.2.5). *R* code can be obtained from both authors upon request. The design and analysis of Experiments 1 and 3 were not pre-registered. The design and analysis of Experiment 2 were pre-registered at OSF (https://osf.io/7kt4y).

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Appendix

Distributional Analysis for RTs in Experiment 1

For analyzing the time course of the mapping effects, we employed Ratcliff's method of vincentizing (Ratcliff, 1979). For each participant and condition, we rank-ordered RTs and subsequently divided this set of rank-ordered RTs into four quartiles. Means were computed for each quartile and then subjected to a three-factorial ANOVA with *Task* (number-location task, location-number task), *Mapping* (compatible, incompatible) and *Quartile* (1-4) as within-subject variables. **Figure A1** illustrates the corresponding means. In this analysis, the interactions between *Quartile* and the other variables were of specific interest.

The two-way interactions *Quartile* x *Task* and *Quartile* x *Mapping* were both significant. The significant *Quartile* x *Task* interaction, $F(3, 174) = 2.707$, $MSE = 742.524$, $p = .047$, $\eta^2_p = .045$, indicated a slightly larger increase in RTs in the number-location task compared to the location-number task for the latter quartiles. The significant *Quartile* x *Mapping* interaction, $F(3, 174) = 52.244$, $MSE = 494.784$, $p < .001$, $\eta^2_p = .474$, indicated an increasing mapping effect with increasing RTs. Most importantly, however, the three-way interaction, $F(3, 174) = 15.195$, $MSE = 713.305$, $p < .001$, $\eta^2_p = .208$, was also significant, revealing that the mapping effect had different time courses in the two tasks.

To determine the source of the significant three-way interaction, we conducted separate two-factorial ANOVAs with *Mapping* and *Quartile* as within-subject variables for the two tasks. In case of significant interactions, we used Tukey's post-hoc tests due to the non-directional hypothesis in the location-number task and to prevent alpha inflation. In the number-location task, the main effect of *Mapping*, $F(1, 58) = 40.704$, $MSE = 5{,}632.726$, $p < .001$, $\eta^2_p = .412$, was significant. Importantly, the *Mapping* x *Quartile* interaction, $F(3, 174) = 43.547$, $MSE = 805.604$, $p < .001$, $\eta^2_p = .429$, was also significant, reflecting that the regular

SNARC effect increased with increasing RTs. While the mapping effect was 15 ms in the first quartile, it increased to 28 ms in the second quartile, 41 ms in the third quartile and 93 ms in the fourth quartile. Post-hoc tests revealed that the regular SNARC effect was non-significant in the first quartile, $t(58) = 2.918$, $p_{Tukey} = .087$, but significant for all three larger quartiles, all ts ≥ 5.128, all $ps_{Tukey} < .001$. This finding is consistent with the established time course pattern of SNARC effects (e.g., Gevers et al., 2006; Mapelli et al., 2003).

In the location-number task, the main effect of *Mapping*, $F(1, 58) = 2.139$, $MSE = 2{,}012.483$, $p = .149$, $\eta^2_p = .036$, did not reach significance, indicating the absence of a reciprocal SNARC effect. However, the *Mapping* x *Quartile* interaction, $F(3, 174) = 3.991$, $MSE = 402.485$, $p = .009$, $\eta^2_p = .064$, was significant, revealing an increase in the RT difference between the compatible and incompatible condition with increasing RTs. This difference increased from 0 ms in the first quartile to 2 ms in the second quartile, 6 ms in the third quartile and 17 ms in the fourth quartile. Post-hoc tests revealed that the reciprocal SNARC effect was non-significant in all four quartiles, all ts ≤ 2.004, all $ps_{Tukey} \geq .488$[17].

After excluding outliers according to the Tukey (1977) criterion, the interaction effect (*Mapping* x *Quartile*) in the location-number task became non-significant, $F(3, 150) = 1.981$, $MSE = 399.097$, $p = .119$, $\eta^2_p = .038$, revealing that the increase in the reciprocal SNARC effect with increasing RTs vanished when outliers were excluded.

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[17] If t-tests were used for pairwise comparisons, the reciprocal SNARC effect was significant in the fourth quartile only, $t(58) = 2.004$, $p = .050$, $d = 0.261$.

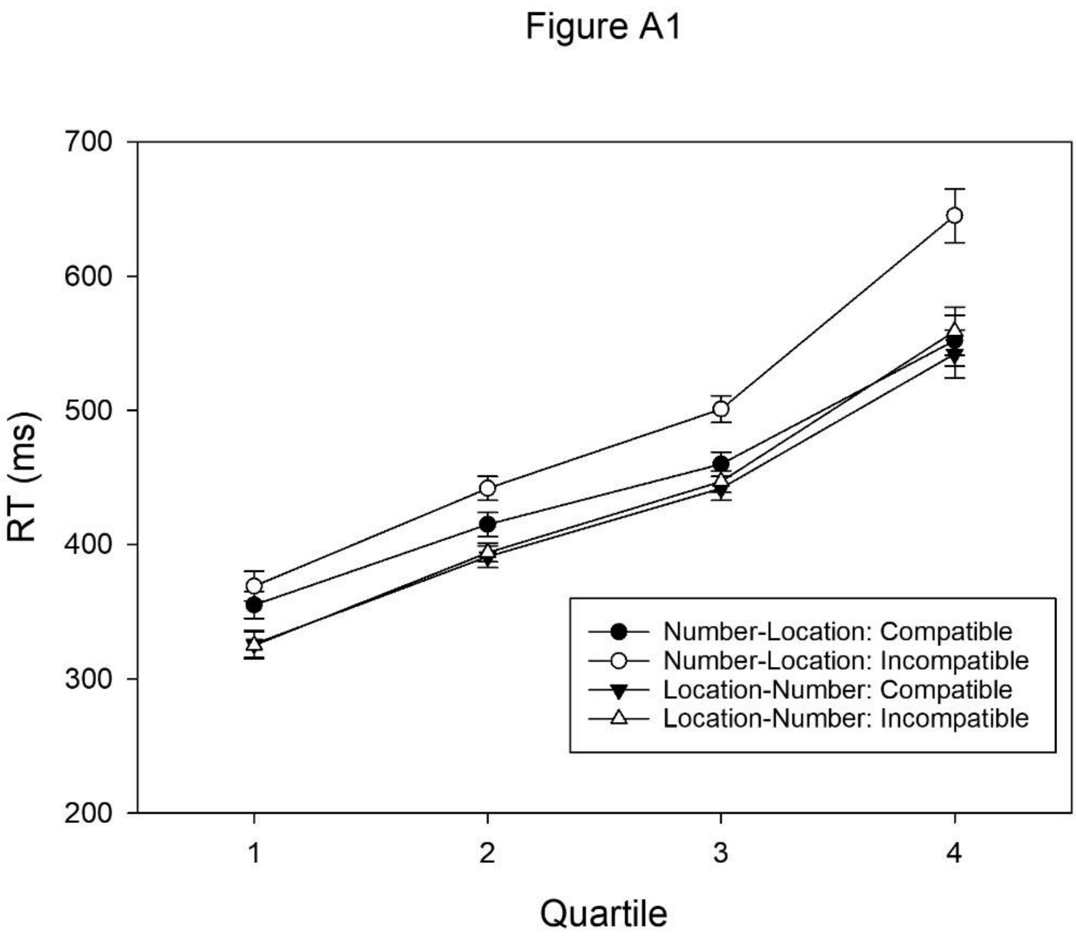

Figure A1. Mean RTs as a function of RT quartile, task, and S-R mapping observed in Experiment 1. Error bars reflect 95% confidence intervals for within-subjects designs (Cousineau, 2017).

Distributional Analysis of RTs in Experiment 2

We conducted a distributional analysis in the form of a three-factorial ANOVA with *Task* (number-location task, location-number task), *Mapping* (compatible, incompatible) and *Quartile* (1-4) as within-subject variables for Experiment 2. The distributional analysis was not pre-registered and must thus be considered an exploratory analysis. **Figure A2** illustrates the corresponding means.

The two-way interactions *Quartile* x *Task* and *Quartile* x *Mapping* were both significant. The *Quartile* x *Task* interaction, $F(3, 171) = 10.908$, $MSE = 811.185$, $p < .001$, $\eta^2_p = .161$, revealed a significantly larger increase in RTs in the number-location task compared to the location-number task for higher quartiles. The significant *Quartile* x *Mapping* interaction, *F*(3, 171) = 9.996, *MSE* = 728.997, $p < .001$, $\eta^2_p = .149$, reflected an increasing mapping effect with increasing RTs. Yet, most importantly, the three-way interaction, *F*(3, 171) = 8.433, *MSE* = 456.066, $p < .001$, $\eta^2_p = .129$, was also significant, indicating different time courses of the mapping effect in the two tasks.

Figure A2

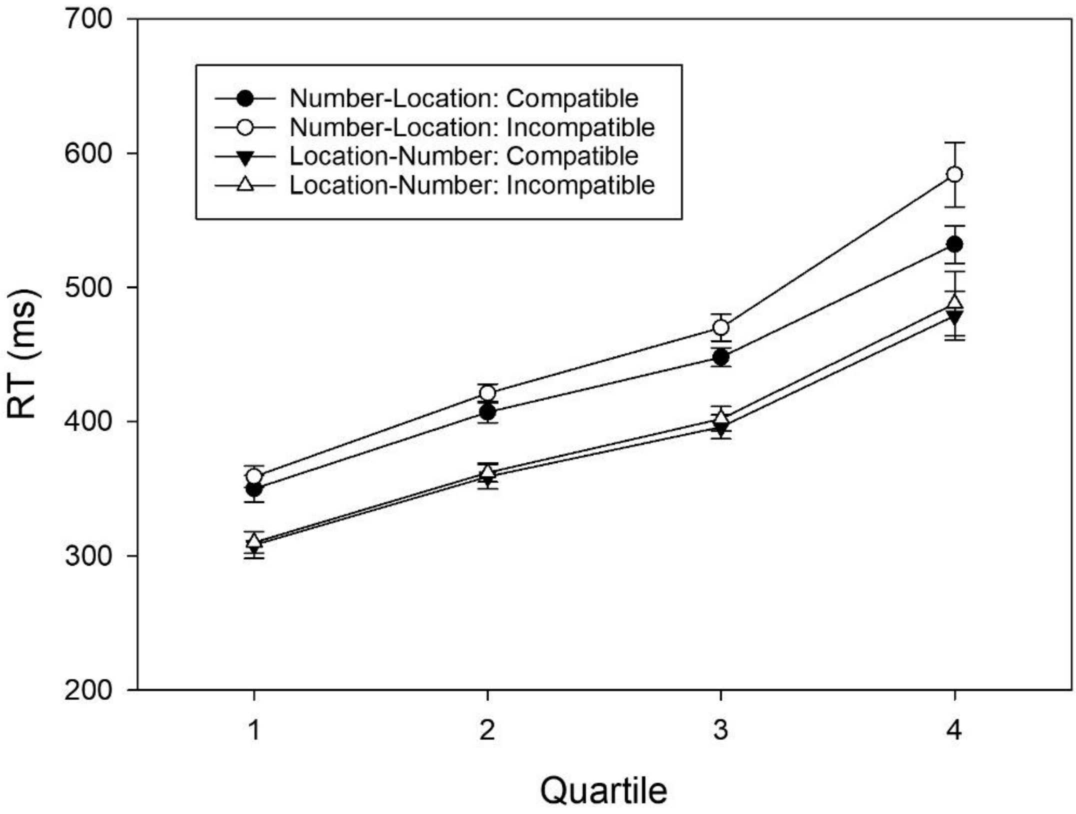

Figure A2. Mean RTs as a function of RT quartile, task, and S-R mapping observed in Experiment 2. Error bars reflect 95% confidence intervals for within-subjects designs (Cousineau, 2017).

To unravel the significant three-way interaction, we conducted two-factorial ANOVAs with *Mapping* and *Quartile* as within-subject factors for each of the two tasks. In the number-location task, the main effect of *Mapping*, $F(1, 57) = 19.729$, $MSE = 3{,}452.889$, $p < .001$, $\eta^2_p = .257$, was significant. Moreover, the *Mapping* x *Quartile* interaction, $F(3, 171) = 19.307$, $MSE = 560.859$, $p < .001$, $\eta^2_p = .253$, was significant, revealing that the regular SNARC effect increased with increasing RTs. Specifically, the mapping effect was 9 ms in the first quartile, 14 ms in the second quartile, 22 ms in the third quartile and 52 ms in the fourth quartile. Post-hoc tests between the compatible and incompatible mapping condition for each quartile revealed that the regular SNARC effect was non-significant in the first quartile, $t(57) = 2.203$, $p_{Tukey} = .366$, but significant in all three larger quartiles, all ts ≥ 3.176, all $ps_{Tukey} \leq .046$. Again, this time course pattern is congruent with the one that has been empirically established for SNARC effects (e.g., Gevers et al., 2006; Mapelli et al., 2003).

In the location-number task, the main effect of *Mapping*, $F(1, 57) = 0.634$, $MSE = 4{,}315.829$, $p = .429$, $\eta^2_p = .011$, was non-significant, reflecting the absence of a reciprocal SNARC effect. Moreover, the *Mapping* x *Quartile* interaction, $F(3, 171) = 0.488$, $MSE = 624.205$, $p = .691$, $\eta^2_p = .008$, was also non-significant, indicating that no small reciprocal SNARC effect emerged at particular RT levels.

After excluding outliers according to the Tukey (1977) criterion, in the location-number task the effect size of the non-significant *Mapping* effect, $F(1, 53) = 0.002$, $MSE = 1435.527$, $p = .963$, $\eta^2_p < .001$, and the effect size of the non-significant interaction effect (*Mapping* x *Quartile*), $F(3, 159) = 0.017$, $MSE = 481.381$, $p = .997$, $\eta^2_p < .001$, further decreased towards zero.

Distributional Analysis of RTs in Experiment 3

We conducted a distributional analysis in the form of a three-factorial ANOVA with *Task* (number-location task, location-number task), *Mapping* (compatible, incompatible) and

Quartile (1-4) as within-subject variables for Experiment 3. **Figure A3** illustrates the corresponding means. The two-way interactions *Quartile* x *Task* and *Quartile* x *Mapping* were both significant. The *Quartile* x *Task* interaction, *F*(3, 147) = 3.874, *MSE* = 957.503, *p* = .011, η^2_p = .073, revealed a significantly larger increase in RTs in the location-number task compared to the number-location task for higher quartiles. The significant *Quartile* x *Mapping* interaction, *F*(3, 147) = 19.687, *MSE* = 1,128.355, *p* < .001, η^2_p = .287, reflected an increasing mapping effect with increasing RTs. The three-way interaction, *F*(3, 147) = 1.499, *MSE* = 663.751, *p* = .217, η^2_p = .030, was non-significant, indicating similar time courses of the mapping effect in the two tasks.

After excluding outliers according to the Tukey (1977) criterion, the three-way interaction, *F*(3, 135) = 3.213, *MSE* = 610.619, *p* = .025, η^2_p = .067, became significant, revealing a greater increase of the mapping effect with increasing RTs for the location-number task than for the number-location task.

Figure A3

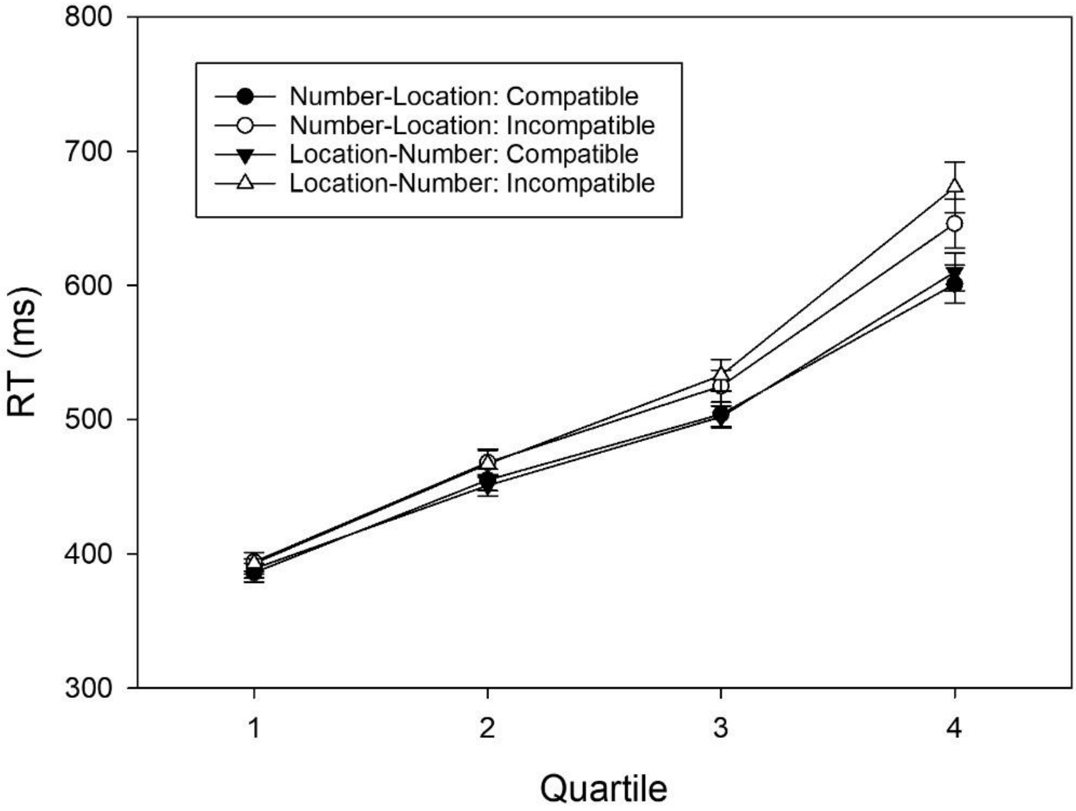

Figure A3. Mean RTs as a function of RT quartile, task, and S-R mapping observed in Experiment 3. Error bars reflect 95% confidence intervals for within-subjects designs (Cousineau, 2017).

Comparison of mapping effects between experiments

We conducted additional analyses to investigate how the changes between experiments affected the regular and the reciprocal SNARC effects, respectively. For each task, we therefore conducted a separate two-factorial ANOVA with *Mapping* (compatible vs. incompatible mapping) as a within-subjects factor, *Experiment* (Exp. 1 vs. Exp. 2 vs. Exp. 3) as a between-subjects factor and RTs from trials with correct responses as a dependent variable. For the number-location task, the main effect of *Experiment* was significant, $F(2, 164) = 8.422$, $MSE = 8{,}467.036$, $p < .001$, $\eta^2_p = .093$, indicating differences in RTs between experiments. Post-hoc test revealed significantly slower responses in Experiment 3 than in Experiment 2, *t*(164) = 4.103, p_{Tukey} < .001. The *Mapping* x *Experiment* interaction was also significant, *F*(2, 164) = 3.206, *MSE* = 1,303.311, *p* = .043, η^2_p = .038, revealing differences in the regular SNARC effect between experiments. To unravel the interaction, we compared the mapping effect within each pair of experiments. The *Mapping* x *Experiment* interaction was significant for Experiments 1 and 2, *F*(1, 115) = 5.185, *MSE* = 1,127.643, *p* = .025, η^2_p = .043, and for Experiments 1 and 3, *F*(1, 107) = 4.208, *MSE* = 1,540.093, *p* = .043, η^2_p = .038, revealing a larger mapping effect in Experiment 1 compared to Experiment 2 and 3, respectively. For Experiments 2 and 3, *F*(1, 106) = 0.038, *MSE* = 1,254.878, *p* = .845, η^2_p = .000, the interaction was not significant, indicating similar mapping effects in Experiment 2 and Experiment 3.

For the location-number task, the main effect of *Experiment* was significant, *F*(2, 164) = 48.306, *MSE* = 7,413.406, *p* < .001, η^2_p = .371, indicating differences in RTs between experiments. Post-hoc test revealed significantly slower responses in Experiment 1 than in Experiment 2, *t*(164) = 3.727, p_{Tukey} < .001, and significantly slower responses in Experiment 3 than in Experiment 1, *t*(164) = 6.217, p_{Tukey} < .001. The *Mapping* x *Experiment* interaction was also significant, *F*(2, 164) = 3.682, *MSE* = 1,294.681, *p* = .027, η^2_p = .043, revealing differences in the reciprocal SNARC effect between experiments. The *Mapping* x *Experiment* interaction was significant for Experiments 1 and 3, *F*(1, 107) = 5.025, *MSE* = 1,418.181, *p* = .027, η^2_p = .045, and for Experiments 2 and 3, *F*(1, 106) = 4.342, *MSE* = 1,736.474, *p* = .040, η^2_p = .039, revealing a larger mapping effect in Experiment 3 compared to Experiment 1 and 2, respectively. For Experiments 1 and 2, *F*(1, 115) = 0.011, *MSE* = 772.554, *p* = .918, η^2_p = .000, the interaction was not significant, indicating similar mapping effects in Experiment 1 and Experiment 2.

4. Article 3 – Richter, M., & Wühr, P. (2023). Associations between physical size and space are strongly asymmetrical. *Scientific Reports*, *13*, 16256.

Associations between physical size and space are strongly asymmetrical

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Abstract

The spatial-size association of response codes (SSARC) effect describes the phenomenon that left responses are faster and more accurate to small stimuli whereas right responses are faster and more accurate to large stimuli, as compared to the opposite mapping. The effect indicates associations between the mental representations of physical size and space. Importantly, the theoretical accounts of SSARC effects make different predictions about the reciprocity and/or symmetry of spatial-size associations. To investigate the reciprocity of SSARC effects, we compared compatibility effects in two verbal[18] choice-response tasks: a size-location (typical SSARC) task and a location-size (reciprocal SSARC) task. In the size-location task, participants responded verbally to a small/large stimulus by saying “left”/“right”. In the location-size task, participants responded verbally to a left-/right-side stimulus by saying “small”/“large”. Participants completed both tasks with a compatible (small-left, large-right; left-small, right-large) and an incompatible (small-right, large-left; left-large, right-small) mapping. A regular SSARC effect emerged in the size-location task. However, no reciprocal SSARC effect emerged in the location-size task if outliers were excluded. If outliers were not excluded, small reciprocal SSARC effects occurred. Associations underlying the SSARC effect are thus strongly asymmetrical: Physical (stimulus) size can prime spatial responses much more strongly than spatial (stimulus) position can prime size-related responses. The finding of asymmetrical associations between size and space is in line with some theoretical accounts of the SSARC effect but at odds with others.

Keywords: SSARC; size; location; reciprocity; symmetry

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[18] Please not that, within this article, responses are referred to as being “verbal” even though they should be referred to as being “vocal” since, in this dissertation, I differentiate between verbal stimuli in the sense of written and vocal responses in the sense of spoken.

Introduction

Stimulus-response compatibility (S-R compatibility) describes the observation that certain assignments between stimulus and response alternatives allow for better performance, i.e., faster responses and higher accuracy, than other assignments [1][2]. The performance difference between such "compatible" and "incompatible" mappings is called *compatibility effect*. Compatibility effects are a widely studied phenomenon in cognitive research because they provide insights into the selection and execution of actions by revealing underlying associations between different stimulus and response dimensions [3][2]. Moreover, those insights can also be of use in applied research, in particular in the field of human factors engineering [4][5].

One example for S-R compatibility is the compatibility effect between physical stimulus size and spatial response position. The so-called *spatial-size association of response codes (SSARC) effect* denotes the observation that left responses are faster and more accurate to physically small stimuli whereas right responses are faster and more accurate to physically large stimuli, as compared to the opposite mapping [6][7][8][9]. While the spatial-quantity association of response codes (SQUARC) effect refers to compatibility effects between any kind of quantity (height, weight, loudness, luminance) on the stimulus level and spatial responses, the SSARC effect refers to a compatibility effect between physical size in particular and spatial responses [10][11].

The SSARC effect thus provides evidence for the existence of associations between the mental representations of physical size and space, so-called *spatial-size associations*. Further studies revealed that the SSARC effect also occurs with physical size as a task-irrelevant stimulus feature providing evidence that size is automatically processed and subsequently associated with spatial position [9][12]. Moreover, Wühr et al. [13] observed that SSARC effects also emerge with different response modalities such as verbal responses. The independence of SSARC effects from response sets implies that the associations between size and space, which underlie the effect, seem to rest upon an intermediate representational level instead of direct relations between stimulus and response codes. Insights from the SSARC effect might also be of use in human factors engineering, which involves, for example, the creation of work environments. Designing manufacturing lines in such a way that small and large items are placed to the left and right of employees, respectively, might for example conform to humans' automatic spatial-size associations and thus reduce cognitive conflict.

The SSARC effect thus illustrates that physical stimulus size influences spatial responses in such a way that physically small stimuli facilitate the selection and execution of left responses whereas physically large stimuli facilitate the selection and execution of right responses. However, it is unclear if this effect can also occur in the opposite direction with spatial position as relevant stimulus feature and physical size as relevant response feature. The present study therefore investigates if the underlying associations between size and space are reciprocal or not by investigating if spatial stimuli can influence the selection and execution of verbal responses referring to physical sizes. Most interestingly, the theories that have been proposed to account for SSARC effects differ in whether they predict uni- or bidirectional SSARC effects and in whether they predict symmetrical or asymmetrical associations between physical size and space.

The *polarity correspondence principle* proposed by Proctor and colleagues assumes that in many binary classification tasks in which stimuli and responses vary on bipolar dimensions, one stimulus and response alternative is encoded as positive polarity whereas the opposite stimulus and response alternative is encoded as negative polarity [14]. Corresponding stimulus and response polarities lead to faster and more accurate responses than non-corresponding polarities [15][14][16]. For example, in a typical SSARC task, the categories “small” and “left” are assigned negative polarity whereas the categories “large” and “right” are assigned positive polarity. According to the polarity correspondence principle, SSARC effects should symmetrically emerge in both the regular and the reciprocal direction because opposing alternatives are encoded as negative or positive polarity regardless of whether they vary as stimulus or response feature.

The *working memory (WM)* account, which has originally been proposed by van Dijck and colleagues to account for compatibility effects between number and space, assumes that the serial order in which stimuli of a given set are stored in WM corresponds with spatial position. Accordingly, early serial positions are associated with left positions in space, while late serial positions are associated with right positions in space [17][18]. The WM account could explain SSARC effects if one assumes that a set of stimuli, which vary in size during an experiment, is (spontaneously) stored in an ascending order in WM. As a result, small stimuli at early serial positions could prime left responses, whereas large stimuli at late serial positions could prime right responses. However, it is debatable if the WM account predicts reciprocal SSARC effects. The WM account might assume that spatial stimuli, which vary in horizontal location, are stored in a canonical order (i.e., from left to right) in WM, but it remains unclear how the spatial links of serial stimulus positions (early-left, late-right) could then prime non-spatial "size" responses. A possible extension of the WM account might assume that not only sets of stimuli varying in size are stored in an ascending order, but sets of responses varying in (or referring to) size are also stored in an ascending order in WM. As a result, left stimuli would prime (“small”) responses at early serial positions, and right stimuli would prime (“large”) responses at late serial positions.

The so-called *correlations in experience (CORE) principle* proposed by Pitt and Casasanto

[19] postulates that “people spatialize abstract domains in their minds according to the ways those domains are spatialized in their experience” (p. 1048). Compatibility effects between two dimensions thus arise because they are correlated in people’s natural or cultural world and transferred to their mental representation accordingly. Wühr et al. [13] observed that handedness and effector strength contribute to the origin of the SSARC effect. In line with the CORE principle, they proposed that the people’s habit to grasp smaller and lighter objects with their weaker non-dominant hand and to grasp larger and heavier objects with their stronger dominant hand determines the associations between physical size and space. Grasping habits consistently involve physical size as stimulus feature and spatial position as response feature and it seems difficult to think of other natural or cultural experiences that might shape spatial-size associations in the reciprocal direction. The account of SSARC effects provided by Wühr et al. [13] should therefore predict unidirectional or at least strongly asymmetrical associations between size and space.

So far, the question of reciprocity has only been addressed with regards to the so-called *spatial-numerical association of response codes (SNARC) effect*. The SNARC effect refers to the finding that left responses are faster and more accurate to small numbers whereas right responses are faster and more accurate to large numbers, as compared to the opposite mapping [20][21][22]. Until now, the question of the origin of spatial-numerical associations has not been finally resolved. While several studies have provided evidence that cultural experiences such as reading direction [23][24][25], finger counting habits [26][27] or visuo-motor activities in general [28] may shape spatial-numerical associations, a spatial representation of numbers has already been found in pre-school children [29][30] and even preverbal infants [31][32] pointing towards a more fundamental origin of spatial-numerical associations. This biological basis of the SNARC effect has also been corroborated by studies revealing that new-born chickens [33], rhesus monkeys [34] and honeybees [35] map numbers onto space.

With human subjects, several studies have demonstrated the bidirectionality of spatial-numerical associations as Stimulus-Stimulus congruency effects in priming tasks [36][37] and as Response-Response effects in random number generation tasks [38][39][40]. Nevertheless, spatial-numerical associations in S-R priming tasks appear to be at least strongly asymmetrical: In a previous study [41], we compared compatibility effects in a number-location task (numerical stimuli, spatial keypress responses), which represents a typical SNARC task, to compatibility effects in a location-number task (spatial stimuli, numerical keypress responses), which represents a reciprocal SNARC task. While we observed regular SNARC effects, we did not observe reciprocal SNARC effects if outlier datasets were excluded. Including outlier datasets led to small reciprocal SNARC effects driven by the small subsample which showed very large reaction times and/or error percentages [41].

Even though previous studies have thus observed that spatial-numerical associations are strongly asymmetrical, several dissociations between the SNARC and the SSARC effect suggest different underlying origins or mechanisms, and thus prevent generalizing findings and conclusions across both effects. First, the generation of response codes is strongly influenced by external spatial coding in the SNARC effect but by anatomical-based coding in the SSARC effect [42]. Second, handedness does not influence SNARC effects, whereas it does affect SSARC effects [13]. Third, Vellan and Leth-Steensen [7] showed that SNARC and SSARC effects do not emerge simultaneously even if conditions for both effects were provided. Different mechanisms underlying the SNARC and SSARC effect thus preclude conclusions about the reciprocity of SSARC effects. To our knowledge, this study is the first to investigate if spatial-size associations are reciprocal or not.

To investigate if the associations between physical size and space, which produce the SSARC effect, are bidirectional or not, we applied a similar design we had employed to examine the reciprocity of the SNARC effect [41]. We therefore compared the compatibility effect in a size-location task, which represents a typical SSARC task, to the compatibility effect in a location-size task, which represents a reciprocal SSARC task. Since responses in the location-size task had to vary in physical size which cannot easily be achieved with manual responses, we employed verbal responses in both tasks. Importantly, Wühr et al. [13] demonstrated that SSARC effects of similar size can be obtained with manual as well as verbal responses. In the size-location task, participants therefore responded to a small or large stimulus by saying “left” or “right”. In the location-size task, participants responded to a left or right stimulus by saying “small” or “large”. Note that participants responded with the German words for “left”, “right”, “small” and “large” in our experiments even though we are using the English words in the text for clarity. Three different patterns of associations between size and space are conceivable. Significant SSARC effects in both directions of similar size would indicate bidirectional and symmetrical associations. Significant SSARC effects in both directions of different size would indicate bidirectional but asymmetrical associations. Significant SSARC effects in the regular but non-significant SSARC effects in the reciprocal direction, however, would point towards unidirectional associations between physical size and space.

Methods

The experiment was preregistered on the website OpenScienceFramework (OSF) (https://osf.io/sz6ub).

Participants

In a previous study [41], we investigated the reciprocity of the SNARC effect and observed a strong main effect of mapping (η^2_p = .20), and a strong two-way interaction between task and mapping (η^2_p = .19). Hence, for the present experiment, we assumed a η^2_p of .20 for the main effect of mapping and for the two-way interaction. We used the software MorePower [43] for conducting a power analysis, which revealed that a sample size of 54 participants would be required to detect an effect of this size with high power (1-beta = .95) at the standard .05 alpha error probability. In order to account for the exclusion of outlier data sets from our analysis, we planned to test a few more than 54 participants.

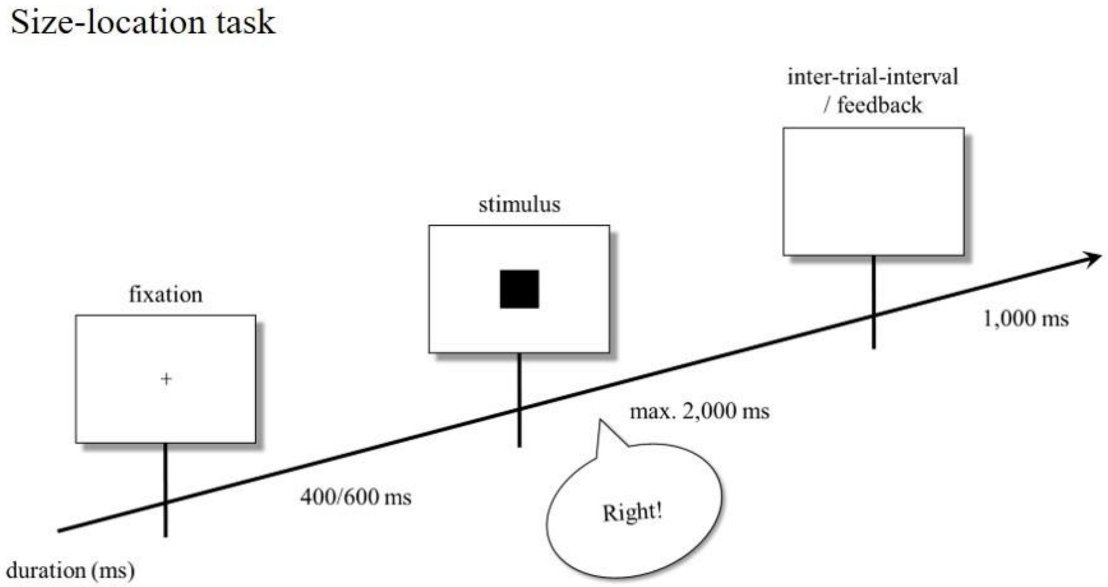
Fifty-nine volunteer students (56 female, 3 male) with a mean age of 21.695 years (*SD* = 3.007) participated in our experiment and received either course credit or a payment of 10 Euro in exchange. All participants reported to have normal (*N* = 36) or corrected-to-normal (*N* = 23) vision. According to self-report, 52 participants were right-handed, whereas the remaining seven participants were left-handed. Prior research has shown that handedness modulates the SSARC effect [13]. We decided to nevertheless include left-handed participants in our sample for two reasons. Firstly, there was only a small number of seven left-handed participants in our sample. Secondly, and more importantly, even though handedness modulates the SSARC effect, it merely weakens but does not reverse the effect. In other words, left-handed participants do show similar but smaller SSARC effects as right-handed participants [13]. Prior to participation, volunteers gave their informed consent. The local Ethics Committee at TU Dortmund University approved the experimental protocol for our study (GEKTUDO_2022_36). We confirm that all methods were performed in accordance with the relevant guidelines and regulations.

Apparatus and Stimuli

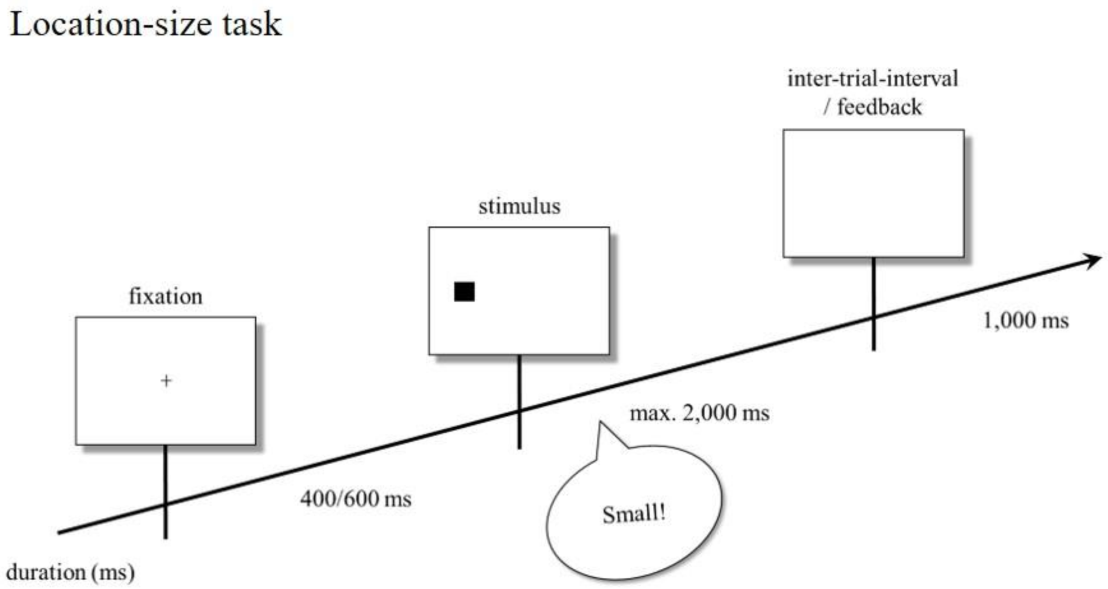
With a viewing distance of approximately 50 cm, participants sat in front of a customary 19-inch color monitor. The software EPrime 3.0 (Psychology Software Tools; Sharpsburg, PA, USA) controlled the presentation of stimuli and registered responses (i.e., verbal response, reaction time (RT)). A small plus sign (Courier font, size 18 pt), which was presented at the screen center at the beginning of each trial, served as a fixation point. All imperative stimuli were presented in black on a white background. In the size-location task, the imperative stimulus was one small (side length = 2 cm) or one large (side length = 4 cm) filled square presented at screen center (position: X = center, Y = center). Participants responded verbally by saying “left” or “right” into a microphone which was placed in front of them and centrally aligned to their midline. To register RTs and record the participants’ verbal responses, the microphone was connected to the voice-key of the Chronos console (Psychology Software Tools; Sharpsburg, PA, USA). Each vocal response was stored in a sound file for a later check of its accuracy. In the location-size task, the imperative stimulus was a black square with a side length of 2 cm that appeared at the center of the left (position: X = 25%, Y = center) or the right screen half (position: X = 75%, Y = center). Participants responded verbally by saying “small” or “large”.

Procedure

The orthogonal combination of two tasks (size-location task, location-size task) and two S-R mappings (compatible, incompatible) resulted in four conditions which were completed by each participant. In the regular size-location task, participants verbally responded to stimulus size (small or large) by saying “left” or “right” according to a compatible mapping (small-left, large-right) or an incompatible mapping (small-right, large-left). In the location-size task, participants verbally responded to stimulus location (left or right) by saying “small” or "large" according to a compatible mapping (left-small, right-large) or an incompatible mapping (left-large, right-small). The time course and sample stimuli of the size-location task and the location-size task are depicted in **Figure 1**.



Size-location task



Location-size task

Figure 1. Time course of events in typical trials of the size-location task (upper panel), and the location-size task (lower panel) according to compatible mappings. Feedback was only provided after a missing response.

Instructions presented at the beginning of each condition informed participants about the content and the procedure of the following task. Each condition consisted of one training block containing 10 trials and two experimental blocks containing 40 trials each. We randomized trials within blocks. Each trial started with the presentation of a fixation point for 400 or 600 ms, with both durations occurring equally often within each block. Subsequently, the imperative stimulus was presented until a response was recorded or for a maximum of 2,000 ms. An inter-trial interval with an empty screen was presented for 1,000 ms after a response was given whereas a corresponding error message was presented during the inter-trial interval after a missing response. Participants were not provided feedback about response accuracy because the program could not determine the correctness of verbal responses. At the beginning of each experimental block, task and S-R mapping instructions were repeated. Participants were able to take a break between blocks or to continue with the subsequent one.

The experiment took about 30-40 min. The experimenter left the laboratory before participants started the experimental blocks. The order of tasks (size-location or location-size first) and the order of mappings (compatible or incompatible mapping first) were counterbalanced between participants. Participants completed both S-R mapping conditions consecutively within one task and the order of mappings was held constant between tasks within one participant.

Design and Data Analysis

For each participant, the verbal responses recorded in each trial were checked for accuracy, and response errors were manually entered into the data file before the statistical analysis. The experimental design was a two-factorial (*Task* x *Mapping*) within-subjects design. The factor *Task* had two levels: the size-location task with size (small vs. large) as the critical stimulus feature and location (left vs. right) as the critical response feature and the location-size task with location (left vs. right) as the critical stimulus feature and size (small vs. large) as the critical response feature. The factor *S-R Mapping* also had two levels: a compatible mapping (small-left, large-right in the size-location task; left-small, right-large in the location-size task) and an incompatible mapping (small-right, large-left in the size-location task; left-large, right-small in the location-size task). Reaction Times (RTs) of correct verbal responses and error percentages served as dependent variables.

With a two-way ANOVA, we planned to investigate the impact of the two independent variables (i.e., Task, Mapping) on the dependent variables (i.e., RTs, error percentages). In case of a significant two-way interaction, we planned to conduct *t* tests to determine the source of the interaction. Even though error percentages are typically not normally distributed, we preferred using *t* tests instead of non-parametric tests because error results often contain a large number of ties, which provide evidence for H0, but are excluded from non-parametric tests and thus bias the results. Since the assumption of unidirectional associations between size and space predicts a null effect in the location-size task, we needed to evaluate the evidence for H1 and H0 likewise and thus reported the Bayes Factor (BF) for each pairwise comparison [44]. We used the evidence categories provided by Jeffreys, 1961 (as cited in Lee & Wagenmakers [45]) to interpret the BF values.

Moreover, we conducted a distributional analysis investigating the time course of the SSARC effect in both the regular and the reciprocal direction. This was motivated by two objectives: Firstly, previous studies have shown that response speed (i.e., RT) determines the size of compatibility or congruency effects [46]. For example, it has been shown that both SNARC effects [47] and SSARC effects with manual responses [48] increase in size with increasing RTs. We therefore investigated the distribution of SSARC effects to, firstly, specify the time course of SSARC effects with verbal responses. Secondly, we aimed to detect small mapping effects which might have emerged in the reciprocal direction for specific RT levels only without reaching significance in the omnibus analysis. We applied Ratcliff's method of vincentizing [49] to analyze the time course of the mapping effects. For each participant and condition, we divided the rank-ordered RTs into four quartiles and computed the corresponding means, which we then subjected to a three-factorial ANOVA with Task (size-location task, location-size task), Mapping (compatible, incompatible) and Quartile (1-4) as within-subject variables.

Results

Data trimming

We excluded three participants (participant numbers 4, 8 and 22 in the dataset) from data analysis because their mean error percentage exceeded 20 % in one of the two tasks. Excluding these datasets reduced the highest error percentages to 11.5% in the size-location task, and 3.2% in the location-size task. Our remaining sample thus included 56 participants. In less than 1% of trials in both the size-location (*M* = 0.096%, *SD* = 0.399) and location-size task (*M* = 0.198%, *SD* = 0.768), participants' responses were too fast (i.e., RT < 100 ms). Likewise, in less than 1% of trials in both the size-location (*M* = 0.344%, *SD* = 0.930) and location-size task (*M* = 0.116%, *SD* = 0.410) participants' responses were too slow (i.e., RT > 1,500 ms). We excluded these trials with RTs below 100 ms or above 1,500 ms as well as the first trial in each block from data analysis.

Reaction Times (RTs)

In a preliminary (not preregistered) analysis, we tested for possible effects of *Task Order* on the effects of *Task* (size-location task vs. location-size task) and *Mapping* (compatible vs.

incompatible) on RTs. Note that the degrees of freedom for this analysis were different from analyses without the order variable, because the number of excluded cases was different for the two order conditions. A three-factorial Analysis of Variance (ANOVA) neither revealed a main effect of *Task Order*, *F*(1, 54) = 1.440, *MSE* = 19,944, *p* = .235, η^2_p = .026, nor any interactions between *Task Order* and the other factors, all *F*(1, 54) < 1.0, all *p* > .450, all η^2_p < .01.

A two-factorial ANOVA, with *Task* and *Mapping* as within-subject factors, revealed two significant main effects and a significant two-way interaction. The significant main effect of *Task*, *F*(1, 55) = 128.230, *MSE* = 1545.239, *p* < .001, η^2_p = .700, reflected shorter RTs in the location-size task (*M* = 410 ms, *SD* = 76) than in the size-location task (*M* = 469 ms, *SD* = 77). The significant main effect of *Mapping*, *F*(1, 55) = 15.207, *MSE* = 893.662, *p* < .001, η^2_p = .217, indicated shorter RTs with the compatible mapping (*M* = 432 ms, *SD* = 80) than with the incompatible mapping (*M* = 447 ms, *SD* = 84). Crucially, however, the significant two-way interaction, *F*(1, 55) = 10.192, *MSE* = 803.552, *p* = .002, η^2_p = .156, revealed different mapping effects in the two tasks.

We conducted pairwise comparisons between compatible and incompatible mappings for each task to determine the source of the two-way interaction. In the size-location task, RTs were significantly shorter in the compatible than in the incompatible condition, *t*(55) = 4.421, *p* < .001, *d* = 0.591, BF_{+0} = 447.399, revealing a regular SSARC effect of 28 ms (cf. **Figure 2**) and extreme evidence for the presence of a mapping effect. In contrast, in the location-size task, RTs did not differ significantly between the two mapping conditions, *t*(55) = 0.753, *p* = .455, *d* = .101, BF_{+0} = 0.191, (cf. **Figure 2**) reflecting moderate evidence against the presence of a reciprocal SSARC effect.

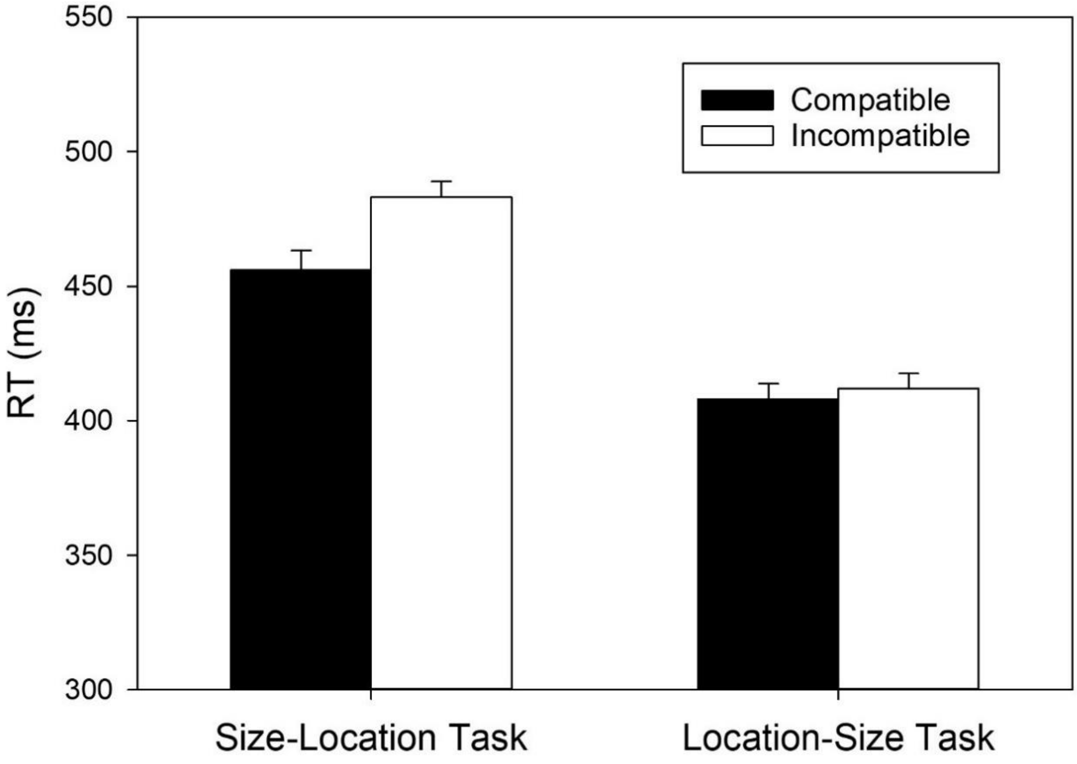


Figure 2. RTs of correct responses as a function of Task and S-R Mapping (*N* = 56). Error bars reflect 95% confidence intervals for within-subjects designs [50].

Error Percentages

Overall error percentages were very low thus limiting the interpretability of the statistical analysis. Even though we report the results for the sake of completeness, the results should therefore be interpreted with caution. A potential speed-accuracy trade-off, however, can be ruled out as error percentages were the highest in the task in which RTs were the slowest.

In a preliminary (not preregistered) analysis, we tested for possible effects of *Task Order* on the effects of *Task* and *Mapping* on error percentages. A three-factorial ANOVA showed a significant effect of *Task Order*, $F(1, 54) = 9.430$, $MSE = 6.790$, $p = .003$, $\eta^2_p = .149$, but no significant interaction between *Task Order* and the other factors, all $F(1, 54) < 3.50$, all $p >$

.050, all $\eta^2_p < .070$. The main effect of task order reflected more errors (across both tasks) when the location-size task was done first ($M = 1.835$, $SD = 3.133$) than when the size-location task was done first ($M = 0,763$, $SD = 1.490$).

A two-factorial ANOVA, with *Task* and *Mapping* as within-subjects factors, also revealed two significant main effects and a significant two-way interaction. The significant main effect of *Task*, $F(1, 55) = 19.255$, $MSE = 4.894$, $p < .001$, $\eta^2_p = .259$, reflected more errors in the size-location task ($M = 1.909$, $SD = 3.173$) than in the location-size task ($M = 0.612$, $SD = 1.072$). The significant main effect of *Mapping*, $F(1, 55) = 8.642$, $MSE = 5.644$, $p = .005$, $\eta^2_p = .136$, indicated less errors with the compatible mapping ($M = 0.794$, $SD = 1.471$) than with the incompatible mapping ($M = 1.727$, $SD = 3.076$). Crucially, however, the significant two-way interaction, $F(1, 55) = 4.286$, $MSE = 3.140$, $p = .043$, $\eta^2_p = .072$, again revealed different mapping effects in the two tasks.

In the size-location task, errors were significantly less frequent in compatible than in incompatible conditions, $t(55) = 2.692$, $p = .009$, $d = 0.360$, $BF_{+0} = 3.797$, revealing a regular SSARC effect of 1.424% (cf. **Figure 3**) and moderate evidence for the presence of a mapping effect. Similarly, in the location-size task, errors were also significantly less frequent in compatible than in incompatible conditions, $t(55) = 2.401$, $p = .020$, $d = 0.321$, $BF_{+0} = 2.014$, revealing a reciprocal SSARC effect of 0.443% (cf. **Figure 3**) and anecdotal evidence for the presence of a mapping effect.

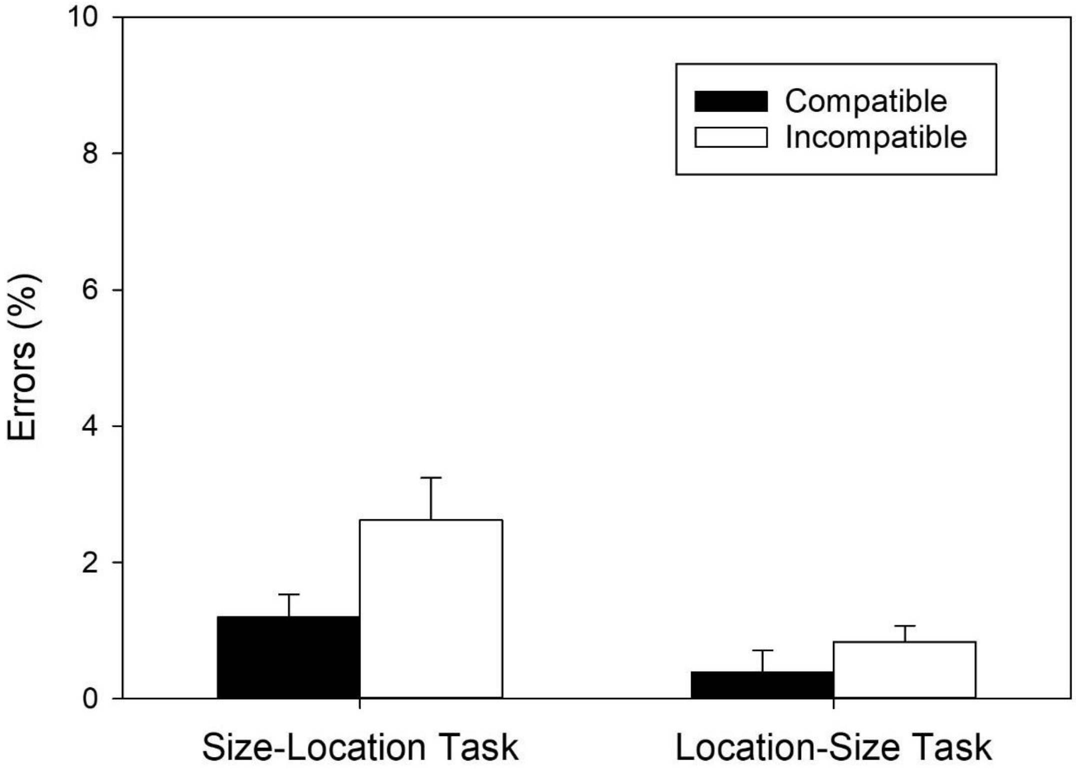


Figure 3. Error percentages as a function of Task and S-R Mapping (*N* = 56). Error bars reflect 95% confidence intervals for within-subjects designs [50].

Distributional analysis for RTs

We conducted a three-factorial ANOVA with *Task* (size-location task, location-size task), *Mapping* (compatible, incompatible) and *Quartile* (1-4) as within-subject variables and RT means as the dependent variable. **Figure 4** illustrates the corresponding means. Note that we will only report results of interest, which are the interactions between *Quartile* and the other variables.

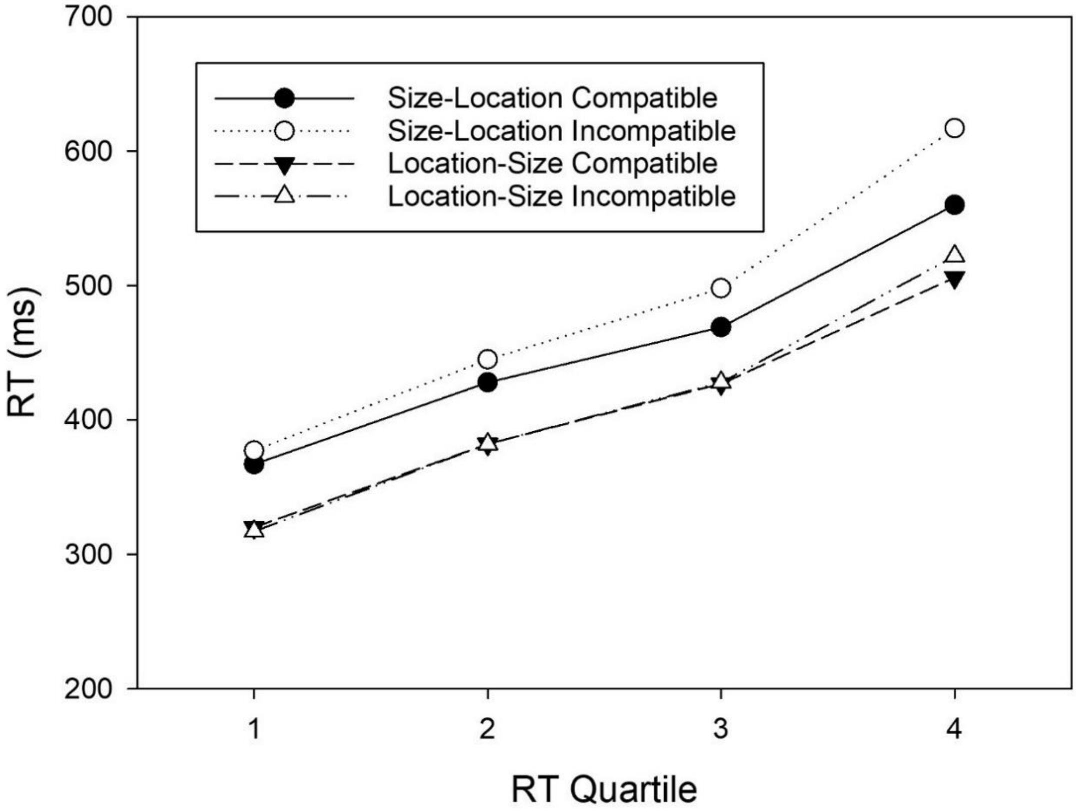


Figure 4. RTs of correct responses as a function of Task, S-R Mapping, and RT Quartile (*N* = 56).

Both two-way interactions *Quartile* x *Task* and *Quartile* x *Mapping*, and the three-way interaction were significant. The significant *Task* × *Quartile* interaction, *F*(3, 165) = 11.179, *MSE* = 477.614, *p* < .001, η^2_p = .169, revealed that, with increasing RTs, mean RTs in the size-location task became increasingly slower compared to the location-size task. The range of RTs was thus smaller in the latter compared to the former task. The significant *Mapping* × *Quartile* interaction, *F*(3, 165) = 22.577, *MSE* = 524.907, *p* < .001, η^2_p = .291, indicated that mapping effects increased with increasing RTs. Crucially, however, the significant three-way interaction, *F*(3, 165) = 5.839, *MSE* = 382.568, *p* < .001, η^2_p = .096, revealed that the time course of the mapping effects differed between both tasks.

To determine the source of the significant three-way interaction, we conducted a 2 x 4 ANOVA, with *Mapping* and *Quartile* as within-subject variables, for each task separately. In the size-location task, the main effect of *Mapping*, *F*(1, 55) = 19.790, *MSE* = 4,413.287, $p < .001$, $\eta^2_p = .265$, as well as the *Mapping* x *Quartile* interaction, *F*(3, 165) = 20.969, *MSE* = 576.469, $p < .001$, $\eta^2_p = .276$, were significant. The two-way interaction indicated that the mapping effect increased with increasing RT level. More specifically, the mapping effect increased from 9 ms in the first quartile, to 17 ms in the second quartile, 28 ms in the third quartile, and 57 ms in the fourth quartile. Post-hoc tests between the compatible and incompatible mapping condition for each quartile indicated that the regular SSARC effect was non-significant in the first quartile, *t*(55) = 1.927, $p_{Tukey} = .539$, but significant in all three larger quartiles, all *t*s ≥ 3.466, all $ps_{Tukey} \leq .022$.

In the location-size task, the main effect of *Mapping*, *F*(1, 55) = 0.546, *MSE* = 2,446.171, $p = .463$, $\eta^2_p = .010$, was non-significant, reflecting the absence of a reciprocal SSARC effect. The *Mapping* x *Quartile* interaction, however, *F*(3, 165) = 6.032, *MSE* = 331.005, $p < .001$, $\eta^2_p = .099$, reached significance revealing that the RT difference between the compatible and incompatible condition increased with increasing RT level. More specifically, the mapping effect increased from -3 ms in the first quartile, to 0 ms in the second quartile, 1 ms in the third quartile, and 16 ms in the fourth quartile. However, post-hoc tests revealed that the reciprocal SSARC effect was non-significant in all four quartiles, all *t*s ≤ 1.922, all $ps_{Tukey} \geq .543$.

Exclusion of outliers

Significant reciprocal SSARC effects emerged in the analysis of error percentages. However, a previous study on the reciprocity of SNARC effects has shown that overall outlier datasets might be driving these reciprocal mapping effects [41]. We therefore decided to exclude outlier participants according to the Tukey criterion [51] and conduct the same set of analysis once again. According to Tukey [51], observations below $Q_{25} - 1{,}5 * IQR$ or above $Q_{75} + 1{,}5 * IQR$ are classified as outliers. After collapsing data across the mapping variable, we applied the criterion to the remaining four variables (mean RT and error percentage in the size-location and location-size task respectively), according to which we excluded seven further participants (participant numbers 16, 31, 35, 48, 55, 57 and 59). The remaining sample thus consisted of 49 participants. In the analysis of error percentages without outliers, the formerly significant pairwise comparison between the compatible and incompatible condition in the location-size task became non-significant, $t(48) = 1.453$, $p = .153$, $d = 0.208$, BF+0 = 0.415, indicating that error percentages did not differ significantly between the two mapping conditions and providing anecdotal evidence against the presence of a reciprocal SSARC effect when outlier datasets were excluded. Excluding outlier datasets, however, did not affect the pattern of results in the distributional analysis. In the location-size task, the *Mapping* x *Quartile* interaction, $F(3, 144) = 6.763$, $MSE = 305.274$, $p < .001$, $\eta^2_p = .123$, remained significant revealing that the reciprocal mapping effect increased with increasing RT level. More specifically, the mapping effect increased from -4 ms in the first quartile, to 0 ms in the second quartile, 1 ms in the third quartile, and 16 ms in the fourth quartile. However, post-hoc tests revealed that the reciprocal SSARC effect remained non-significant in all four quartiles, all ts ≤ 1.844, all $p\text{s}_{\text{Tukey}} \geq .594$, when outlier datasets were excluded.

Discussion

In the present experiment, we investigated if associations between space and physical size, which give rise to the SSARC effect, are reciprocal or not by comparing compatibility effects in a typical size-location task to compatibility effects in a reciprocal location-size task. As expected, we found a regular SSARC effect in the size-location task indicating faster and more accurate left responses to small stimuli and faster and more accurate right responses to large stimuli as compared to the opposite mapping. Interestingly, the regular SSARC effect increased in size with increasing RTs suggesting that the effects of spatial-size associations gradually evolve in the course of response selection and execution. Hence, the SSARC effect with verbal responses shows a similar time course as the SSARC effect with manual responses [48], and the SNARC effect [52][47].

In the location-size task, we did not find a significant reciprocal SSARC effect for RTs: RTs did not differ between the compatible (left S – "small"; right S – "large") and the incompatible mapping condition (left S – "large"; right S – "small"). We did, however, observe a significant reciprocal SSARC effect for error percentages with more accurate responses in the compatible compared to the incompatible mapping condition. Yet, this reciprocal SSARC effect vanished when outlier participants were excluded implying that only a small subsample of participants with very large RTs and/or error percentages showed a reciprocal SSARC effect in error percentages. The distributional analysis of reciprocal SSARC effects revealed a significant interaction between the mapping effect and the quartile in the location-size task which indicated increasing numerical SSARC effects with increasing response time. Even though post-hoc tests demonstrated that no significant reciprocal SSARC effect occurred throughout the entire RT range, the time course pattern of reciprocal SSARC effects thus seems to be similar to the one of regular SSARC effects with the effects of potential associations gradually evolving in the course of response selection and execution.

Implications for theoretical accounts of SSARC effects

Taken together, we observed that associations between physical size and space are strongly asymmetrical in such a way that the physical size of stimuli influences the selection and execution of spatial responses but that spatial positions of stimuli do not to the same extent influence the selection and execution of responses that vary in physical size. This finding has several implications for the theoretical accounts of the SSARC effect. The polarity correspondence principle, for example, proposes that SSARC effects emerge because the categories “small” and “left” are assigned negative polarity whereas the categories “large” and “right” are assigned positive polarity and corresponding polarities facilitate performance [15][14][16]. Importantly, in our view, the polarity correspondence principle should predict reciprocal and symmetrical SSARC effects because categories are assigned polarities regardless of whether those categories vary on a stimulus or response level. More precisely, “small” and “left”/ “large” and “right” should be encoded as negative/positive polarity both as a stimulus or response feature. Our observation of strongly asymmetrical SSARC effects therefore cannot be explained by the polarity correspondence principle.

According to the WM account, SSARC effects occur because of short-term associations between the serial order in which stimuli of variable size are stored in WM and corresponding spatial positions [17][18]. Assuming that location stimuli are represented in WM in a canonical (i.e., left-to-right) order in the location-size task would not suffice to produce a reciprocal SSARC effect because there is no overlap between serial (or physical) stimulus positions and non-spatial "size" responses. Assuming that not only stimuli of variable size are stored in an ascending order in WM, but responses varying in or referring to different sizes are also stored in an ascending order in WM would render reciprocal SSARC effects possible. The fact that reciprocal SSARC effects were much weaker than the regular SSARC effect in our experiment, hence suggests that participants do not, or rarely, represent responses varying in size in an ascending order in WM.

According to the CORE principle, SSARC effects occur because participants have experienced a systematic relationship between physical stimulus size and response position in their everyday life [19]. Wühr et al. [13] proposed that the habit to grasp smaller/lighter objects with the weaker non-dominant hand and to grasp larger/heavier objects with the stronger dominant hand is responsible for the spatialization of physical size. Since grasping habits consistently involve physical size as stimulus feature and spatial position as response feature, the account of SSARC effects provided by Wühr et al. [13] predicts unidirectional or at least strongly asymmetrical associations between size and space. This prediction is compatible with our observation of strongly asymmetrical SSARC effects.

Comparing reciprocity in SSARC and SNARC effects

This study is the first to investigate if spatial-size associations are reciprocal or not by directly comparing SSARC effects in a size-location and a location-size task. In a previous study [41], we had used a similar experimental design to investigate the reciprocity of SNARC effects. Most interestingly, the pattern we found in this study for SSARC effects is quite similar to the one we observed for SNARC effects. Spatial-numerical associations in S-R priming tasks also seem to be strongly asymmetrical: While we observed regular SNARC effects with numerical stimuli, we did not observe reciprocal SNARC effects with spatial stimuli, if outlier datasets were excluded. Similar to SSARC effects, including outlier datasets led to small reciprocal SNARC effects driven by a small subsample with very large RTs and/or error percentages [41]. Even though several differences between SSARC and SNARC effects have so far been documented [42][13][7], the pattern of strongly asymmetrical compatibility effects seems to be a shared characteristic between the SSARC and the SNARC effect. Moreover, in both effects, a small subsample with very large RTs and/or error percentages can produce small reciprocal effects.

Limitations and avenues for future research

In the present study, we found trends of small reciprocal SSARC effects, however, the circumstances under which they occur are not yet clear. The results of our experiment suggest that two factors might contribute to the occurrence of reciprocal SSARC effects: RT duration and participants' features. The distributional analysis revealed that reciprocal SSARC effects increased with increasing RTs but did not reach significance in our experiment. This raises the question if prolonged RTs could induce significant reciprocal SSARC effects. Manipulating task demands in such a way that RTs increase might thus form an approach for future research. Moreover, a small subsample of outlier participants with very large RTs and/or error percentages showed reciprocal SSARC effects in error percentages. This raises the question which inter-individual differences are responsible for the occurrence of reciprocal SSARC effects, which so far also remains an issue of future research.

One limitation of our study is that our sample was not balanced in terms of gender. While there is some evidence for an effect of gender on the spatial representation of numbers, which seems to be stronger for male than for female participants [53], it is unclear if gender affects the SSARC or reversed SSARC effect in a similar manner. However, even if male participants showed a stronger SSARC effect and potentially also a stronger reversed SSARC effect, it seems unlikely that the asymmetry of spatial-size associations vanishes for male participants. Nevertheless, effects of gender on spatial-size representations should be addressed by future research. Furthermore, we can so far primarily conclude the existence of strongly asymmetrical associations between physical size and space for right-handers since our sample consisted of mostly right-handed participants. For left-handers, the asymmetry of spatial-size associations remains to be tested.

Conclusion

The present experiment demonstrates that the associations between physical size and space which underlie the SSARC effect are strongly asymmetrical: Physical (stimulus) size can prime spatial responses much more strongly than spatial (stimulus) position can prime size-related responses. This finding has implications for several theoretical accounts: while the polarity correspondence principle cannot explain asymmetrical associations between size and space, the finding of asymmetrical spatial-size associations is in line with an application of the CORE principle by Wühr et al. [13].

Additional information

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Availability of data and materials

The dataset has been published on the “Mendeley Data” repository (https://doi.org/10.17632/b57tbsprzb.1). The audio-files containing participants’ vocal responses can be obtained by contacting the corresponding author (melanie2.richter@tu-dortmund.de). Materials and codes used in this study can also be obtained by contacting the corresponding author (melanie2.richter@tu-dortmund.de).

Declaration of interest

The authors have no competing interests to declare.

Informed consent

Before the experiment, all participants gave written informed consent to participate.

Ethics approval

The local Ethics Committee at TU Dortmund University had approved the experimental protocol for our study (approval no. GEKTUDO_2022_36). We confirm that all methods were performed in accordance with the relevant guidelines and regulations.

CRediT Author Statement

M. R.: Conceptualization, Methodology, Software, Validation, Formal analysis, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization

P. W.: Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing - Original Draft, Writing - Review & Editing, Visualization, Project administration

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5. Article 4 – Richter, M., & Wühr, P. (2024). Verbal stimuli allow for symmetrical S-R priming effects between size and space. *PsyArXiv Preprints*.

Verbal stimuli allow for symmetrical S-R priming effects between size and space

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Abstract

The spatial-size association of response codes (SSARC) effect refers to the observation that left responses are faster and more accurate to small stimuli whereas right responses are faster and more accurate to large stimuli, as compared to the reverse assignment. The underlying spatial-size associations are strongly asymmetrical with physical size/location stimuli and vocal location/size responses and allow for regular but not reciprocal SSARC effects. Recent evidence, however, points towards an important role of stimulus mode in the emergence of reciprocal compatibility effects. We investigated the reciprocity of the SSARC effect with a different stimulus mode, namely with verbal size/location stimuli and vocal responses. In a size-location task, participants vocally responded to the words “small” or “large” by saying “left” or “right” according to a compatible (“small”-“left”/“large”-“right”) or an incompatible mapping (“small”-“right”/“large”-“left”). In a location-size task, participants vocally responded to the words “left” or “right” by saying “small” or “large” according to a compatible (“left”-“small”/“right”-“large”) or an incompatible (“left”-“large”/“right”-“small”) mapping. We observed a regular and a reciprocal SSARC effect of similar size indicating symmetrical spatial-size associations. While regular SSARC effects thus emerge with verbal and physical size stimuli, reciprocal SSARC effects only emerge with verbal but not with physical location stimuli and vocal responses. Existing theoretical accounts of the SSARC effect differ in whether they predict reciprocal effects and whether they can account for the effect of stimulus mode on the reciprocal SSARC effect.

Keywords: SSARC; size; location; reciprocity; symmetry; verbal stimulus mode

Introduction

Certain assignments between stimulus and response alternatives allow for a better performance in terms of response speed and accuracy than other assignments of stimulus and response alternatives [1][2]. This observation is commonly referred to as *Stimulus-Response (S-R) Compatibility* and the performance advantage, which arises for “compatible” compared to “incompatible” mappings, is termed *compatibility effect*. Compatibility effects do not only occur when stimuli and responses vary on the same dimension, such as horizontal location, but also when stimuli and responses vary on different dimensions, such as physical size and spatial location [3][2]. When stimuli and responses vary on different – but associated – dimensions, the question of reciprocity arises: Do tasks in which dimension A (e.g., size) varies on the stimulus side and dimension B (e.g., location) varies on the response side, and tasks in which dimension B varies on the stimulus side and dimension A on the response side produce equivalent compatibility effects or not?

Associations between physical stimulus size and space (i.e., horizontal response location) give rise to the so-called *spatial-size association of response codes (SSARC) effect* [4][5][6]. The SSARC effect describes the phenomenon that left responses are faster and more accurate to physically small(er) stimuli whereas right responses are faster and more accurate to physically large(r) stimuli. The SSARC effect thus indicates that the mental representations between physical size and space are associated, which can be referred to as *spatial-size associations*. Several studies have so far investigated the SSARC effect and, for example, revealed that the effect also emerges when size is a task-irrelevant stimulus feature, thereby testifying to the automatic processing of physical size and its subsequent association with space [7][6]. Moreover, Wühr et al. [8] demonstrated that the SSARC effect also occurs with vocal responses and thus seems to be independent of response mode. Spatial-size associations therefore do not seem to rely on direct links between stimulus and response codes but instead seem to be located on an intermediate representational level.

Spatial-size associations robustly emerge in the form of a regular SSARC effect with physical stimuli and spatial responses. However, they do not seem to emerge in the opposite direction in the form of a reciprocal SSARC effect with spatial stimuli and responses referring to physical size [9]. In a previous study, we have investigated the reciprocity of the SSARC effect by comparing the compatibility effects in two vocal choice-response tasks [9]. In a size-location task, participants vocally responded to a physically small (2cm) or physically large (4 cm) stimulus by saying “left” or “right” according to a compatible (small-“left”; large-“right) and an incompatible mapping (small-“right”; large-“left”). In a location-size task, participants vocally responded to a left or right physical stimulus location by saying “small” or “large” according to a compatible (left-“small”; right-“large”) and an incompatible (left-“large”; right-“small”) mapping. Importantly, we used vocal responses because a) SSARC effects with manual and vocal responses are of comparable size [8] and b) manual responses referring to physical size are difficult to implement.

The results of our study revealed a significant regular SSARC effect in the size-location task but a non-significant reciprocal SSARC effect in the location-size task when outliers were excluded. Without the exclusion of outliers, merely small reciprocal SSARC effects emerged. These findings provide preliminary evidence that spatial-size associations underlying the SSARC effect with physical stimuli and vocal responses are strongly asymmetrical. While physical stimulus sizes can prime vocal location responses, physical stimulus locations cannot prime vocal size responses with a similar strength [9].

However, a recent study investigating the reciprocity of the so-called *spatial-numerical associations of response codes (SNARC) effect* has shown that the reciprocity of the SNARC effect depends on the stimulus mode [10]. The regular SNARC effect describes the phenomenon that left responses are faster and more accurate to small(er) numbers whereas right responses are faster and more accurate to large(r) numbers [11][12][13]. The reciprocal SNARC effect, in turn, describes the phenomenon that responses referring to small(er) numbers are faster and more accurate to left locations whereas responses referring to large(r) numbers are faster and more accurate to right locations. While the regular SNARC effect emerges with numerosity, digit as well as verbal number stimuli and vocal responses, the reciprocal SNARC effect only emerges with verbal location stimuli (i.e., location words “left” and “right”) and vocal responses but not with physical location stimuli (i.e., stimuli appearing in the left and right screen half) and vocal responses. This implies that stimulus mode affects the emergence of the reciprocal but not the regular SNARC effect [10].

In our previous experiment investigating the reciprocity of the SSARC effect, we did not observe a reciprocal SSARC effect with physical location stimuli and vocal size responses. Since we have found that a reciprocal effect of the related SNARC effect only emerges with verbal but not with physical location stimuli, it seems plausible to assume that a reciprocal SSARC effect might also emerge with verbal instead of physical location stimuli. In our present experiment, we therefore investigate the reciprocity of the SSARC effect with verbal stimuli and vocal responses. In the size-location task, participants vocally respond to the size word “small” or “large” by saying “left” or “right” according to a compatible (“small”-“left”; “large”-“right) and an incompatible mapping (“small”-“right”; “large”-“left”). In the location-size task, participants vocally respond to the location word “left” or “right” by saying “small” or “large” according to a compatible (“left”-“small”; “right”-“large”) and an incompatible (“left”-“large”; “right”-“small”) mapping.

In doing so, we aim to address two research questions. Firstly, does the reciprocal SSARC effect emerge with verbal location stimuli instead of physical location stimuli or, in other words, does the reciprocal SSARC effect – similar to the SNARC effect – depend on stimulus mode? Since stimulus mode might not only affect the reciprocal SSARC but potentially also the regular SSARC effect, we secondly ask: Does the regular SSARC effect also emerge with verbal instead of physical size stimuli or, in other words, is the regular SSARC effect independent of stimulus mode? While the regular SSARC effect seems to be independent of response mode [8], its independency of stimulus mode still remains to be tested.

We use the term regular SSARC effect to denote the compatibility effect between physical stimulus size and spatial responses as in a typical SSARC task and we use the term reciprocal SSARC effect to denote a compatibility effect in the opposite direction, that is, between spatial stimuli and responses referring to physical size. Importantly, several theoretical accounts which have been proposed to explain the SSARC effect differ in whether they predict bidirectional associations between size and space and whether they predict (or at least can account for) an influence of stimulus mode on the emergence of reciprocal and/or regular SSARC effects.

The *polarity correspondence principle* by Proctor and colleagues [14] assumes that in many binary classification tasks, one stimulus and response alternative is assigned a positive polarity whereas the other stimulus and response alternative is assigned a negative polarity. Corresponding polarities of stimuli and responses in turn lead to faster and more accurate responses than non-corresponding polarities [15][14][1614]. According to the polarity correspondence principle, the SSARC effect arises because the stimulus and response alternatives “small” and “left” are given negative polarity while the stimulus and response alternatives “large” and “right” are given positive polarity. In our view, the polarity correspondence principle predicts bidirectional and symmetrical SSARC effects since “small”/“left” and “large”/“right” are encoded as negative and positive polarity regardless of being varied as a stimulus or response feature. Moreover, stimulus mode should neither influence the emergence of the regular nor the reciprocal SSARC effect since polarities should be assigned to the bipolar dimensions of space and size regardless of their given format.

The *working memory (WM) account* by van Dijck and colleagues [17][18] proposes that it is the serial order in which stimuli of a given task are stored in WM that corresponds with spatial response location thus leading to compatibility effects. While stimuli at early serial positions are associated with left responses, stimuli at late serial positions are associated with right responses [17][18]. In terms of the WM account, in a typical SSARC task, stimulus sizes are spontaneously stored in an ascending order in WM. Accordingly, small stimuli then facilitate left responses while large stimuli facilitate right responses. Even when extending the WM account by the *mental whiteboard hypothesis* [19][20][21], an account which proposes that the serial order of stimuli is encoded in (verbal) WM by connecting the stimuli to spatial position markers, the possibility of reciprocal effects is not addressed. To explain a reciprocal SSARC effect, one would have to assume that location stimuli are serially stored by connecting them to spatial position markers. Those spatial position markers could, however, only prime size-related responses if responses were also spontaneously stored in a canonical order and connected to spatial position markers. The predictions of the WM account in terms of reciprocity are thus unclear. The fact that the serial order of stimuli is encoded in verbal WM allows for a regular SSARC effect with verbal instead of physical size stimuli but also for a reciprocal SSARC effect with verbal instead of physical location stimuli.

The *correlations in experience (CORE) principle* by Pitt and Casasanto [22] assumes that associations between the mental representations of two dimensions arise because those dimensions are correlated in people’s experience, that is, in their natural or cultural world, in the first place. Wühr et al. [8] applied the CORE principle to account for the SSARC effect and proposed that people's grasping habits determine the associations between physical size and space: While people tend to grasp smaller and lighter objects with their weaker non-dominant hand, they tend to grasp larger and heavier objects with their stronger dominant hand. During grasping movements, size is consistently involved as stimulus feature while space is involved as response feature. The account proposed by Wühr et al. [8] should therefore predict at least strongly asymmetrical spatial-size associations and thus also no effect of stimulus mode on the emergence of a reciprocal SSARC effect. The account can, however, explain a regular SSARC effect with verbal size stimuli if one assumes that spatial-size associations are not restricted to the stimulus mode, the correlation was originally experienced in. This assumption is in line with the broader *hierarchical mental metaphors theory* (HMMT; [23][24]) and previous findings that have demonstrated that spatial-size associations are not limited to the manual response mode [8].

Methods

The experiment was preregistered on the website OpenScienceFramework (OSF) (https://osf.io/uqvz2).

Participants

In our previous study [9], in which we investigated the reciprocity of the SSARC effect with physical location/size stimuli and vocal size/location responses, we observed a strong main effect of mapping (η^2_p = .22), and a strong two-way interaction between task and mapping (η^2_p = .16). Accordingly, we assumed a η^2_p of .20 for the main effect of mapping and for the two-way interaction for the present experiment. We conducted a power analysis with the software MorePower [25] which revealed that a sample size of 54 participants is sufficient to detect an effect of this size with high power (1-beta = .95) at the standard .05 alpha error probability. To account for the exclusion of potential outlier data sets, we planned to test 60 participants.

Sixty volunteer students (47 female, 13 male) with a mean age of 22.333 years (*SD* = 3.139) took part in our experiment. They were compensated by either course credit or a payment of 10 Euro. According to self-report, all participants had normal (*N* = 35) or corrected-to-normal (*N* = 25) vision. Fifty-four participants classified themselves as right-handed, whereas six participants classified themselves as left-handed. Even though a prior study has shown that handedness affects the SSARC effect [8], we included left-handed participants because they merely show weaker but no reverse SSARC effect. All participants gave their informed consent prior to participation. Moreover, the local Ethics Committee at TU Dortmund University approved the experimental protocol for the present study (GEKTUDO_2022_36). We confirm that all methods were performed in accordance with the relevant guidelines and regulations.

Apparatus and Stimuli

Participants sat in front of a 19-inch color monitor with a viewing distance of approximately 50 cm. We employed the software EPrime 3.0 (Psychology Software Tools; Sharpsburg, PA, USA) to control stimuli presentation, register vocal responses, and measure reaction time (RT). A small plus sign (Courier font, size 18 pt) was presented at the screen center at the beginning of each trial and thus served as a fixation point. All imperative stimuli were presented at the center of the screen. Moreover, all imperative stimuli were written in 40 pt in Times New Roman and presented in black on a white background. In the size-location task, the size words “small” and “large” served as imperative stimuli to which participants responded vocally by saying “left” or “right” into a microphone. The microphone was placed in front of the participants and centrally aligned to their body midline. It was connected to the voice-key of the Chronos console (Psychology Software Tools; Sharpsburg, PA, USA) to register RTs and record participants' vocal responses. Each vocal response was stored in a separate sound file and later checked for accuracy. In the location-size task, the location words "left" and "right" served as imperative stimuli to which participants responded vocally by saying "small" or "large". Even though all stimuli were presented in German and participants responded in German, we use the corresponding English words in the text for consistency. Please note that we differentiate between verbal stimuli (i.e., in the sense of written) and vocal responses (i.e., in the sense of spoken). In other words, all stimuli were presented visually in the form of size or location words whereas all responses were given vocally.

Procedure

Four conditions resulted from the orthogonal combination of two tasks (size-location task, location-size task) and two S-R mappings (compatible, incompatible) and were thus completed by each participant. In the size-location task, participants responded vocally to the stimulus words "small" or "large" by saying "left" or "right" according to a compatible mapping ("small"-"left", "large"-"right") or an incompatible mapping ("small"-"right", "large"-"left"). In the location-size task, participants responded vocally to the stimulus words "left" or "right" by saying "small" or "large" according to a compatible mapping ("left"-"small", "right"-"large") or an incompatible mapping ("left"-"large", "right"-"small"). The time course and sample stimuli of the size-location task and the location-size task are depicted in **Figure 1**.

Figure 1

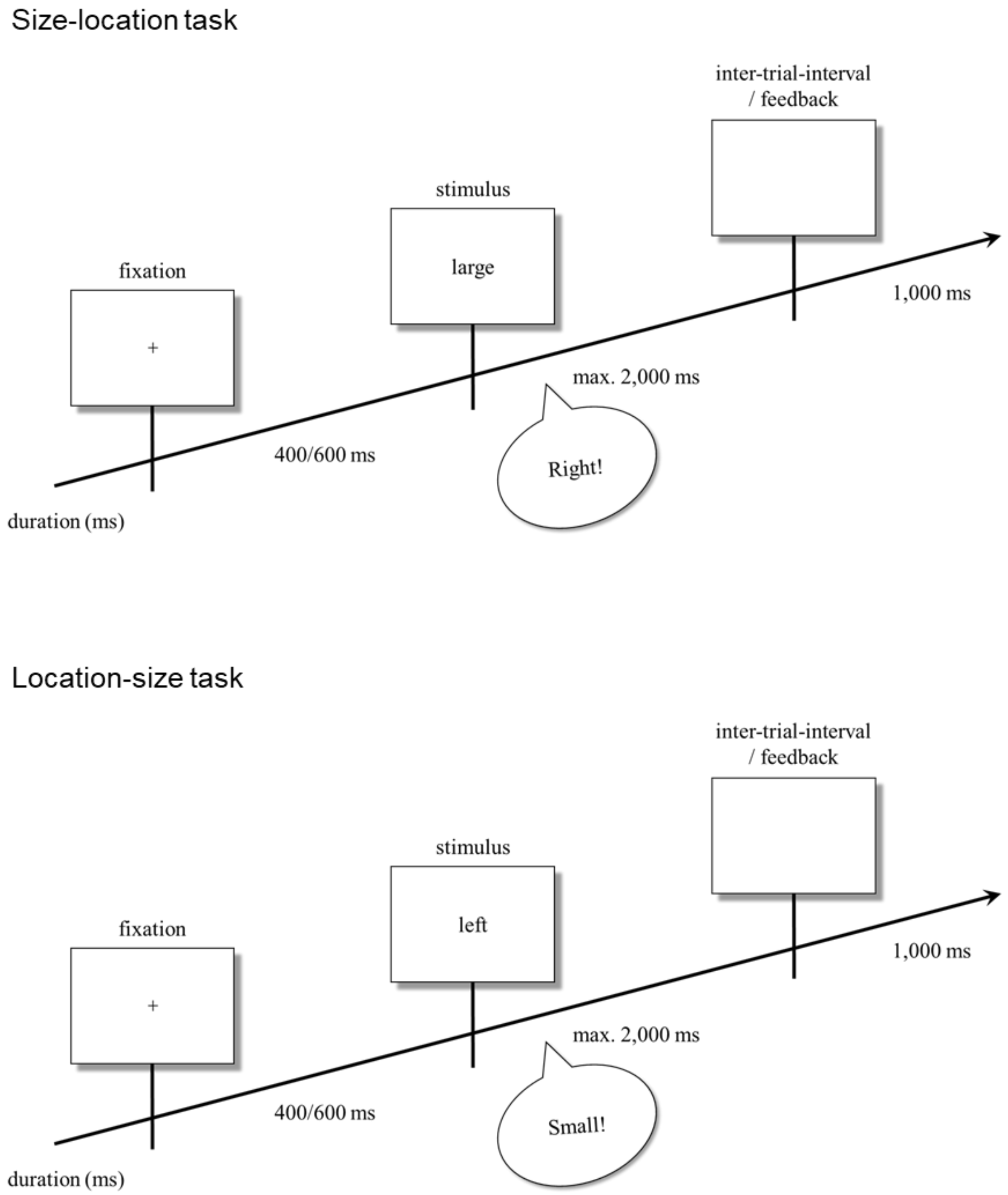

Figure 1. Time course of events in a typical trial of the size-location task (upper panel), and the location-size task (lower panel) according to compatible mappings. Stimulus displays are depicted as rectangles whereas a vocal response is depicted as a speech bubble.

At the beginning of each condition, instructions informed participants about the content and the procedure of the task. Each condition contained one training block with 10 trials and two experimental blocks with 40 trials each. Trials were randomized within each block. At the beginning of each trial, a fixation point was presented for 400 or 600 ms, with both durations occurring equally often in each block. The imperative stimulus was then presented for a maximum of 2,000 ms or until a response was given. An empty screen was presented for 1,000 ms during an inter-trial interval after a response was recorded, whereas a corresponding error message was presented during the inter-trial interval after a missing response. Since the program could not determine the accuracy of the vocal responses, participants did not receive feedback about the correctness of their responses. Instructions were repeated at the beginning of each experimental block to remind participants of the present task and S-R mapping. Between block participants were allowed to take a break or to continue with the subsequent block.

Both variables (i.e., task and S-R mapping) were varied within-subjects but between different blocks of trials. The order of tasks (size-location or location-size task first) and the order of mappings (compatible or incompatible mapping first) were both counterbalanced between participants. Participants completed both S-R mapping conditions consecutively within one task and the order of mappings was consistent between tasks for one participant. The experiment took about 30 min. The experimenter stayed in the laboratory for the practice trials but left the room before participants started the experimental blocks.

Design and Data Analysis

Before the analysis, the audio files with participants' vocal responses were checked in terms of accuracy. Errors were manually entered into the data file. The experimental design was a two-factorial (*Task* x *Mapping*) within-subjects design. The factor *Task* had two levels: the size-location task and the location-size task. The factor *S-R Mapping* also had two levels:

the compatible mapping and the incompatible mapping. We employed RTs of correct vocal responses and error percentages as dependent variables.

We planned to investigate the impact of the two independent variables (i.e., Task, Mapping) on the dependent variables (i.e., RTs, error percentages) with a two-way ANOVA. In case of a significant two-way interaction, we planned to employ *t* tests to determine the source of the interaction. Error percentages often contain a large number of ties that are often excluded from non-parametric tests, which biases the results towards H1. We therefore planned to employ *t* tests instead of non-parametric tests even though error percentages typically violate the normality assumption. Moreover, we additionally report the Bayes Factor (BF) for each pairwise comparison because we intended to evaluate the evidence for both the null (absence of effect) and the experimental (presence of effect) hypothesis [26]. To interpret the BF values, we follow Jeffreys' (1961) evidence categories (as cited in Lee and Wagenmakers [27]). Since overall outliers might be driving reciprocal SSARC effects [9], we conducted the same analyses once again after the exclusion of outlier participants according to the Tukey criterion [28]. We report these results in the **Appendix**.

Previous studies have shown that response speed (i.e., RT) affects the size of compatibility or congruency effects [29]. The regular SSARC effect with physical stimuli and manual or vocal responses has been shown to increase with increasing RTs [30][9]. Moreover, small trends of reciprocal SSARC effects with physical stimuli and vocal responses merely emerged for higher RTs levels and also increased with increasing RTs [9]. Since we employed verbal stimuli instead of physical stimuli in the present experiment, we conducted a distributional analysis (cf. **Appendix**) to determine the time course of the regular as well as the reciprocal SSARC effect with verbal stimuli and vocal responses. Moreover, with the distributional analysis we also aimed to detect small reciprocal SSARC effects, which might have emerged for specific RT levels but did not reach significance in the omnibus analysis. To analyze the time course of the mapping effects, we employed Ratcliff's method of vincentizing [31]. We rank-ordered RTs for each participant and condition before we divided them into four quartiles and computed the corresponding means. The means were then subjected to a three-factorial ANOVA with *Task* (size-location task, location-size task), *Mapping* (compatible, incompatible) and *Quartile* (1-4) as within-subject variables.

Results

Data trimming

On an overall level, we excluded one participant (number 44 in the dataset) whose mean error percentage exceeded 20% in one of the two tasks. After excluding this dataset, the highest error percentage was 16.883% in the size-location task, and 14.810% in the location-size task. Our final sample thus contained 59 participants. On a trial level, we excluded trials with RTs below 100 ms or above 1,500 ms and the first trial in each block. Participants' responses were too fast (i.e., RT < 100 ms) in less than 1% of trials in both the size-location (*M* = 0.212%, *SD* = 0.838) and location-size task (*M* = 0.088%, *SD* = 0.327). Similarly, participants' responses were too slow (i.e., RT > 1,500 ms) in less than 1% of trials in both the size-location (*M* = 0.286%, *SD* = 0.662) and location-size task (*M* = 0.406%, *SD* = 0.890).

Reaction Times (RTs)

The two-factorial ANOVA with *Task* and *Mapping* as within-subject factors revealed two significant main effects. The significant main effect of *Task*, $F(1, 58) = 15.986$, $MSE = 2{,}730.712$, $p < .001$, $\eta^2_p = .216$, indicated shorter RTs in the size-location task (*M* = 508 ms, *SD* = 76) than in the location-size task (*M* = 536 ms, *SD* = 98). The significant main effect of *Mapping*, $F(1, 58) = 62.600$, $MSE = 2{,}628.025$, $p < .001$, $\eta^2_p = .519$, reflected shorter RTs with the compatible mapping (*M* = 496 ms, *SD* = 76) than with the incompatible mapping (*M* = 548 ms, *SD* = 92). Importantly, however, the two-way interaction was non-significant, *F*(1, 58) = 2.051, *MSE* = 1,176.874, *p* = .157, η^2_p = .034, revealing similar mapping effects in the two tasks.

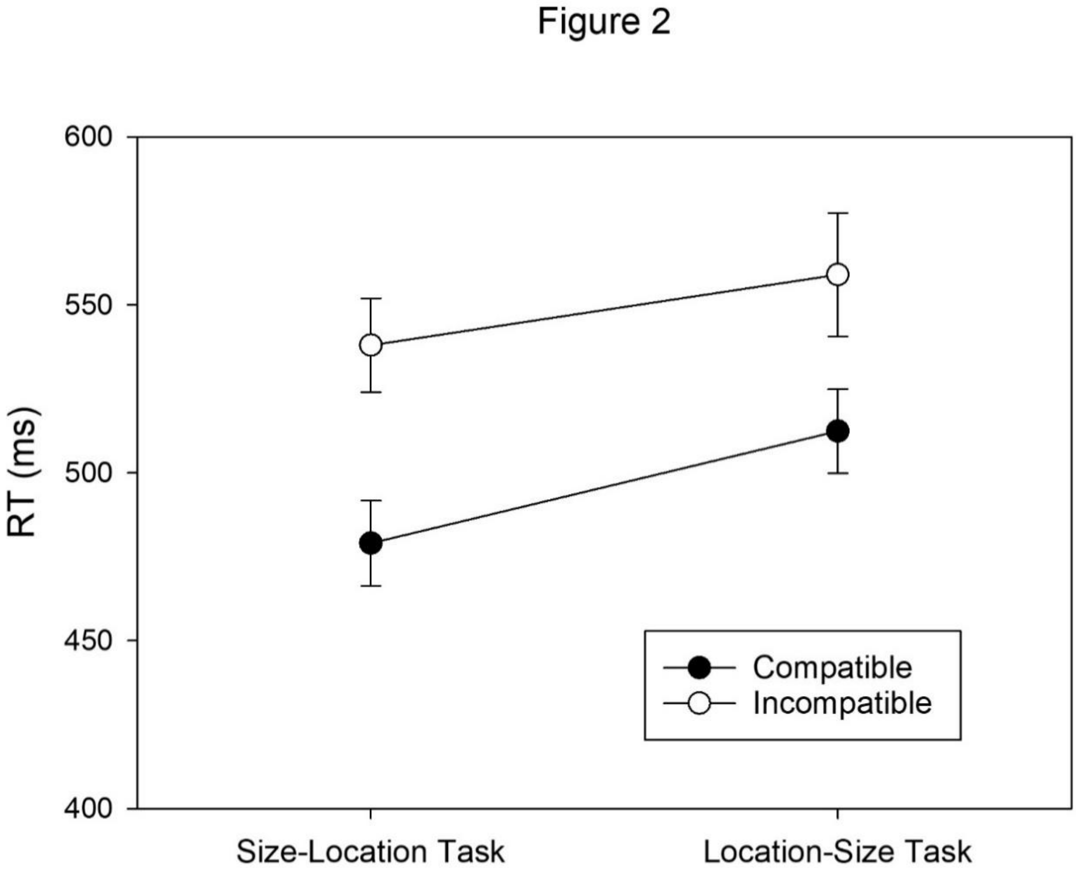

Figure 2. RTs of correct responses as a function of Task and S-R Mapping. Error bars reflect 95% confidence intervals for within-subjects designs [32].

For each task, we conducted a pairwise comparison between the compatible and incompatible mapping to determine the size of the mapping effect. In the size-location task, RTs were significantly shorter with the compatible than with the incompatible mapping, *t*(58) = 8.666, *p* < .001, *d* = 1.128, BF_{+0} > 10,000.000, reflecting a regular SSARC effect of 59 ms (cf. **Figure 2**) and extreme evidence for its presence. In the location-size task, RTs were significantly shorter with the compatible than with the incompatible mapping, *t*(58) = 5.115, $p < .001$, $d = .666$, BF_{+0} = 4,650.531, revealing a reciprocal SSARC effect of 46 ms (cf. **Figure 2**) and extreme evidence for its presence.

Figure 3

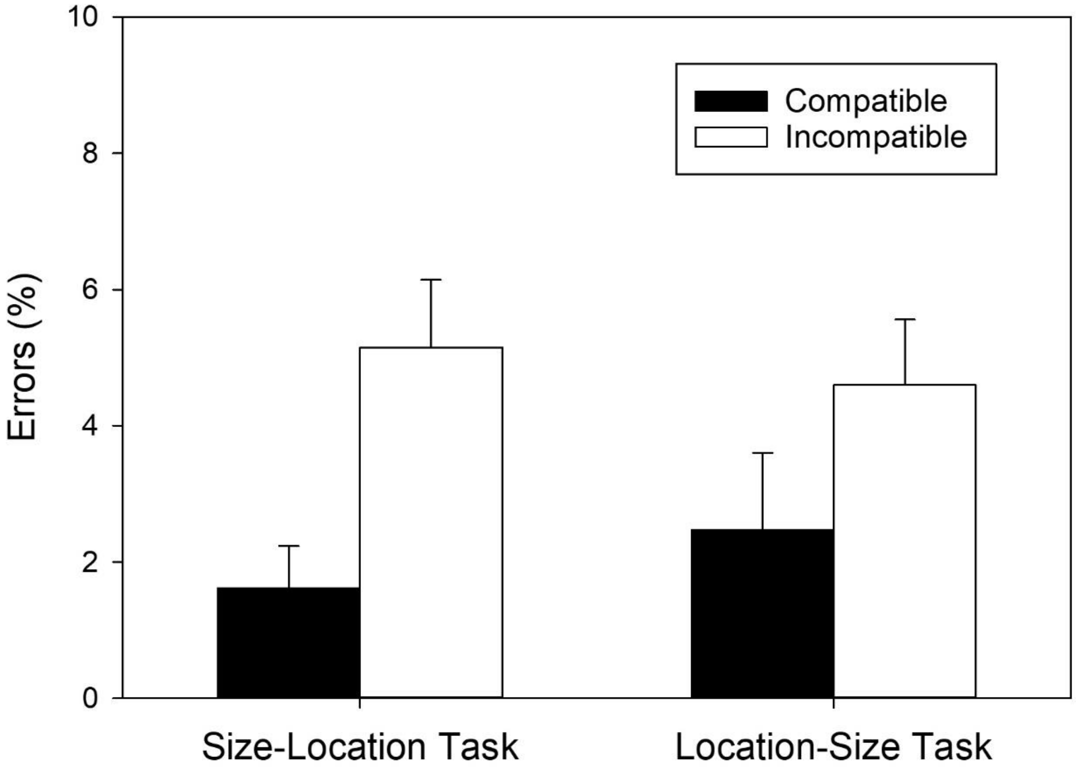

Figure 3. Error percentages as a function of Task and S-R Mapping. Error bars reflect 95% confidence intervals for within-subjects designs [32].

Error Percentages

The two-factorial ANOVA with *Task* and *Mapping* as within-subjects factors revealed a significant main effect of *Mapping* and a significant two-way interaction. The significant main effect of *Mapping*, $F(1, 58) = 37.976$, $MSE = 12.456$, $p < .001$, $\eta^2_p = .396$, revealed less errors with the compatible mapping ($M = 2.045$, $SD = 3.339$) than with the incompatible mapping (*M*

= 4.876, *SD* = 4.619). A non-significant main effect of *Task*, *F*(1, 58) = 0.116, *MSE* = 8.038, *p* = .685, η^2_p = .003, indicated similar error percentages in the size-location (*M* = 3.385, *SD* = 4.194) and the location-size task (*M* = 3.536, *SD* = 4.351). Importantly, however, the significant two-way interaction, *F*(1, 58) = 4.221, *MSE* = 6.941, *p* = .044, η^2_p = .068, revealed different mapping effects in the two tasks.

To determine the source of the two-way interaction, we conducted a pairwise comparison between the compatible and incompatible mapping for each task. In the size-location task, errors were significantly less frequent with the compatible than with the incompatible mapping, *t*(58) = 7.492, *p* < .001, *d* = 0.975, BF_{+0} > 10,000.000, revealing a regular SSARC effect of 3.536% (cf. **Figure 3**) and extreme evidence for its presence. Likewise, in the location-size task, errors were also significantly less frequent with the compatible than with the incompatible mapping, *t*(58) = 3.226, *p* = .002, *d* = 0.420, BF_{+0} = 14.076, revealing a reciprocal SSARC effect of 2.127% (cf. **Figure 3**) and strong evidence for its presence.

Comparison of mapping effects between experiments

We conducted additional analyses to investigate how the stimulus mode affected the regular and the reciprocal SSARC effect by comparing the mapping effects of our previous experiment [9], where we had used physical size/location stimuli, to the mapping effects of our present experiment, where we used verbal size/location stimuli. We conducted a two-factorial ANOVA with *Mapping* as within-subjects variable, *Experiment* as between-subjects variable and RTs from trials with correct responses as dependent variable for each task separately. For the typical SSARC task (i.e., size-location task), the main effect of *Experiment* was significant, *F*(1, 113) = 9.202, *MSE* = 9,526.334, *p* = .003, η^2_p = 0.075, indicating higher RTs in the present (*M* = 508 ms, *SD* = 76) than in the previous experiment (*M* = 469 ms, *SD* = 77). The two-way interaction was also significant, *F*(1, 113) = 11.513, *MSE* = 1,240.457, *p* < .001,

$\eta^2_p = 0.092$, indicating a larger regular SSARC effect in the present than in the previous experiment. For the reciprocal SSARC task (i.e., location-size task), we observed a similar pattern: the main effect of *Experiment* was significant, $F(1, 113) = 67.092$, $MSE = 13{,}541.428$, $p < .001$, $\eta^2p = 0.373$, indicating higher RTs in the present ($M = 536$ ms, $SD = 98$) than in the previous experiment ($M = 410$ ms, $SD = 76$). The two-way interaction was also significant, $F(1, 113) = 17.203$, $MSE = 1{,}538.578$, $p < .001$, $\eta^2p = 0.132$, indicating a larger reciprocal SSARC effect in the present than in the previous experiment.

Discussion

In our present experiment, we investigated the reciprocity of the SSARC effect with verbal stimuli and vocal responses by comparing the compatibility effects in a typical size-location task and a reciprocal location-size task. In particular, we aimed to find out if the regular SSARC effect emerges with verbal instead of physical size stimuli and if the reciprocal SSARC effect emerges with verbal instead of physical location stimuli. For both RTs and error percentages, we observed a regular SSARC effect with verbal size stimuli and vocal location responses: Participants were faster and more accurate when saying “left” to the size word “small” and when saying “right” to the size word “large” as compared to the opposite mapping. While the regular SSARC effect typically emerges with physical sizes as stimuli [6], the present results demonstrate that the effect also emerges with size words as stimuli.

A direct comparison between the results with physical [9] and verbal stimuli, however, reveals that stimulus mode affects the effect size: The regular SSARC effect was larger with verbal instead of physical stimuli. Yet, this finding can be attributed to the finding of overall higher RTs with verbal stimuli and the observation that the regular SSARC effect increased with increasing RTs (cf. **Appendix**), which is also in line with previous observations [30][9]. The regular SSARC effect thus not only occurs with different response modes (manual, vocal; [8]) but also with different stimulus modes (physical, verbal; [9]).

Most interestingly, for both RTs and error percentages we also observed a reciprocal SSARC effect with verbal location stimuli and vocal size responses: Participants were faster and more accurate when saying “small” to the location word “left” and when saying “large” to the location word “right” as compared to the opposite mapping. Moreover, for RTs the reciprocal and the regular SSARC effect were of similar size indicating bidirectional and symmetrical spatial-size associations. Location words can thus influence the selection and execution of vocal size responses to a similar extent as size words can influence the selection and execution of vocal location responses. For error percentages, the regular SSARC effect was larger than the reciprocal SSARC effect indicating bidirectional but asymmetrical spatial-size associations. The distributional analysis (cf. **Appendix**) further demonstrated that the time course of the reciprocal SSARC effect was similar to the time course of the regular SSARC effect: the compatibility effect increased with increasing RTs.

The observation that the reciprocal SSARC effect emerges with verbal location stimuli and vocal size responses is of particular interest because it does not emerge with physical location stimuli and vocal size responses [9]. In our previous study with the same experimental design, we had employed physical location stimuli and vocal size responses and observed a non-significant reciprocal SSARC effect in the location-size task [9]. The reciprocal SSARC effect therefore depends on stimulus mode: Verbal locations but not physical locations can influence the selection and execution of vocal size responses. Most interestingly, this property seems to be shared with the SNARC effect. In a previous study investigating the reciprocity of the SNARC effect, the reciprocal SNARC effect only emerged with verbal location stimuli and vocal (number) responses but not with physical location stimuli and vocal (number) responses [10].

This consistent finding across both effects indicates that physical location stimuli differ from verbal location stimuli in one (or more) aspect(s) that is (are) essential in eliciting a reciprocal SSARC/SNARC effect.

Theoretical implications

The present findings have several implications for the theoretical accounts of the SSARC effect, which need to explain the effect of stimulus mode on the emergence of a reciprocal SSARC effect. The polarity correspondence principle assumes that the SSARC effect arises because “small” and “left” are given negative polarity while “large” and “right” are given positive polarity and a correspondence in polarities facilitates performance [15][14][16]. In our view, this account predicts bidirectional and symmetrical SSARC effects since the binary categories are assigned negative and positive polarity regardless of being situated on the stimulus or response level. This prediction is in line with the bidirectional and symmetrical SSARC effects we observed with verbal location/size stimuli and vocal size/location responses. Yet, in order to also account for the effect of stimulus mode on the emergence of the reciprocal SSARC effect and in particular for the absence of a reciprocal SSARC effect with physical location stimuli and vocal size responses [9], the polarity correspondence principle would have to claim that physical location stimuli or vocal size responses are not encoded in terms of polarity. However, while previous studies have already shown polarity coding of physical location stimuli [33][34][35][36], the reciprocal SSARC effect in our present experiment demonstrates polarity coding of vocal size responses.

The WM account assumes that the SSARC effect arises because stimulus sizes of a given task are spontaneously stored in an ascending order in WM and the early (late) serial position of a small (large) size corresponds with the left (right) response location [17][18]. The mental whiteboard hypothesis [19][20][21] further accounts for the encoding of the serial order by proposing that spatial position markers are connected to the stimuli stored in WM. To account for the reciprocal SSARC we observed in our experiment, one would have to assume that not only location stimuli but also size-related responses are serially stored in WM and connected to spatial position markers, which then correspond or do not correspond. The WM account, however, remains mute about such processes. Yet, the observation of a reciprocal SSARC effect with verbal but not with physical location stimuli might be in line with the WM account and attributed to the account's assumption that the serial order of stimuli is encoded in verbal WM [20]. Nevertheless, the account faces difficulties in explaining why stimulus mode in contrast does not affect the emergence of the regular SSARC effect, which occurs with both verbal and physical size stimuli [9].

The CORE principle assumes that the SSARC effect emerges because people experience correlations between stimulus size and response location in their natural or cultural environment [22]. In line, Wühr et al. [8] proposed that it is the people's habit to grasp smaller (larger) and lighter (heavier) objects with their weaker (stronger) non-dominant (dominant) hand that shapes associations between size and space. Since grasping movements involve size as stimulus feature and space as response feature, the account should predict strongly asymmetrical spatial-size associations and consequently also no effect of stimulus mode on the emergence of a reciprocal SSARC effect. Both predictions are at odds with the results of our experiment. However, according to Wühr et al. [8] "other variables, beyond handedness and effector strength, also contribute to the origin and/or the size of SSARC effect" (p. 12) and thus might be responsible for the occurrence of a reciprocal SSARC effect with verbal stimuli. Moreover, the CORE principle can account for a regular SSARC effect with verbal size stimuli assuming that – in line with HMMT [23][24] and previous evidence [8] – the associations are not restricted to the stimulus and response mode in which the correlation was originally experienced.

Potential determinants for the emergence of a reciprocal SSARC effect

Physical location stimuli seem to differ from verbal location stimuli in some kind of property that seems to be essential in eliciting a reciprocal SSARC (and reciprocal SNARC) effect. One potential property – and thus one potential explanation for the influence of stimulus mode on the reciprocal SSARC effect – might be the overall higher RT level with verbal (M = 536 ms) than with physical stimuli (M = 410 ms). Since the reciprocal SSARC effect increased with increasing RTs, the occurrence of a reciprocal SSARC effect with verbal size stimuli might be mediated by higher RTs. Another potential explanation for the occurrence of a reciprocal SNARC effect with verbal location stimuli might reside in a higher set-level compatibility [37] with verbal stimuli and vocal responses than with physical stimuli and vocal responses. Even though a higher set-level compatibility could also explain the larger regular SSARC effect with verbal stimuli and vocal responses, the overall higher RT level with this combination of stimuli and responses contradicts this hypothesis. Attention allocation might constitute a third potential explanation: While attention remains focused on the screen center with verbal location stimuli, it is shifted to the left or right with physical location stimuli. Future research could address the question why a reciprocal SSARC effect emerges with verbal but not with physical location stimuli.

Conclusion

The results of our experiment revealed a regular and a reciprocal SSARC effect of similar size with verbal size/location stimuli and vocal location/size responses. With this combination of stimuli and responses, the spatial-size associations underlying the SSARC effect are thus bidirectional and result in symmetrical effects. Together with a previous study [9], the results furthermore demonstrate an effect of stimulus mode on the emergence of the reciprocal but not on the emergence of the regular SSARC effect: While the regular SSARC effect occurs both with verbal and physical size stimuli, the reciprocal SSARC effect only emerges with verbal but not with physical location stimuli and vocal responses. This pattern has likewise been observed for the SNARC effect [10] pointing towards some essential property of verbal location stimuli in the emergence of reciprocal effects. Moreover, these findings have implications for the theoretical accounts of the SSARC effect which, firstly, need to explain the occurrence of a reciprocal SSARC effect and, secondly, need to account for the effect of stimulus mode on the emergence of the reciprocal but not on the emergence of the regular SSARC effect.

Additional information

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Availability of data and materials

Data, materials and codes used in this study can be obtained by contacting the corresponding author (melanie2.richter@tu-dortmund.de).

Declaration of interest

The authors have no competing interests to declare.

Informed consent

Before the experiment, all participants gave written informed consent to participate.

Ethics approval

The local Ethics Committee at TU Dortmund University had approved the experimental protocol for our study (approval no. GEKTUDO_2022_36). We confirm that all methods were performed in accordance with the relevant guidelines and regulations.

CRediT Author Statement

M. R.: Conceptualization, Methodology, Software, Validation, Formal analysis, Data Curation, Writing - Original Draft, Writing - Review & Editing

P. W.: Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing - Original Draft, Writing - Review & Editing, Visualization, Project administration

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Appendix

Distributional analysis for RTs

We conducted a three-factorial ANOVA with *Task* (size-location task, location-size task), *Mapping* (compatible, incompatible) and *Quartile* (1-4) as within-subject variables and RT means as the dependent variable. Please note that we will only report results involving the variable *Quartile*. The corresponding means are depicted in **Figure 4**.

Figure 4

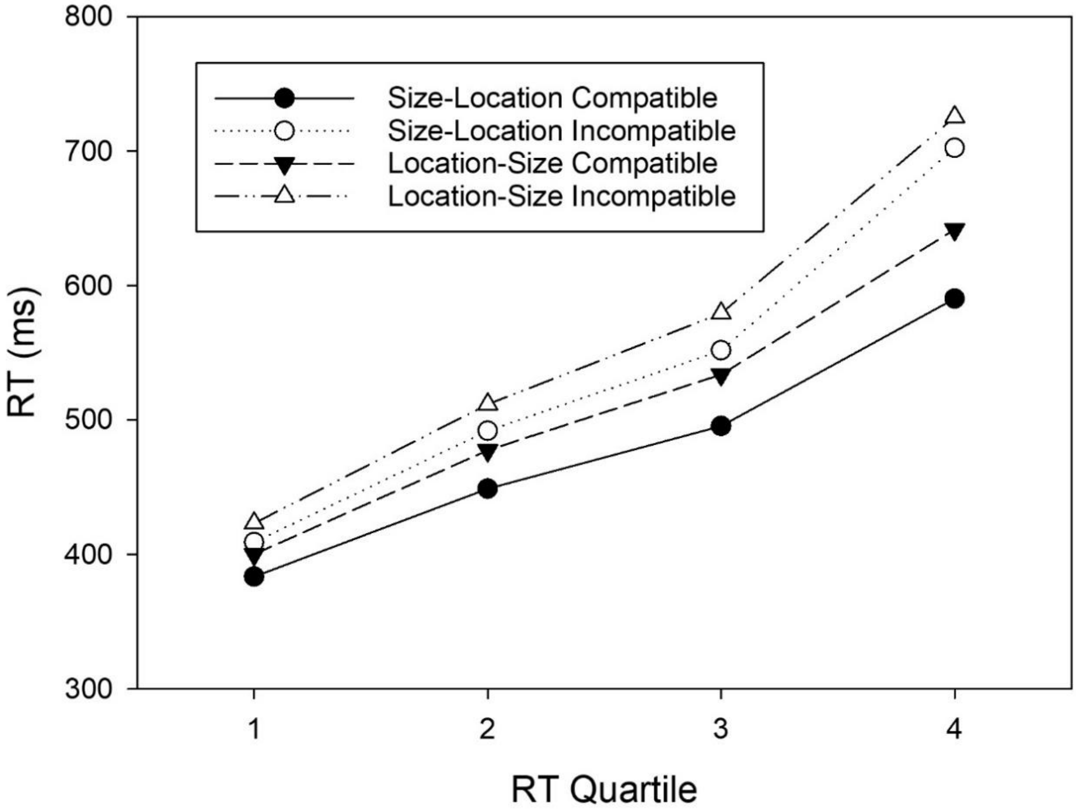

Figure 4. RTs of correct responses as a function of Task, S-R Mapping, and RT Quartile.

Both two-way interactions *Quartile* x *Task* and *Quartile* x *Mapping* were significant. The significant *Task* × *Quartile* interaction, *F*(3, 174) = 8.525, *MSE* = 651.440, *p* < .001, η^2_p = .128, reflected that, with increasing RTs, mean RTs in the location-size task became increasingly slower compared to the size-location task. The range of RTs was thus smaller in the size-location task compared to the location-size task. The significant *Mapping* × *Quartile* interaction, *F*(3, 174) = 45.526, *MSE* = 1,312.927, $p < .001$, $\eta^2_p = .440$, reflected that mapping effects increased with increasing RTs. Crucially, the three-way interaction, *F*(3, 174) = 2.335, *MSE* = 788.448, $p = .076$, $\eta^2_p = .039$, was non-significant revealing similar time courses of the mapping effects between both tasks.

In the size-location task, the regular SSARC effect increased from 26 ms in the first quartile to 43 ms in the second quartile, 56 ms in the third quartile and 112 ms in the fourth quartile. Post-hoc tests comparing the compatible and incompatible mapping condition for each quartile revealed that the regular SSARC effect was significant in all four quartiles, all *t*s ≥ 5.460, all $ps_{Tukey} < .001$. In the location-size task, the reciprocal SSARC effect increased from 23 ms in the first quartile to 34 ms in the second quartile, 45 ms in the third quartile and 83 ms in the fourth quartile. Post-hoc tests indicated that the reciprocal SSARC effect was significant in all four quartiles, all *t*s ≥ 4.034, all $ps_{Tukey} \leq .014$.

Exclusion of outliers

Our previous study on the reciprocity of SSARC effects has shown that overall outliers might be driving reciprocal effects [9]. We thus decided to conduct the same set of analyses after having excluded outlier participants according to the Tukey criterion [28]. The Tukey criterion classifies observations below Q_{25} – 1,5*IQR or above Q_{75} + 1,5*IQR as outliers. We collapsed data across the mapping variable, applied the criterion to the remaining four variables (mean RT and error percentage in the size-location and location-size task, respectively) and excluded seven further participants (numbers 10, 20, 30, 36, 51, 54 and 60). The remaining sample therefore contained 52 participants.

In the analysis of error percentages without outliers, the formerly significant *Task* x

Mapping interaction became non-significant, $F(51) = 0.832$, $MSE = 5.073$, $p = .366$, $\eta^2_p = 0.016$, indicating similar mapping effects between the two tasks when outlier datasets were excluded. This can be attributed to the observation that, by removing outliers, the reciprocal SSARC effect in error percentages increased from 2.127% ($d = 0.420$) to 2.772% ($d = 0.692$) while evidence for its presence increased from strong ($BF_{+0} = 14.076$) to extreme ($BF_{+0} = 2{,}533.262$). The exclusion of outliers did not affect the pattern of results in the analysis of RTs or in the distributional analysis.

6. General Discussion

The major aim of this dissertation was to examine the bidirectionality and symmetry of associations between numerical and physical size on the one hand and space on the other hand as they emerge as SNARC and SSARC effects. This overall objective splits up into two pairs of research questions which were answered in a total of four studies and seven experiments. The first pair of research questions addressed the bidirectionality and symmetry of the SNARC effect: Is the SNARC effect bidirectional allowing for the emergence of a regular and reciprocal SNARC effect? Provided that the SNARC effect is bidirectional, the research question continues: Are the regular and reciprocal SNARC effect symmetrical or asymmetrical? I thereby sought to determine if the associations between numerical size and space, which underlie the SNARC effect, are a) unidirectional allowing for a regular SNARC effect but not for a reciprocal SNARC effect, b) bidirectional and symmetrical allowing for a regular as well as a reciprocal SNARC effect of similar size or c) bidirectional and asymmetrical allowing for a regular as well as a reciprocal SNARC effect of different sizes. Studies 1 and 2 comprising Exp. 1-5 addressed these research questions by comparing the compatibility effect of a number-location task, in which participants responded to numerical stimulus size with location responses (typical SNARC task), to the compatibility effect of a location-number task, in which participants responded to stimulus location with responses referring to numerical size (reciprocal SNARC task).

The regular SNARC effect robustly emerged with all combinations of stimulus and response sets that were employed. The regular SNARC effect occurs with numerosity stimuli and manual keypress responses but also with digit stimuli and manual keypress responses: Participants responded faster when pressing a left key to a small number/amount and when pressing a right key to a large number/amount as compared to the reverse assignment.

Moreover, the regular SNARC effect occurs with digit stimuli and vocal responses as well as with verbal number stimuli and vocal responses: Participants responded faster and more accurate to the digit 1/number word “one” by saying “left” and to the digit 9/number word “nine” by saying “right” as compared to the reverse assignment. Numerical stimuli can thus prime location responses irrespective of different stimulus and response modes. This corroborates previous findings that have demonstrated regular SNARC effects of similar size with different stimulus modes (Nuerk et al., 2005) and different response modes (i.e., manual and vocal; Gevers et al., 2010). Moreover, across the combinations of stimulus and response sets that were employed, the time course of the regular SNARC effect consistently revealed increasing SNARC effects with increasing RTs, which is also in line with previous evidence (Gevers et al., 2006; Mapelli et al., 2003).

In contrast to the regular SNARC effect, the reciprocal SNARC effect did not emerge with all different stimulus and response sets that were employed. Only a small reciprocal SNARC effect emerged with physical location stimuli and manual number responses, which disappeared when outlier datasets were excluded. Likewise, only a small reciprocal SNARC effect emerged with physical location stimuli and vocal number responses, which also disappeared when outlier datasets were excluded. Similar to the regular SNARC effect, response mode (manual, vocal) did not affect the size of a reciprocal SNARC effect with these stimulus sets. However, with verbal location stimuli and vocal number responses, a reciprocal SNARC effect emerged: Participants responded faster and more accurate to the location word “left” by saying “one” and to the location word “right” by saying “nine” as compared to the reverse assignment. Stimulus mode therefore affects the emergence of the reciprocal SNARC effect: Verbal location stimuli but not physical location stimuli can prime vocal number responses. Moreover, similar to the time course of the regular SNARC effect, the reciprocal SNARC effect increased with increasing RTs.

With numerosity or digit/physical location stimuli and manual or vocal location/number responses, regular SNARC effects were much larger than reciprocal SNARC effects revealing that physical location stimuli cannot prime manual or vocal number responses to the same extent as numerosity or digit stimuli can prime manual or vocal location responses. With these stimulus and response combinations, spatial-numerical associations thus seem to be at least strongly asymmetrical. In contrast, with verbal number/location stimuli and vocal location/number responses, the regular and reciprocal SNARC effect were of similar size revealing that verbal location stimuli can prime vocal number responses to the same extent as verbal number stimuli can prime vocal location responses. With verbal stimuli and vocal responses, spatial-numerical associations thus seem to be bidirectional and symmetrical.

The second pair of research questions addressed the bidirectionality and symmetry of the SSARC effect: Is the SSARC effect bidirectional allowing for the emergence of a regular and reciprocal SSARC effect? Provided that the SSARC effect is bidirectional, the research question continues: Are the regular and reciprocal SSARC effect symmetrical or asymmetrical? I thereby sought to determine if the associations between physical size and space, which underlie the SSARC effect, are a) unidirectional allowing for a regular SSARC effect but not for a reciprocal SSARC effect or b) bidirectional and symmetrical allowing for a regular as well as a reciprocal SSARC effect of similar size or c) bidirectional and asymmetrical allowing for a regular as well as a reciprocal SSARC effect of different sizes. Studies 3 and 4 comprising Exp. 6 and 7 addressed this research question by comparing the compatibility effect of a size-location task, in which participants responded to stimulus size with location responses (typical SSARC task), to the compatibility effect of a location-size task, in which participants responded to stimulus location with responses referring to physical size (reciprocal SSARC task).

The regular SSARC effect emerged with physical size stimuli and vocal location responses as well as with verbal size stimuli and vocal location responses. Participants responded faster and more accurate to a small stimulus/the size word “small” by saying “left” and to a large stimulus/the size word “large” by saying “right” as compared to the reverse assignment. Together with previous evidence demonstrating that the regular SSARC effect emerges with physical size stimuli and manual keypress responses (Wühr & Seegelke, 2018), the results suggest that sizes can prime location responses irrespective of different stimulus and response modes. Moreover, the time course of the regular SSARC effect consistently revealed increasing SSARC effects with increasing RTs, which corroborates previous findings (Heuer et al., 2023).

Only a small reciprocal SSARC effect emerged with physical location stimuli and vocal size responses, which disappeared when outlier datasets were excluded. However, with verbal location stimuli and vocal size responses, a reciprocal SSARC effect emerged: Participants responded faster and more accurate to the location word “left” by saying “small” and to the location word “right” by saying “large” as compared to the reverse assignment. Stimulus mode therefore affects the emergence of the reciprocal SSARC effect: Verbal location stimuli but not physical location stimuli can prime vocal size responses. Moreover, similar to the time course of the regular SSARC effect, the reciprocal SSARC effect increased with increasing RTs.

With physical size/location stimuli and vocal location/size responses, the regular SSARC effect was much larger than the reciprocal SSARC effect revealing that physical location stimuli cannot prime vocal size responses to the same extent as physical size stimuli can prime vocal location responses. With physical stimuli and vocal responses, spatial-size associations thus seem to be at least strongly asymmetrical. In contrast, with verbal size/location stimuli and vocal location/size responses, the regular and reciprocal SSARC effect were of similar size revealing that verbal location stimuli can prime vocal size responses to the same extent as verbal size stimuli can prime vocal location responses. With verbal stimuli and vocal responses, spatial-size associations thus seem to be bidirectional and symmetrical.

Most interestingly, both the reciprocal SNARC and the reciprocal SSARC effect depend on stimulus mode: While both reciprocal effects do not occur with physical location stimuli, they do occur with verbal location stimuli. Stimulus mode therefore affects the emergence of the reciprocal SNARC and SSARC effect. This shared property between both the SNARC and SSARC effect emphasizes the role of verbally labeling spatial information in eliciting reciprocal effects and suggests that verbal location stimuli differ from physical location stimuli in some aspect(s) that is (are) crucial for the emergence of a reciprocal SNARC/SSARC effect. In turn, stimulus mode (i.e., numerosity, digit and verbal number stimuli/physical and verbal size stimuli) neither affects the emergence of the regular SNARC nor the regular SSARC effect. Moreover, both the regular SNARC and SSARC effect emerge with different response modes (i.e., manual and vocal location responses). In how far response mode affects the emergence of a reciprocal SNARC/SSARC effect with verbal stimuli, however, remains to be tested.

These studies were the first to test the bidirectionality and symmetry of spatial-numerical and spatial-size associations in S-R priming effects. In sum, with certain combinations of stimulus and response sets, the associations between numerical and physical size on the one hand and space on the other hand are bidirectional, allowing for a regular as well as a reciprocal SNARC/SSARC effect of similar size. With other combinations of stimulus and response sets, however, the associations between numerical and physical size on the one hand and space on the other hand are unidirectional (or at least strongly asymmetrical), allowing for a regular but not for a reciprocal SNARC/SSARC effect. Previous studies employing priming and random number generation tasks have already demonstrated the bidirectionality of spatial-numerical associations in S-S (Kramer et al., 2011; Stoianov et al., 2008) and R-R congruency effects (Loetscher et al., 2008, 2010; Shaki & Fischer, 2014). The present results further extend these findings and provide evidence for the bidirectionality of spatial-numerical associations in S-R effects while pointing towards an important role of stimulus mode in the emergence of a reciprocal SNARC effect. Since the bidirectionality of spatial-size associations has not been investigated previously, the present results are the first to demonstrate that bidirectional spatial-size associations may emerge as S-R effects in the form of a reciprocal SSARC effect while also emphasizing the role of stimulus mode for its emergence.

Implications for the theoretical accounts of the SNARC/SSARC effect

By investigating the bidirectionality of the SNARC and the SSARC effect as the first main objective of this dissertation, I aimed to accomplish the second main objective of this dissertation, namely, to differentiate between the existing theories that have been proposed in order to account for the SNARC/SSARC effect. The novel findings allow to differentiate between the theoretical accounts since they differ in whether they predict or at least can account for the reciprocal SNARC/SSARC effect and the impact of stimulus mode on its emergence. With that, this dissertation makes several theoretical contributions. Importantly, in their current form, none of the existing theories can account for the entire pattern of effects that were revealed by the four studies emphasizing the necessity to develop and advance the theoretical accounts according to the insights gained.

As one of the first theories to account for the SNARC effect, the MNL proposes that numbers are mentally represented in an ascending order from left to right. According to the MNL, the SNARC effect arises because a number which is activated during number processing simultaneously activates its spatial location on the MNL, which in turn primes a corresponding spatial response (Dehaene et al., 1993; Fischer et al., 2003; Restle, 1970). Since the MNL assumes one joint mental representation and thus activation of both dimensions (Fischer & Shaki, 2014), it can account for bidirectional and symmetrical SNARC effects. However, the MNL is assumed to be located on a central level between stimulus and response representations (Dehaene et al., 1993; Ginsburg & Gevers, 2015; Huber et al., 2016; Umiltà et al., 2010), which allows the MNL to also account for unidirectional and (bidirectional but) asymmetrical SNARC effects. Directional asymmetries might, for instance, arise between stimulus codes and the MNL and/or between the MNL and response codes.

The observation of bidirectional and symmetrical SNARC effects with verbal stimuli and vocal responses is in line with the assumption of a joint activation of number and space on the MNL. Additionally, the observation that the reciprocal SNARC effect was much weaker than the regular SNARC effect when physical instead of verbal location stimuli were employed in the reciprocal SNARC task indicates that this asymmetry arises between the stimulus code and the MNL: Verbal location stimuli seem to activate the MNL to a greater extent than physical location stimuli resulting in a stronger reciprocal SNARC effect with verbal than with physical location stimuli. Even though the MNL is thus able to account for both findings, it lacks a plausible explanation why verbal location stimuli activate the MNL more strongly than physical location stimuli. Especially in light of the fact that the MNL is considered a visuospatial account of spatial-numerical associations (Umiltà et al., 2010), a greater activation of the MNL by the visuospatial stimulus mode would seem more plausible. Moreover, it remains unclear why strongly asymmetrical effects arise due to an effect of stimulus mode on the emergence of the reciprocal but not the regular SNARC effect: Both numerosity, digit and verbal number stimuli activate the MNL to a similar extent and the activation of the MNL in turn activates manual or vocal location responses to a similar extent. Thus, even though the MNL may account for both the symmetrical and asymmetrical SNARC effects, it lacks an explanation of the impact of stimulus mode on the emergence of the reciprocal but not the regular SNARC effect.

The WM account assumes that the SNARC/SSARC effect emerges because the serial position of a stimulus stored in WM corresponds with the spatial response location (Abrahamse et al., 2016; Van Dijck & Fias, 2011; Van Dijck et al., 2015). In particular, according to the mental whiteboard hypothesis, the numerical/physical stimulus sizes of a given stimulus set are canonically ordered and stored in verbal WM from left to right by connecting early serial positions to left position markers and late serial positions to right position markers (Abrahamse et al., 2014, 2017; De Belder et al., 2015). Accordingly, the left position markers of small numbers/sizes prime left responses whereas the right position markers of large numbers/sizes prime right responses resulting in the regular SNARC/SSARC effect.

Importantly, the WM account/mental whiteboard hypothesis remains mute about reciprocal effects and it also remains mute about other potential processes such as the spatial encoding of responses. However, to explain the observed bidirectional and symmetrical SNARC/SSARC effects with verbal stimuli and vocal responses, the account would have to assume that spatial stimuli as well as numerical/physical-size-related responses are systematically stored from left to right in verbal WM by connecting them to spatial position markers. The corresponding position markers of left (right) stimuli and numerically/physically small (large) responses would then facilitate performance whereas non-corresponding position markers of left (right) stimuli and numerically/physically large (small) responses would impede performance. To explain the strongly asymmetrical SNARC/SSARC effects with physical instead of verbal location stimuli in the reciprocal SNARC/SSARC task, the WM account/mental whiteboard hypothesis would have to assume that verbal location stimuli but not physical location stimuli are systematically stored from left to right in verbal WM by connecting them to spatial position markers.

The account's assumption that the spatial encoding of the serial order of stimuli takes place in verbal WM (Abrahamse et al., 2014, 2017; De Belder et al., 2015) might explain the systematic encoding and storage of verbal but not physical location stimuli. The WM account/mental whiteboard hypothesis could thus account for the effect of stimulus mode on the emergence of the reciprocal SNARC/SSARC effect. Similar to the results of our studies, Ginsburg and colleagues (2017) also observed that physical location stimuli were not spatially encoded in WM. Since they found evidence that "position markers are only spatially coded when the to-be-remembered information is processed at the semantic level" (Ginsburg et al., 2017, p. 632), they hypothesized that physical location stimuli are processed without receiving semantic meaning (Ginsburg et al., 2017). Given that verbal stimuli are more likely to receive semantic meaning, semantic processing might explain the spatial encoding of verbal but not physical location stimuli.

However, the account fails to explain why stimulus mode affects the emergence of the reciprocal but not the regular SNARC/SSARC effect. Since the regular SNARC/SSARC effect not only emerges with verbal number/size stimuli but also with numerosity and digit/physical size stimuli, also non-verbal number/size stimuli must be systematically encoded and stored in verbal WM. It remains unclear, why the spatial encoding of stimuli in verbal WM should occur for numerosity/physical size stimuli but not for physical location stimuli. In terms of Ginsburg and colleagues (2017), semantic processing might only take place for numerosity/physical size stimuli but not physical location stimuli, but the reason for such a deviation nevertheless remains open to question. In sum, even though the WM account/mental whiteboard hypothesis can explain both the symmetrical and asymmetrical SNARC/SSARC effects and the effect of stimulus mode on the emergence of the reciprocal SNARC/SSARC effect, several additional assumptions have to be made in advance. Moreover, the account lacks a direct explanation of the impact of stimulus mode on the emergence of the reciprocal but not the regular SNARC/SSARC effect.

The polarity correspondence principle assumes that the categories "(numerically/physically) small" and "left" are assigned negative polarity whereas the categories "(numerically/physically) large" and "right" are assigned positive polarity (Proctor & Cho, 2006). Since corresponding polarities facilitate performance and non-corresponding polarities impede performance, the SNARC/SSARC effect occurs (Lakens, 2012; Proctor & Cho, 2006; Proctor & Xiong, 2015). The observed bidirectional and symmetrical SNARC/SSARC effects with verbal stimuli and vocal responses are in line with the polarity correspondence principle according to which small (large) numerical/physical sizes and left (right) locations are assigned negative (positive) polarity regardless of being varied as stimulus or response feature.

However, the strongly asymmetrical SNARC/SSARC effects with physical instead of verbal location stimuli in the reciprocal SNARC/SSARC task are at odds with the theoretical account. The observation that the reciprocal SNARC/SSARC effect does not emerge with physical location stimuli and manual or vocal number/vocal size responses would indicate that either physical location stimuli or number/size responses were not encoded in terms of polarity. Previous findings have, however, demonstrated polarity encoding of physical location stimuli, for example in picture-word verification (Just & Carpenter, 1975; Olson & Laxar, 1973) as well as orthogonal S-R correspondence effects (Cho & Proctor, 2003; Weeks & Proctor, 1990). Moreover, the reciprocal SNARC/SSARC effect with verbal stimuli and vocal responses demonstrates polarity encoding of number/size responses. Since polarities should be assigned to the binary categories of numerical/physical size and location regardless of their given format (Proctor & Cho, 2006), regular and reciprocal SNARC/SSARC effects should not be affected by stimulus or response mode. The polarity correspondence effect therefore can explain neither the strongly asymmetrical SNARC/SSARC effects nor the impact of stimulus mode on the emergence of the reciprocal SNARC/SSARC effect.

The CORE principle assumes that the SNARC/SSARC effect emerges because number/size and space have been experienced to be correlated in people's natural or cultural world and thus become associated in their mental representation (Pitt & Casasanto, 2020). In particular, the SNARC effect emerges because of experiences such as finger counting during which number and space are correlated whereas the SSARC effect emerges because of experiences such as grasping habits during which physical size and left/right hands are correlated (Pitt & Casasanto, 2020; Wühr et al., 2024). In terms of the HMMT, mental metaphors are created that employ space as a source domain to mentally represent numerical/physical size as a target domain (Casasanto, 2017; Casasanto & Bottini, 2014).

During finger counting, number and space are both varied on the stimulus as well as response level, which is why both dimensions should be mentally represented as being correlated regardless of being varied as a stimulus or response feature. The observed bidirectional and symmetrical SNARC effects with verbal stimuli and vocal responses are thus in line with the CORE principle. Contrarily, the strongly asymmetrical SNARC effects with physical instead of verbal location stimuli in the reciprocal SNARC task are at odds with the CORE principle. During grasping movements, physical size is varied as a stimulus feature whereas spatial location is varied as a response feature, which is why physical size and space should be associated in a unidirectional form in people's minds. The observed strongly asymmetrical SSARC effects with physical instead of verbal location stimuli in the reciprocal SSARC task are thus in line with the CORE principle. Contrarily, the observed bidirectional and symmetrical SSARC effects with verbal stimuli and vocal responses are at odds with the CORE principle.

The discrepancy between the observations and the principle's predictions might, however, be explained by the fact that "any experience should affect metaphorical mappings between any two conceptual domains" (Pitt & Casasanto, 2020, p. 1067). Therefore, apart from finger counting or grasping movements, other experiences such as language might affect the mental metaphors (Pitt & Casasanto, 2020; Wühr et al., 2024) and thus lead to the lacking reciprocal SNARC effect with non-verbal stimuli or to the emergence of a reciprocal SSARC effect with verbal stimuli. The CORE principle may additionally account for the observation that the regular SNARC/SSARC effect is independent of stimulus and response mode assuming that associations are stored in a modality-independent form regardless of the stimulus/response mode the correlation was experienced in. This has been hypothesized in the HMMT (Casasanto, 2017; Casasanto & Bottini, 2014) and already been observed in previous studies (Wühr et al., 2024). In contrast, the CORE principle cannot account for an effect of stimulus mode on the emergence of the reciprocal SSARC effect given that its emergence is at odds with the account's predictions in the first place. Moreover, it cannot provide any explanation why some associations but not others are stored in a modality-independent form, which would account for the effect of stimulus mode on the emergence of the reciprocal but not the regular SNARC effect.

Alternatively, the CORE principle might assume that merely the correlative relationship between two dimensions is mentally represented without specifying which dimension is situated on the stimulus or response level. This would lead to undirected associations in people's minds and predict bidirectional and symmetrical SNARC and SSARC effects. Another potential assumption that could be made is that an activation of the target domain necessarily activates the employed source domain, but an activation of the source domain does not activate any potential target domain, which would predict unidirectional or at least strongly asymmetrical SNARC and SSARC effects in the form of significant regular but non-significant reciprocal effects. None of these assumptions fit the complete pattern of results of the four studies, emphasizing the necessity to further develop the account by explicitly stating the account's predictions regarding bidirectionality.

Potential determinants of reciprocal effects

The series of experiments revealed that two factors contribute to the emergence of reciprocal effects: stimulus mode and inter-individual differences. The finding of a reciprocal SNARC/SSARC effect with verbal location stimuli but not with physical location stimuli implies that stimulus mode affects the emergence of reciprocal effects. In particular, verbal location stimuli seem to differ from physical location stimuli in some aspect(s) that is (are) crucial for the emergence of a reciprocal SNARC/SSARC effect. One potential explanation for the effect of stimulus mode resides in the overall higher RT level that has been observed with verbal compared to physical stimuli. Considering that the reciprocal SNARC/SSARC effect increases with increasing RTs, the overall higher RTs with verbal stimuli might have led to larger effects and thus might have mediated the effect of stimulus mode on the emergence of reciprocal effects.

Enhanced verbal-spatial coding constitutes a second potential explanation for the effect of stimulus mode. While verbal stimuli emphasize verbal-spatial coding, physical stimuli emphasize visual-spatial coding. In line with Gevers and colleagues (2010) who have shown that "verbal-spatial coding was the dominant factor in driving the SNARC effect" (p. 187), verbal-spatial coding might not only drive the regular SNARC – and potentially also SSARC – effect but might conversely also foster the emergence of a reciprocal SNARC and SSARC effect. In the same vein, the storage of stimuli in verbal working memory could also play a crucial role in eliciting reciprocal effects.

A third aspect, in which physical and verbal location stimuli differ, involves visual-spatial attention. While physical location stimuli direct attention to the left and right, verbal location stimuli allow attention to remain fixated at the screen center. In light of previous evidence suggesting that numbers can cause spatial shifts of attention given that magnitude itself is processed (Fischer et al., 2003; Shaki & Fischer, 2024) – a phenomenon that has been termed *attentional SNARC (att-SNARC) effect* (Fattorini et al., 2015) –, it seems surprising that, in the opposite direction, stimuli that do not require spatial shifts of attention allow for reciprocal effects but stimuli that require spatial shifts of attention do not[19]. However, the results of our studies provide evidence that the att-SNARC effect does not emerge in a reciprocal direction and, in other words, spatial shifts of attention do not prime corresponding numerical responses. For the SSARC effect, attentional effects in the regular direction remain to be tested.

A higher set-level compatibility (Kornblum et al., 1990) between verbal stimuli and vocal responses compared to physical stimuli and vocal responses might at first sight provide a fourth explanation for the effect of stimulus mode on the emergence of reciprocal effects. The higher set-level compatibility could not only explain the significant reciprocal effects with verbal stimuli and vocal responses but also the larger regular SSARC effect observed with this

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[19] Please note that even though verbal location stimuli do not require any spatial shifts of attention, spatial attention may be cued by explicit spatial words as demonstrated in spatial congruency effects (Shaki & Fischer, 2023a, 2023b)

stimulus and response combination. However, the overall higher RT level with verbal stimuli and vocal responses which was observed both in SNARC and SSARC studies as well as the observation of comparable regular SNARC effects with high and low set-level compatibility contradict this hypothesis.

Inter-individual differences constitute a second determinant of reciprocal effects. The results consistently showed a small reciprocal SNARC/SSARC effect with physical location stimuli which, however, disappeared when outlier datasets are excluded. Those effects cannot alone be explained by the time course of reciprocal effects indicating that a small subsample of participants with high RTs and/or error percentages shows reciprocal effects with non-verbal location stimuli which are not solely mediated by the higher RT level. Inter-individual differences thus seem to be another determinant of the emergence of reciprocal effects.

Limitations and future research

Certain limitations need to be taken into account when interpreting the studies' results. First, the samples were not balanced in terms of gender. With regards to the SNARC effect, previous evidence (Bull et al., 2013) suggests an effect of gender on the strength of associations between numerical size and space: Male participants seem to show a stronger SNARC effect than female participants. However, gender merely affects the size but not the emergence or the direction of the SNARC effect implying that male and female participants show similar spatial-numerical associations which merely differ in strength. Accordingly, there should be no reason to assume that the patterns of bidirectionality observed in the studies with non-balanced gender samples should qualitatively deviate from patterns of bidirectionality with balanced gender samples. A potential effect of gender so far has not been investigated with regards to the SSARC effect and should be addressed by future research. Since the proportion of male participants was consistently smaller than the proportion of female participants in both studies, it nevertheless seems unlikely that the differences between the patterns of bidirectionality in Studies 3 and 4 were caused by an effect of gender.

Second, the samples of the experiments were not restricted in terms of handedness. Since handedness does not affect the regular SNARC effect (Cipora et al., 2019; Dehaene et al., 1993), there should be no reason to assume that it in turn affects the reciprocal SNARC effect. Participants' handedness therefore should not be of any relevance in Studies 1 and 2. In contrast, handedness does affect the SSARC effect (Wühr et al., 2024) and should thus be taken into consideration when interpreting the results of Studies 3 and 4. In particular, right-handed participants show a stronger SSARC effect than left-handed participants. Importantly, however, handedness merely affects the size but not the emergence or the direction of the SSARC effect implying that left-handed and right-handed participants show similar SSARC effects which merely differ in strength. Even though the patterns of bidirectionality thus should not differ qualitatively between left- and right-handed samples, the experiments' results should mainly pertain for right-handed participants which constitute the majority of the sample and should be verified for left-handed participants in future research.

A third limitation bears on the shortcoming not to be able to differentiate between facilitation and inhibition processes which underlie the observed effects. According to dual-route models (Gevers et al., 2006; Kornblum et al., 1990; Proctor & Cho, 2006), compatibility effects arise due to an interplay of one controlled (conditional) and one automatic (unconditional) process of response identification. While the slow controlled process activates the required response according to the task-specific S-R mapping, the fast automatic process activates the response that corresponds to the stimulus on the basis of pre-existing associations due to dimensional overlap. In compatible trials, both processes identify the same required response which thus facilitates performance, whereas in incompatible trials, both processes identify different responses which thus impedes performance (Gevers et al., 2006; Kornblum et al., 1990; Proctor & Cho, 2006). Dual-route models therefore predict the involvement of both facilitation and inhibition processes in the emergence of compatibility effects. This has been affirmed for other correspondence effects such as the Simon effect (Umiltà et al., 1999, as cited in Ferraro et al., 2011; Wühr & Ansorge 2005) but remains to be tested for the SNARC and SSARC effect. The experiments reported in this dissertation did not involve a neutral condition that would have allowed to disentangle facilitation and inhibition processes. It therefore cannot be concluded either if the regular and reciprocal SNARC/SSARC effect emerged because the compatible mapping facilitates performance or because the incompatible mapping impedes performance or both.

Future research should address the underlying processes which contribute to the emergence of the reciprocal SNARC/SSARC effect. Since stimulus mode has been identified as one determinant of the emergence of reciprocal effects, future research should investigate which specific property of verbal location stimuli in contrast to physical location stimuli is responsible for the emergence of reciprocal effects. Potential candidates such as the involvement of RT level, verbal encoding, verbal WM and visual-spatial attention should be systematically varied to detect potential effects. In line with Gevers and colleagues (2010), in future research “special interest should be given to the role of language or verbal labeling of spatial information” (p. 188). As a second determinant of the emergence of reciprocal effects, inter-individual differences should also be further investigated.

7. Conclusion

The present dissertation investigated the bidirectionality and symmetry of associations between numerical and physical size on the one hand and space on the other hand as they emerge as S-R compatibility effects. Importantly, with verbal number/location stimuli and vocal location/number responses, the spatial-numerical associations which underlie the SNARC effect are bidirectional and symmetrical allowing for a regular and reciprocal SNARC effect of similar size. However, with numerosity or digit/physical location stimuli and manual or vocal location/number responses, the spatial-numerical associations are unidirectional or at least strongly asymmetrical and allow for the regular but not for the emergence of a reciprocal SNARC effect. Similarly, with verbal size/location stimuli and vocal location/size responses, the spatial-size associations which underlie the SSARC effect are bidirectional and symmetrical allowing for a regular and reciprocal SSARC effect of similar size. Contrarily, with physical size/location stimuli and vocal location/size responses, the spatial-size associations are unidirectional or at least strongly asymmetrical and allow for the regular but not for the emergence of a reciprocal SSARC effect. The discrepant patterns observed with verbal location stimuli and physical location stimuli in the reciprocal tasks, which were, however, consistent between the SNARC and the SSARC effect, reveal an effect of stimulus mode on the emergence of reciprocal effects. In particular, reciprocal effects emerged with verbal location but not with physical location stimuli, indicating some crucial feature of verbal location stimuli in eliciting reciprocal effects. Moreover, the results of the four studies contained in this dissertation entail important implications for the theoretical accounts of the SNARC/SSARC effect which not only need to explain the emergence of bidirectional and symmetrical SNARC/SSARC effects but also the effect of stimulus mode on the emergence of the reciprocal but not the regular SNARC/SSARC effect. So far, none of the theories can account for the complete set of findings without making additional assumptions thus underlining the necessity to develop and advance the current theoretical accounts.

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List of Articles and Declaration of Author Contributions

Article 1

Richter, M., & Wühr, P. (2023). Spatial-numerical associations of manual response codes are strongly asymmetrical. *Cognition*, *238*, 105538. https://doi.org/10.1016/j.cognition.2023.105538

Melanie Richter: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - Original Draft, Writing - Review and Editing.

Peter Wühr: Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing - Original draft, Writing - Review and Editing, Visualization, Project administration.

Article 2

Richter, M., & Wühr, P. (2024). The reciprocity of spatial-numerical associations of verbal response codes depends on stimulus mode. *Memory & Cognition*. https://doi.org/10.3758/s13421-023-01511-6

Melanie Richter: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review and Editing

Peter Wühr: Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing - Original Draft, Writing - Review and Editing, Visualization, Project administration

Article 3

Richter, M., & Wühr, P. (2023). Associations between physical size and space are strongly asymmetrical. *Scientific Reports*, *13*, 16256. https://doi.org/10.1038/s41598-023-43313-5

Melanie Richter: Conceptualization, Methodology, Software, Validation, Formal analysis, Data Curation, Writing - Original Draft, Writing - Review and Editing, Visualization

Peter Wühr: Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing - Original Draft, Writing - Review and Editing, Visualization, Project administration

Article 4

Richter, M., & Wühr, P. (2024). Verbal stimuli allow for symmetrical S-R priming effects between size and space. *PsyArXiv Preprints*. https://doi.org/10.31234/osf.io/baq7p

Melanie Richter: Conceptualization, Methodology, Software, Validation, Formal analysis, Data Curation, Writing - Original Draft, Writing - Review and Editing

Peter Wühr: Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing - Original Draft, Writing - Review and Editing, Visualization, Project administration

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Hiermit versichere ich schriftlich und eidesstattlich gemäß § 11 Abs. 2 PromO v. 08.02.2011/08.05.2013:

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3. Weiterhin erkläre ich schriftlich und eidesstattlich, dass mir der „Ratgeber zur Verhinderung von Plagiaten“ und die „Regeln guter wissenschaftlicher Praxis der Technischen Universität Dortmund“ bekannt und von mir in der vorgelegten Dissertation befolgt worden sind.

______________________________	______________________________
Ort, Datum	Unterschrift