Psychological Research
https://doi.org/10.1007/s00426-024-01990-5

RESEARCH

Different grasping experiences affect mapping effects but not correspondence effects between stimulus size and response location

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Received: 8 December 2023 / Accepted: 9 June 2024

Abstract

The so-called spatial-size association of response codes (SSARC) effect denotes that humans respond faster and more accurately with a left response to physically small stimuli and a right response to physically large stimuli, as compared to the opposite mapping. According to an application of the CORE principle to the SSARC effect, the habit to grasp larger/heavier objects with one's dominant hand and smaller/lighter objects with one's non-dominant hand creates spatial-size associations. We investigated if grasping habits play a causal role in the formation of spatial-size associations by testing if the mapping of a preceding object-grasping task affects the size of the SSARC effect in subsequent choice-response tasks with keypress responses. In the object-grasping task, participants were instructed to grasp wooden cubes of variable size either according to a compatible (small-left; large-right) or according to an incompatible (small-right; large-left) mapping. In the choice-response tasks, participants responded with left or right keypresses to the size or color of a small or large stimulus. The results showed that participants with the compatible mapping in the object-grasping task showed a larger SSARC effect in the size discrimination task, but not in the color discrimination task, than participants with the incompatible mapping in the object-grasping task. Results suggest that a short period of practice with different size-location mappings can modulate size-location links used for controlled S–R translation, but not links underlying automatic S–R translation. In general, the results support the hypothesis that grasping habits play a causal role in the formation of spatial-size associations.

Introduction

Stimulus–response (S–R) compatibility is a widely studied phenomenon in cognitive research because it provides insights into the selection and execution of human actions. S–R compatibility denotes the observation that certain elements of a stimulus set and certain elements of a response set "match" in so far that their assignment allows for better performance than the assignment of stimulus and response alternatives that do not match (Alluisi & Warm, 1990; Proctor & Vu, 2006). The difference between the performance (i.e., response speed and accuracy) in such a compatible and incompatible assignment is termed S–R compatibility effect. Compatibility effects therefore reveal associations between stimulus and response dimensions that underlie human actions, and thus provide valuable insights into human action control. The so-called spatial-size association of response codes (SSARC) effect, for example, constitutes a compatibility effect between physical stimulus size and horizontally aligned spatial response location. The effect refers to the phenomenon 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 (Ren et al., 2011; Weis et al., 2018; Wühr & Seegelke, 2018). The SSARC effect thus provides evidence for the existence of associations between the mental representations of physical size and space.

According to Kornblum et al., (1990; Kornblum and Lee, 1995), compatibility effects arise because of a dimensional overlap between stimulus and response sets which means that stimuli and responses involve the same or associated dimensions. This overlap might occur on a perceptual, conceptual or structural level. The spatial compatibility effect denotes that left (right) responses are faster and more accurate to left (right) stimuli as compared to the opposite mapping (Brebner, 1973; Fitts & Deininger, 1954). This effect

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constitutes a typical example of a compatibility effect due to perceptual overlap because the match or mismatch is clearly perceivable. While the spatial compatibility effect occurs when stimulus location is task-relevant, which is termed spatial S–R compatibility proper, the effect also occurs when stimulus location is task-irrelevant, which is referred to as the Simon effect (Simon & Rudell, 1967; see Proctor & Vu, 2006, for a review). In a typical Simon task, participants respond to stimulus color while stimulus location is varied as a task-irrelevant feature, leading to corresponding (left S–left R, right S–right R) and non-corresponding (left S–right R, right S–left R) trials.

To account for the observation that both relevant and irrelevant stimulus features can activate response alternatives, dual-route models have been proposed for various compatibility effects (Gevers et al., 2006; Kornblum et al., 1990; Proctor & Cho, 2006). According to the dual-route model by Kornblum et al., (1990; see also Zhang et al., 1999), two sources of delay contribute to the spatial compatibility proper and the Simon effect: one controlled and one automatic process of response identification. The controlled process identifies the correct response according to the S–R mapping instruction. If the mapping instruction is congruent with the dimensional overlap (i.e., left S–left R; right S–right R), participants can choose the correct response by using the homomorphism which is inherent in the (in this case perceptual) dimensional overlap. The response identification according to this so-called identity rule is assumed to be relatively fast. If the mapping instruction is incongruent with the dimensional overlap (i.e., left S–right R; right S–left R) and precludes the usage of the identity rule, participants need to apply a more complex and time-consuming rule or a memory search to identify the correct response. This controlled process is one source which contributes to the differences in response speed and accuracy between compatible and incompatible mapping instructions, i.e., to the spatial-compatibility proper effect (Kornblum et al., 1990; Zhang et al., 1999).

Moreover, in case of dimensional overlap between the relevant or irrelevant stimulus and the relevant response, the relevant or irrelevant stimulus feature automatically activates its corresponding response. If this automatically activated response is also the required correct response as in spatially compatible or corresponding trials, the response can be executed quickly because it was pre-activated. If the automatically activated response is the incorrect response as in spatially incompatible or non-corresponding trials, the automatically activated response needs to be aborted and replaced by the correct response before it is subsequently executed. Because the abortion and substitution process is time-consuming, this constitutes a second source of delay, which contributes to both compatibility and correspondence effects, i.e., the spatial-compatibility proper and the Simon effect (Kornblum et al., 1990; Zhang et al., 1999). While both the controlled and automatic process of response identification therefore contribute to the spatial compatibility proper effect, only the automatic process contributes to the Simon effect.

The Stroop effect constitutes a compatibility effect due to conceptual overlap. This effect indicates that naming the ink color of a color word stimulus is faster and more accurate if the ink color is congruent with the word color compared to if it is incongruent (MacLeod & MacDonald, 2000; Stroop, 1935). Here, the conceptual overlap consists in the shared conceptual dimension, namely color, between stimuli and responses. One example of a compatibility effect that relies on structural overlap is the aforementioned SSARC effect, which reveals associations between the mental representations of physical size and space. In case of structural overlap, stimuli and responses do not refer to the same perceptual or conceptual dimension but to different dimensions, such as size and space, which are correlated and associated due to their convergent internal structure.

Several studies have so far investigated which stimulus and response features contribute to the emergence of the SSARC effect. It has, for example, been shown that the SSARC effect emerges regardless of whether physical size is varied as a task-relevant or -irrelevant stimulus feature, indicating that physical size is automatically encoded and subsequently associated with spatial location (Wühr & Richter, 2022; Wühr & Seegelke, 2018). Moreover, the SSARC effect seems to be independent of response modality because it occurs with manual as well as with verbal responses (Wühr et al., 2024). The spatial-size associations, which underlie the effect, therefore do not seem to constitute direct associations between specific stimulus and response codes. Instead, they rather seem to have generalized across motor systems and formed modality-independent associations on an intermediate representational level. Wühr et al. (2024) also found evidence that functional differences between the hands, in particular handedness and the strength of effectors (fingers, hands), contribute to the origin of the SSARC effect.

Several theories have so far been proposed in order to account for the structural overlap between physical size and space and thus for SSARC effects. One of them is the correlations in experience (CORE) principle, which has originally been proposed by Pitt and Casasanto (2020) to account for the spatial-numerical association of response codes (SNARC) effect. The SNARC effect denotes faster and more accurate left responses to small(er) numbers and right responses to large(r) numbers as compared to the opposite mapping (Dehaene et al., 1990; Fischer & Shaki, 2014; Gevers & Lammertyn, 2005). To explain compatibility effects between an abstract domain and space, the CORE principle assumes that “people spatialize abstract domains in their minds according to the ways those domains are spatialized in their experience" (p. 1048). While, for instance, the habit of finger counting produces a distinct correlation between numbers and spatial positions, reading and writing do not produce a distinct correlation between numbers and spatial positions (Pitt & Casasanto, 2020). According to CORE, among those three experiences only finger counting should thus contribute to the formation of spatial-numerical associations with small numbers being associated with left positions and large numbers being associated with right positions.

In their study, Pitt and Casasanto (2020) conducted several experiments to test the predictions of the CORE principle in terms of spatial-numerical associations. In Experiment 1, they trained participants to read a normal or mirror-reversed English text before measuring the SNARC effect in a magnitude discrimination task. Participants, however, showed a similar SNARC effect regardless of the reading direction of the previous task. In Experiment 2, they trained participants in finger counting from left-to-right or from right-to-left before measuring the SNARC effect in a magnitude discrimination task, in which numerical size was task-relevant, and in a parity discrimination task, in which numerical size was task-irrelevant. In both discrimination tasks, Pitt and Casasanto (2020) observed that the rightward finger-counting routine gave rise to a standard SNARC effect, whereas the leftward finger-counting routine significantly weakened the SNARC effect. The observation that finger counting but not reading direction seems to play a causal role in shaping spatial-numerical associations thus supported the CORE principle.

Wühr et al. (2024) applied the CORE principle to also account for SSARC effects. Since most people are right-handed, and the dominant (right) hand is stronger than the non-dominant (left) hand, they hypothesized that people learn to grasp larger and heavier objects with their dominant (right) hand, and to grasp smaller and lighter objects with their non-dominant (left) hand. This functional difference in using the hands then creates and strengthens associations between small and left and between large and right, respectively. In their study, Wühr et al. (2024) provided evidence for their hypothesis. They observed that the SSARC effect was larger in right-handed than left-handed participants for both manual and verbal responses. They also found that participants' dominant effectors were stronger than their non-dominant effectors and that strength differences between the effectors were correlated with the size of the SSARC effect.

Despite providing evidence in favor of the CORE principle, these correlational results do not experimentally test the hypothesis that functional differences between the effectors create and strengthen spatial-size associations. In the present study, we aim to close this gap and investigate if grasping habits play a causal role in the formation of spatial-size associations. We employed a similar design as Pitt and Casasanto (2020) when they tested the influence of reading direction and finger counting onto spatial-numerical associations. More specifically, we trained participants to grasp objects according to a compatible (small-left; large-right) or according to an incompatible (small-right; large-left) mapping before measuring the SSARC effect in two subsequent choice-response tasks. As far as we know, this is the first study to test the predictions made by the CORE principle regarding the SSARC effect. If—in line with the CORE principle—grasping habits play a causal role in the formation of spatial-size associations, manipulating grasping habits in a preceding object-grasping task should influence the SSARC effect in the following SSARC task.

In the present study, we investigated if the mapping of a preceding object-grasping task affects the size of the SSARC effect in subsequent choice-response tasks with keypress responses. In the object-grasping task, participants were required to grasp wooden cubes of variable size and to sort them into two boxes. While one group of participants was instructed to grasp the cubes according to a compatible mapping, i.e., to grasp smaller cubes with the left and larger cubes with the right hand, the other group was instructed to grasp the cubes according to the opposite, incompatible mapping. After the object-grasping task, participants completed two choice-response tasks in which the SSARC effect was measured. Participants completed a size discrimination task with relevant stimulus size and a color discrimination task with irrelevant stimulus size. The object-grasping task was completed twice, once before the size discrimination task and once before the color discrimination task.

In both choice-response tasks, we expected to find the typical SSARC effect: we expected a significant mapping effect between stimulus size and response location in the size discrimination task and a significant correspondence effect between stimulus size and response location in the color discrimination task. If the mapping in the preceding object-grasping task affects the size of the SSARC effect in the size or color discrimination task, the group with the small-left/large-right mapping in the object-grasping task should show a larger SSARC effect in the discrimination task than the group of participants with the small-right/large-left mapping in the object-grasping task. This would provide first evidence that spatial-size associations can flexibly adapt to previous experiences such as grasping habits and may also transfer from one task to another pointing towards a causal role of such experiences in the formation of spatial-size associations.

We employed the size and the color discrimination task to measure the compatibility effect as well as the correspondence effect between stimulus size and response location, respectively. With this we aimed to determine which source of the SSARC effect is influenced by the previous manipulation of grasping habits. Recall that, according to dual-route models (Kornblum et al., 1990; Zhang et al., 1999), both the controlled and automatic process of response identification contribute to compatibility effects, whereas only the automatic process contributes to correspondence effects. In contrast to compatibility effects which rely on perceptual overlap, the SSARC effect relies on structural overlap, which precludes the use of an "identity rule" within the controlled process of response identification. Instead, we argue that the controlled response identification process contributes to the structural compatibility effect insofar as the compatible mapping rule (small S–left R; large S–right R) is more familiar and habitual than the incompatible mapping rule (small S–right R; large S–left R). This controlled practice effect contributes to the compatibility effect whereas the automatically activated spatial-size associations contribute to both the compatibility and correspondence effect.

Practice with the compatible mapping in the object-grasping task should increase both the mapping effect in the size discrimination task, and the correspondence effect in the color discrimination task. In the size discrimination task, previous practice with the compatible mapping in the object-grasping task might facilitate processing of the compatible mapping rule through the controlled route, and strengthen the "compatible" S–R associations that produce direct response activation through the automatic route. In the color discrimination task, practice with the compatible mapping might increase correspondence effects only by means of the latter mechanism. In contrast, practice with the incompatible mapping in the object-grasping task should decrease both the mapping effect in the size discrimination task, and the correspondence effect in the color discrimination task. In the size discrimination task, previous practice with the incompatible mapping in the object-grasping task might facilitate processing of the incompatible mapping rule through the controlled route, and/or weaken the "compatible" S–R associations that produce direct response activation. Both mechanisms could decrease mapping effects in the size discrimination task, whereas only the latter mechanism might decrease the correspondence effect in the color discrimination task.

If the mapping of the object-grasping task influences the SSARC effect in the size discrimination task only, this would imply that manipulating grasping habits solely affects the controlled response identification process of the subsequent SSARC task. If the mapping of the object-grasping task influences the SSARC effect in both the size and the color discrimination task to an equal extent, this would imply that manipulating grasping habits solely affects the automatic response identification process of the subsequent SSARC task. If the mapping of the object-grasping task influences the SSARC effect in the size discrimination task to a greater extent than in the color discrimination task, this would imply that manipulating grasping habits affects the controlled as well as the automatic response identification process of the subsequent SSARC task.

Methods

Participants

Previous studies have not only revealed a strong SSARC effect with a η_p^2 of 0.326 when size was a task-relevant stimulus feature but also a strong SSARC effect with a η_p^2 of 0.356 when size was a task-irrelevant stimulus feature (Wühr & Seegelke, 2018). Accordingly, a sample size of 30 participants would be required to detect a SSARC effect in a size or color discrimination task. Since we were, however, interested in a so far unknown 2 × 2 interaction effect between the mapping in a grasping task and the mapping/correspondence in a size/color discrimination task, we assumed an intermediate effect size of $\eta_p^2 = 0.10$. A power analysis revealed that a sample size of 74 participants is required to detect main effects of a two-level variable and 2 × 2 interactions of intermediate size (i.e., $\eta_p^2 = 0.10$) with acceptable power (1-beta = 0.80) at the standard 0.05 alpha error probability. We used the software MorePower (Campbell & Thompson, 2012) for conducting our power analysis. The study by Pitt and Casasanto (2020) which addressed a similar research question on the origin of the SNARC effect used a smaller sample size of 64 participants in a similar design. Importantly, post-hoc power analyses by Pitt and Casasanto (2020) revealed a power of above 80% with a sample size of 64 participants. Moreover, in a previous study by Pitt and Casasanto (2014), a similar training effect of finger-counting on the SNARC effect was observed with an even smaller sample of 32 participants. We therefore consider a sample size of 74 participants to be reasonable.

Seventy-five[1] volunteer students (60 female, 15 male) with a mean age of 23.15 years (*SD* = 3.77) participated in our experiment and received either course credit or a payment of 10 Euro in exchange. All participants reported to have normal or corrected-to-normal vision and normal color vision. According to self-report, 66 participants were right-handed, whereas the remaining nine participants were left-handed. Even though prior research has shown that handedness modulates the SSARC effect, we decided to include left-handed participants in our sample because handedness merely weakens but does not reverse the effect (Wühr et al., 2024). Volunteers gave their informed consent prior to participation and the local Ethics Committee at TU Dortmund

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[1] Please note that the original sample size was seventy-six but one data set (no. 73) was excluded because this participant had inadvertently been tested twice.

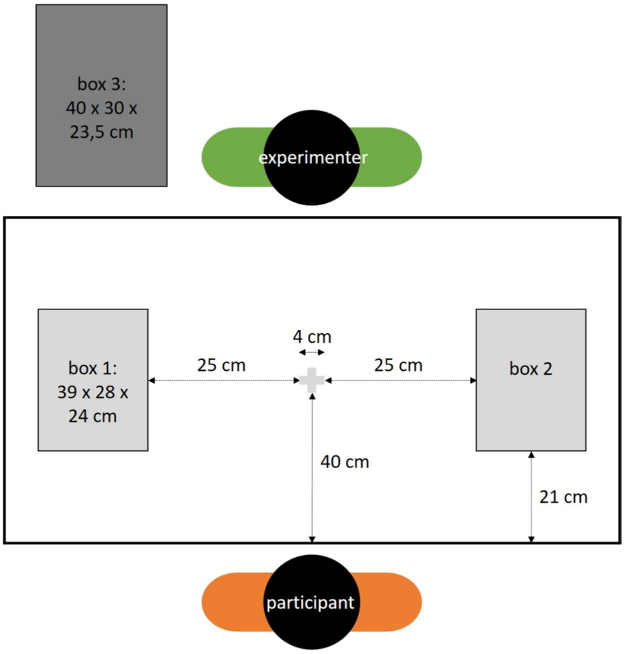

Fig. 1 Experimental setup of the object-grasping task (viewed from above)

University had approved the experimental protocol for our study (approval no. 2018-09).

Apparatus and stimuli

In the object-grasping task, participants sat centrally at a plain white table. Two non-transparent boxes (39 cm × 28 cm × 24 cm; boxes 1 and 2 in Fig. 1) without lid were placed within participants' reach, one at the left and the other at the right end of the table. The center of the table was marked with white tape. 120 wooden cubes of four sizes (2 cm, 3 cm, 4 cm, 5 cm side length)–that is, 30 cubes per size–served as imperative stimuli. The four different cubes weighed 5, 20, 40, and 85 g, respectively. The wooden cubes with a side length of 2 and 3 cm were classified as "small" whereas the wooden cubes with a side length of 4 and 5 cm were classified as "large". The participants responded by grasping them with their left or right hand and placing them into the box to their left or right side, respectively. The experimenter sat opposite the participant at the same table. A grey, non-transparent box (40 × 30 × 23.5 cm; box 3 in Fig. 1), which was partly covered by a grey lid, was placed at chair height to the experimenter's right side. At the beginning of each grasping task, the grey box contained all wooden cubes which were not visible from the participants' perspective. The experimental setup of the object-grasping task is depicted in Fig. 1.

In both choice-response tasks, participants sat in front of a customary 19 inch color monitor with a viewing distance of approximately 50 cm. We used the software EPrime 3.0 (Psychology Software Tools; Sharpsburg, PA, USA) to control the presentation of stimuli and register responses (i.e., key pressed, reaction time (RT)). All stimuli were presented on a grey (EPrime color: "silver") background. As a fixation point, a small plus sign (Courier font, size 18 pt) was presented in black at the screen center at the beginning of each trial. As imperative stimuli, one small (side length = 2.5 cm) and one large (side length = 4.5 cm) filled square were presented in red or green color at the screen center[2]. The size of the small/large stimulus was determined by taking the mean of the two small/large wooden cubes. Participants responded by pressing the left Control key or the right Enter key with the index fingers of their left and right hand, respectively. The keyboard was centrally aligned to participants' midline and fixed to the table. Both relevant keys were highlighted with white tape.

Procedure

Each participant completed three tasks: the object-grasping task, the size discrimination task and the color discrimination task. In the object-grasping task, the experimenter, who sat opposite to the participant, drew a wooden cube from her box and placed it in the middle of the table. The participants responded to the size (small or large) of the wooden cube by grasping it with the left or right hand and placing it into the corresponding left or right box. Participants completed the grasping-task according to either a compatible or an incompatible mapping. In the compatible mapping condition, participants responded to the small cubes (2 or 3 cm) by grasping them with their left hand and placing them in the left-side box and to the large cubes (4 or 5 cm) by grasping them with their right hand and placing them in the right-side box. In the incompatible mapping condition, participants responded to the small cubes (2 or 3 cm) by grasping them with their right hand and placing them in the right-side box and to the large cubes (4 or 5 cm) by grasping them with their left hand and placing them in the left-side box. In case of an error, the experimenter gave the verbal feedback "wrong" but the error was left uncorrected. The task consisted of 120 trials (4 sizes × 30 exemplars). After the participant had completed the task, the experimenter counted the errors made by checking the white boxes. For each participant, the number of errors was written down in a corresponding error list, which also served as a manipulation check. Participants completed the grasping task twice, once before (both mapping conditions of) the size discrimination

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[2] The size of the objects was slightly larger than in our previous studies, in which the small stimulus had a side length of 2 cm, and the large object had a side length of 4 cm (e.g., Wühr & Seegelke, 2018). Otherwise, the stimulus material and procedure matched those of our previous studies.

task and once before the color discrimination task. The relevant mapping of the grasping task varied between participants, but was consistent for each participant.

The size discrimination task consisted of two conditions: one compatible and one incompatible mapping condition. In the compatible mapping condition, participants responded to stimulus size by pressing the left key to the small stimulus and the right key to the large stimulus. In the incompatible mapping condition, participants responded to stimulus size by pressing the left key to the large stimulus and the right key to the small stimulus. Stimulus color (red, green) was additionally varied as an irrelevant feature to ensure consistency between both choice-response tasks. Participants completed both mapping conditions of the size discrimination task consecutively and the order of mappings (compatible or incompatible first) was counterbalanced between participants. In the color discrimination task, participants responded to stimulus color (red, green) while stimulus size was varied as an irrelevant stimulus feature thus resulting in corresponding (small-left; large-right) and non-corresponding (small-right; large-left) trials. The relevant mapping between color and response location was counterbalanced between participants. That is, half of participants pressed the left key to the green stimulus, and the right key to the red stimulus, whereas the other half of participants received the reverse mapping.

The experimental procedure was the same for both choice-response tasks. To inform participants about the content and the procedure of the following task or condition, instructions were presented at the beginning of each experimental program. Each program consisted of one training block containing 16 trials (2 sizes × 2 colors × 4 repetitions) and two experimental blocks containing 48 trials (2 sizes × 2 colors × 12 repetitions) each. Trials were randomized within blocks. A fixation point was presented at the beginning of each trial for 400 or 600 ms, with both durations occurring equally often within one block[3]. The imperative stimulus was then presented until a response was recorded or for a maximum of 2000 ms. After a correct response, an inter-trial interval with an empty screen was presented for 1000 ms whereas after an erroneous or missing response, a corresponding error message was presented during the inter-trial interval. 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 one.

The experiment took about 40–45 min. For each task or condition, the experimenter stayed in the laboratory for the practice block but left before participants started the experimental blocks. For each participant, the order of tasks was the following: object-grasping task–choice-response task–object-grasping task–choice-response task. The order of choice-response tasks (size or color discrimination task) was counterbalanced between participants.

Design and data analysis

For both choice-response tasks (size and color discrimination task), the experimental design was a two-factorial (Mapping in grasping task × Mapping/Correspondence in choice response task) mixed design. The factor Mapping in grasping task was varied between-subjects and had two levels: a compatible mapping (small-left, large-right) and an incompatible mapping (small-right, large-left). The factor Mapping/Correspondence in choice response task was varied within-subjects and also had two levels: a compatible mapping (small-left, large-right) and an incompatible mapping (small-right, large-left) in the size discrimination task or a corresponding condition (small-left, large-right) and a non-corresponding condition (small-right, large-left) in the color discrimination task. Reaction Times (RTs) of correct keypress responses and error percentages of both choice-response tasks served as dependent variables.

With a two-way ANOVA, we planned to investigate the impact of the two independent variables (Mapping in grasping task, Mapping in size discrimination task) on the dependent variables (i.e., RTs, error percentages) of the size discrimination task. With a two-way ANOVA, we planned to investigate the impact of the two independent variables (Mapping in grasping task, Correspondence in color discrimination task) on the dependent variables (i.e., RTs, error percentages) of the color discrimination task. In case of significant two-way interactions, we planned to conduct pairwise comparisons (t tests if the normality assumption was fulfilled, non-parametric tests if the normality assumption was violated) to determine the source of the interactions. For each pairwise comparison, we planned to additionally report the Bayes Factor (BF; Rouder et al., 2009). We use the term BF_{+0}, also known as BF_{10}, to indicate evidence for the alternative hypothesis H1 over the null hypothesis H0 and the term BF_{0+}, also known as BF_{01}, to indicate evidence for the null hypothesis H0 over the alternative hypothesis H1. We planned to interpret the BF values according to the evidence categories provided by Jeffreys (1961, as cited in Lee & Wagenmakers, 2014), who classifies 1–3 as anecdotal evidence, 3–10 as moderate evidence, 10–30 as strong evidence, 30–100 as very strong evidence, and values above 100 as extreme evidence. Since participants completed the size discrimination task according to a compatible and incompatible mapping, one of both mapping conditions might work against the previous manipulation of grasping experiences in the object-grasping task. We therefore

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[3] We varied the duration of the fixation point, to keep participants more alert, and to avoid that participants responded in a constant rhythm.

conducted an exploratory analysis to additionally investigate the impact of Task order (size or color discrimination task first).

Results

Data trimming

On a participant level, we followed a suggestion by Tukey (1977), and excluded cases whose RTs or error rates were above Q_{75}+1.5*IQR. The exclusion criteria were applied in a task-specific manner, that is for each task separately. We excluded six participants when analyzing the impact of the grasping task on performance in the size discrimination task: three participants (#31, 33, 65) were excluded because of long RTs (mean RTs > 550 ms), and three participants (#28, 38, 75) were excluded because of high error rates (error percentages > 10%). The remaining sample included 69 participants, with 33 participants (7 males, 26 females, average age = 22.85 years, 30 right-handers) in the condition with a compatible mapping in the grasping task, and 36 participants (6 males, 30 females, average age = 23.53 years, 30 right-handers) with an incompatible mapping in the grasping task.

We also excluded six participants when analyzing the impact of the grasping task on performance in the color discrimination task: three participants (#15, 17, 48) were excluded because of a high number of errors in the grasping task (all errors > 10), and three participants (#18, 65, 75) were excluded because of long RTs (mean RTs > 550 ms). The remaining sample included 69 participants, with 33 participants (9 males, 24 females, average age = 23.09 years, 30 right-handers) in the condition with a compatible mapping in the grasping task, and 36 participants (6 males, 30 females, average age = 23.33 years, 31 right-handers) with an incompatible mapping in the grasping task.

On a trial level, we excluded trials with RTs below 100 ms or above 1500 ms as well as the first trial in each block from data analysis. In less than 1% of trials in both the size ($M < 0.01\%$, $SD = 0.09$) and color discrimination task ($M < 0.01\%$, $SD < 0.01$), participants' responses were too fast (i.e., RT < 100 ms). Likewise, in less than 1% of trials in both the size ($M = 0.02\%$, $SD = 0.20$) and color discrimination task ($M = 0.02\%$, $SD = 0.18$) participants' responses were too slow (i.e., RT > 1500 ms).

Size discrimination task

Reaction times (RTs)

A two-factorial ANOVA, with Mapping in size discrimination task as within-subjects factor and Mapping in grasping task as between-subjects factor, revealed a significant main effect and a significant two-way interaction. The significant main effect of Mapping in size discrimination task, $F(1, 67) = 31.364$, $MSE = 718.183$, $p < 0.001$, $\eta_p^2 = 0.319$, indicated shorter RTs in the compatible ($M = 392$ ms, $SD = 40$) than in the incompatible mapping ($M = 418$ ms, $SD = 50$). The main effect of Mapping in grasping task was not significant, $F(1, 67) = 1.922$, $MSE = 3{,}345.201$, $p = .170$, $\eta_p^2 = 0.028$. Crucially, however, the significant two-way interaction, $F(1, 67) = 6.027$, $MSE = 718.183$, $p = 0.017$, $\eta_p^2 = 0.083$, revealed a weaker mapping effect in the size discrimination task for the group that completed the grasping task with an incompatible mapping compared to the group with a compatible mapping in the grasping task.

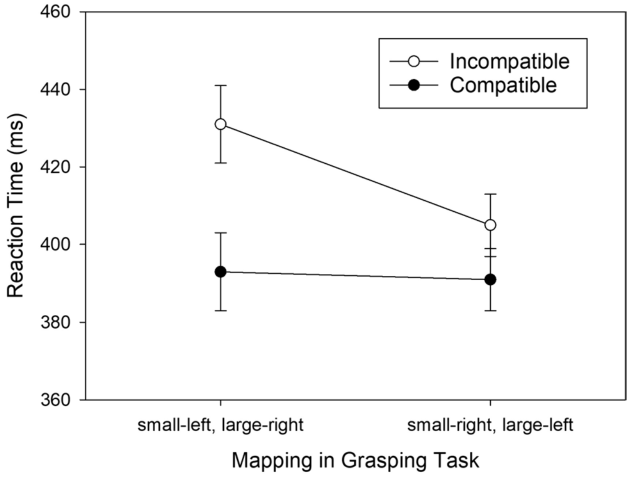

Fig. 2 RTs of correct responses as a function of mapping in the grasping task and mapping in the size discrimination task. Error bars reflect 95% confidence intervals for within-subjects designs (Cousineau, 2017)

To determine the source of the two-way interaction, we conducted pairwise comparisons between the compatible and incompatible mapping for each grasping task group. The group that completed the grasping task with a compatible mapping showed significantly shorter RTs in the compatible than in the incompatible condition in the size discrimination task, $t(32) = -4.646$, $p < 0.001$, $d = -0.809$, $BF_{+0} = 434.115$, revealing a SSARC effect of 37 ms (Fig. 2) and extreme evidence for the mapping effect in the regular direction. The group that completed the grasping task with an incompatible mapping also showed significantly shorter RTs in the compatible than in the incompatible condition in the size discrimination task, $W(35) = 133.000$, $p = 0.001$, $r_{rb} = -0.601$, $BF_{+0} = 6.813$, revealing a SSARC effect of 13 (Fig. 2), and moderate evidence for the mapping effect in the regular direction.

Table 1 Error percentages (with standard deviations) as a function of mapping in the grasping task and mapping in the size discrimination task

	Mapping in size-discrimination task	
	Small-left, large-right	Small-right, large-left
Mapping in grasping task		
Small-left, large-right	2.10 (2.20)	3.04 (2.75)
Small-right, large-left	2.19 (1.67)	2.99 (2.84)

Error percentages

Overall, errors were rare ($M = 2.58$, $SD = 1.87$) in this task. Moreover, across conditions, errors and RTs were not correlated ($r = -0.032$, $p = 0.794$), providing no hint of a speed-accuracy tradeoff. A two-factorial ANOVA, with Mapping in size discrimination task as within-subjects factor and Mapping in grasping task as between-subjects factor, revealed a significant main effect of Mapping in size discrimination task, $F(1, 67) = 5.856$, $MSE = 4.453$, $p = .018$, $\eta_p^2 = 0.033$, which indicated fewer errors in the compatible ($M = 2.14$, $SD = 1.93$) than in the incompatible mapping ($M = 3.01$, $SD = 2.78$). The main effect of Mapping in grasping task, $F(1, 67) = 0.002$, $MSE = 7.130$, $p = 0.967$, $\eta_p^2 < 0.001$, and the two-way interaction, $F(1, 67) = 0.040$, $MSE = 4.453$, $p = .841$, $\eta_p^2 < .001$, were not significant. The cell means are shown in Table 1.

Impact of task order

As exploratory analysis, we conducted a three-way ANOVA with Mapping in size discrimination task as within-subjects factor as well as Mapping in grasping task and Task Order (i.e., choice-response task with relevant or irrelevant size first) as between-subjects factor. The analysis revealed that none of the interactions involving the variable Task Order was significant for RTs or error percentage. A more detailed description of these results can be found in the Appendix.

Color discrimination task

Reaction times (RTs)

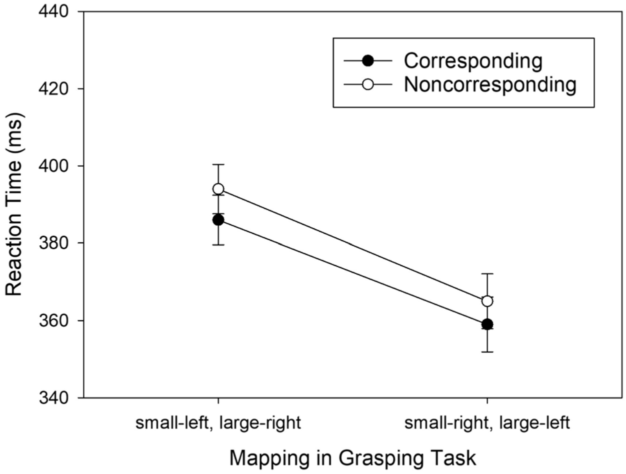

Fig. 3 RTs of correct responses as a function of mapping in the grasping task and correspondence in the color discrimination task. Error bars reflect 95% confidence intervals for within-subjects designs (Cousineau, 2017)

Table 2 Error percentages (with standard deviations) as a function of mapping in the grasping task and S–R correspondence in the color discrimination task.

	S–R correspondence	
	Corresponding	Non-corresponding
Mapping in grasping task		
Small-left, large-right	2.20 (2.17)	2.45 (2.78)
Small-right, large-left	1.72 (2.36)	2.05 (2.64)

A two-factorial ANOVA, with Correspondence in color discrimination task as within-subjects factor and Mapping in grasping task as between-subjects factor, revealed two significant main effects. The significant main effect of Correspondence in color discrimination task, $F(1, 67) = 5.022$, $MSE = 295.317$, $p = 0.028$, $\eta_p^2 = 0.070$, indicated shorter RTs in the corresponding ($M = 373$ ms, $SD = 44$) than in the non-corresponding condition ($M = 379$ ms, $SD = 48$). The significant main effect of Mapping in grasping task, $F(1, 67) = 7.512$, $MSE = 3623.992$, $p = 0.008$, $\eta_p^2 = 101$, indicated that participants with an incompatible mapping in the grasping task showed shorter RTs in the color discrimination task ($M = 362$ ms, $SD = 34$) than participants with a compatible mapping ($M = 390$ ms, $SD = 50$). The two-way interaction, $F(1, 67) = 0.129$, $MSE = 295.317$, $p = 0.720$, $\eta_p^2 = 0.002$, was, however, not significant. The cell means are shown in Fig. 3.

Error percentages

Similar to the size discrimination task, errors were rare ($M = 2.11$, $SD = 1.09$) and not correlated with RTs ($r = 0.063$, $p = 0.606$) in the color discrimination task. Hence, there was no hint of a speed-accuracy tradeoff. A two-factorial ANOVA, with Correspondence in color discrimination task as within-subjects factor and Mapping in grasping task as between-subjects factor, revealed no significant effects, all $Fs(1, 67) < 1.0$, all $ps > 0.30$. The cell means are shown in Table 2.

Impact of task order

A three-way ANOVA with Correspondence in color discrimination task as within-subjects factor as well as Mapping in grasping task and Task Order (i.e., choice-response task with relevant or irrelevant size first) as between-subjects factor revealed that none of the interactions involving the variable Task Order was significant for RTs or error percentages. A more detailed description of these results can be found in the Appendix.

Grasping task

In a final analysis, we compared the mean number of sorting errors in the manual grasping task between the two conditions (i.e., S–R mappings) in that task. In the grasping task that preceded the size discrimination task, the number of errors did not differ significantly between the two mapping conditions, $U = 571$, $p = 0.743$, $\mathrm{r}_{\mathrm{bis}} = 0.039$. The correlation between the number of errors in the grasping task (across mapping conditions) and the mapping effect in the size discrimination task was positive, but not significant ($r = 0.181$, $p = 0.137$). Similarly, in the grasping task that preceded the color discrimination task, the number of errors did not differ significantly between the two mapping conditions, $U = 519$, $p = 0.119$, $r_{bis} = 0.198$. The correlation between the number of errors in the grasping task (across mapping conditions) and the congruency effect in the color discrimination task was positive, but not significant ($r = 0.153$, $p = 0.210$).

Discussion

In the present study, we investigated if the size of the SSARC effect can be modulated experimentally by preceding experiences. In particular, we investigated if the mapping of a preceding object-grasping task affected the size of the SSARC effect in subsequent choice-response tasks. By manipulating the mapping in the object-grasping task we also experimentally tested our hypothesis that it is the habit to grasp larger and heavier objects with the dominant (right) hand and to grasp smaller (and lighter) objects with the non-dominant (left) hand that contributes to the emergence of the SSARC effect. As expected, we observed the typical SSARC effect in both choice-response tasks. We observed a significant mapping effect between stimulus size and response location for RTs and error percentages in the size discrimination task and a significant correspondence effect between stimulus size and response location for RTs in the color discrimination task. Left responses to small stimuli and right responses to large stimuli were faster (and more accurate) than left responses to large stimuli and right responses to small stimuli. These mapping and correspondence effects replicate the results of previous studies (e.g., Wühr & Seegelke, 2018). The observation that the mapping effect occurred both in RTs and in error percentages, whereas the correspondence effect occurred in RTs only, most likely reflects the fact that size is a relevant stimulus feature in the former task, but not in the latter, and relevant stimulus features have stronger effects than irrelevant stimulus features.

The most important finding was, however, that for RTs, the mapping in the preceding object-grasping task affected the size of the SSARC effect in the size discrimination task. The group with the small-left/large-right mapping in the object-grasping task showed a larger SSARC effect in the size discrimination task than the group of participants with the small-right/large-left mapping in the object-grasping task[4]. Our observation that manipulating grasping habits in a preceding object-grasping task influenced the SSARC effect in the following SSARC task thus revealed three notable insights. Firstly, spatial-size associations seem to be malleable by current experiences such as grasping activities, which demonstrates the flexibility of spatial-size associations. Secondly, activated spatial-size associations seem to be transferable from one task to another. Thirdly, grasping habits seem to play a causal role in the formation of spatial-size associations.

We employed a size and a color discrimination task to determine which source of the SSARC effect is influenced by the previous manipulation of grasping habits. While, according to dual-route models (Kornblum et al., 1990; Zhang et al., 1999), both the controlled and automatic process of response identification can contribute to mapping effects, only the automatic process contributes to correspondence effects. Our observation that the mapping in the object-grasping task affected the SSARC effect in the size discrimination task, whereas it did not affect the SSARC effect in the color discrimination task thus implies that manipulating grasping habits affected the controlled response identification process of the subsequent SSARC task but not the automatic response identification process.

The controlled process identifies the correct response according to the S–R mapping instruction which can either be compatible or incompatible with the dimensional overlap (Kornblum et al., 1990; Zhang et al., 1999). While employing a compatible mapping rule (small S–left R;

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[4] Please note that, in both choice-response tasks, task order affected neither any main effects nor interactions, which indicates that completing the size discrimination task according to a mapping contrary to the mapping in the object-grasping task did not diminish the previous manipulation.

large S–right R) is more familiar and habitual for participants, employing an incompatible mapping rule (small S–right R; large S–left R) is more complex and time-consuming. This controlled practice effect contributes to the compatibility effect in the size discrimination task. The finding that the group with the incompatible mapping in the object-grasping task showed a weaker SSARC effect than the group with the compatible mapping demonstrates that the incompatible mapping becomes more familiar and habitual for participants after they have practiced it, which in turn leads to a reduced compatibility effect. In contrast, the automatic activation of the corresponding response due to the dimensional overlap between the (relevant or irrelevant) stimulus size and response location is not affected by the previous manipulation of grasping habits. Manipulating grasping habits neither reduces its automatic activation nor does it improve its abortion and subsequent substitution by the correct response. Contrary to the controlled response identification process, the automatic response identification process therefore still contributes to the compatibility and the correspondence effect in the size and color discrimination task in its usual way.

The fact that the automatic response identification process still contributes to the compatibility effect might also explain why the SSARC effect was weakened but not reversed in the size discrimination task. Even though the group of participants with an incompatible mapping in the preceding object-grasping task showed a significantly weaker SSARC effect in the size discrimination task than the group of participants with a compatible mapping in the object-grasping task, both groups still showed a regular SSARC effect. The fact that the SSARC effect did not reverse for the group that was previously trained to grasp objects according to an incompatible mapping, indicates that automatically activated spatial-size associations are quite stable. Such spatial-size associations might either be well-established because grasping habits themselves are automated or because other factors also contribute to the origin of spatial-size associations. We do not want to claim that grasping habits are the only factor contributing to the formation of spatial-size associations. Rather, we aimed to show that grasping habits are one factor playing a causal role in the emergence of the SSARC effect. Demonstrating that a short training phase of approximately 10 min suffices to weaken the SSARC effect despite the lifelong formation of participants' usual grasping habits provides evidence in favor of this hypothesis. The assumption that other factors might nevertheless also play a causal role is in line with the study by Wühr et al. (2024) who showed that handedness and effector strength modulate but do not reverse the SSARC effect. The authors concluded "that other variables, beyond handedness and effector strength, also contribute to the origin and/or the size of SSARC effect" (p. 274).

Our account of the origin of associations that underlie the SSARC effect resonates with the CORE principle, which is part of hierarchical mental-metaphors theory (HMMT), proposed by Pitt and Casasanto (2020). HMMT and CORE provide an explanation for the origin of associations between apparently unrelated dimensions such as numerical or physical size on the one hand, and spatial (i.e., horizontal) location on the other hand. According to CORE (Pitt & Casasanto, 2020), people register and store systematic correlations between physical size and location, or between numerical size and location, in their experience. Repeated experience of these correlations may lead to the formation of associations between "small" and "left", and "large" and "right", or between "soon" and "near", and "late" and "far (away)". Having established these correlations, people may later start to think of, and describe, states of one dimension (e.g., time or number) in terms of the other dimension (e.g., space), for example, when saying "the time is near" or "the battery is low". In these cases, the more concrete dimension has become a mental metaphor for the more abstract dimension.

We believe that the experience of a correlation between physical size and hand or location has led to the formation of the associations that underlie the SSARC effect, as proposed by the CORE principle. In particular, we hypothesized that it is the people's habit to grasp larger and heavier objects with their dominant hand, and to grasp smaller and lighter objects with their non-dominant hand that determines how people spatialize physical size thus creating associations between small and left and between large and right, respectively (Wühr et al., 2024). Wühr et al. (2024) provided first evidence in favor of this hypothesis by showing that the SSARC effect was larger in right-handed than left-handed participants and that strength differences between the dominant and non-dominant effectors were correlated with the size of the SSARC effect. The present study extends this evidence and shows that manipulating grasping habits in a preceding object-grasping task influences the SSARC effect in a subsequent SSARC task. The experimental evidence that grasping habits play a causal role in shaping spatial-size associations therefore corroborates the CORE principle. Note, however, that we do not wish to claim that space or location serves as a mental metaphor for physical size.

The results of our study are in line with the findings of Pitt and Casasanto (2020) who showed that finger counting but not reading direction seems to play a causal role in the formation of spatial-numerical associations, thereby also supporting the CORE principle. Interestingly, in their study, previous finger counting experience did not only influence the SNARC effect in a magnitude discrimination task, in which number was task-relevant, but also in a parity discrimination task, in which number was task-irrelevant.

Following dual-route models, manipulating finger counting habits affected both the controlled and the automatic response identification process of the subsequent SNARC task (Kornblum et al., 1990; Zhang et al., 1999). This finding deviates from the SSARC effect for which we found that manipulating grasping habits affected only the controlled response identification process. In contrast to the automatic spatial-size associations, which seem to be rather stable, the automatic spatial-numerical associations thus seem to be modifiable more easily (e.g., Bächtold et al., 2008; Fischer et al., 2010). However, it is possible that finger-counting practice in the study of Pitt & Casasanto, (2020) was more effective, as compared to grasping practice in our study, and therefore increasing the extent of grasping practice might affect the automatically activated spatial-size associations.

We observed that the mapping in the grasping task affected the size of the SSARC effect in the size discrimination task. However, since there was no neutral condition in the grasping task, it cannot be clearly determined if the SSARC effect in the size discrimination task was reduced by a prior incompatible assignment in the object-grasping task or if it was increased by a prior compatible assignment in the object-grasping task. Yet, a qualitative comparison between the size of the SSARC effect in previous studies and in the present experiment rather points towards a reduction of the SSARC effect due to having experienced an incompatible mapping before: while previous studies have reported effect sizes of 29 ms (*SD* = 44; Wühr & Seegelke, 2018), 40 ms (*SD* = 55; Seegelke et al., 2023), and 48 ms (*SD* = 70; Wühr et al., 2024), in the present study, we observed a SSARC effect of 38 ms after a compatible mapping in the grasping task, but a SSARC effect of only 13 ms after an incompatible mapping in the grasping task[5].

Limitations and suggestions for future research

A first issue concerns performance in the object-grasping task. In this task, one group of participants sorted wooden cubes according to a compatible rule (put small objects in the left box with the left hand, and put large objects in the right box with the right hand), whereas another group of participants sorted wooden objects according to an incompatible rule (put large objects in the left box with the left hand, and put small objects in the right box with the right hand). Since similar mappings affect performance in choice-response tasks (e.g., Wühr & Seegelke, 2018), one could have expected an effect of mapping on performance in the grasping task as well. However, error rates did not significantly differ between the groups. A possible reason for the absence of a (significant) mapping effect in errors in the object-grasping task is that participants did not perform this task with explicit time pressure. It seems clear that, without time pressure, errors are less frequent, and performance is less affected by the S–R mapping, than in a task with time pressure. It would be interesting to see how time pressure in the object-grasping task might affect performance both in this task and in the two choice-response tasks.

Previous research has shown that the presence of an observer can affect the behavior of participants (e.g., Belletier et al., 2015; Bond & Titus, 1983; Zajonc, 1965). Hence, it is possible that the presence of the experimenter, who also observed participant's performance, affected behavior in the object-grasping task. For example, it is possible that participants chose a more conservative speed-accuracy criterion in the presence of the experimenter, as compared to when working alone. A more conservative speed-accuracy tradeoff should decrease the number of errors, which could also explain why we did not observe a significant mapping effect in the object-grasping task. Yet, the presence of the experimenter cannot have affected performance in the two mapping conditions differently, because each of the two experimenters tested equal numbers of participants in both conditions (groups).

A final issue concerns an unexpected main effect of the grasping-task mapping on performance (RTs) in the color discrimination task, where the group with the incompatible mapping had shorter RTs than the group with the incompatible mapping. A similar, although non-significant, difference was observed in the grasping task, where the incompatible-mapping group made fewer errors than the compatible-mapping group. Together, these results suggest that the group with the incompatible mapping in the grasping task was generally faster and more accurate than the group with the compatible mapping in this task. Although we know from previous studies that the size of the SSARC effect increases with RT (cf. Heuer et al., 2023), we do not think that RT differences between groups affected our results in problematic ways. First, there was no significant group difference (i.e., main effect of grasping-task mapping) in the size discrimination task, where we observed an impact of the grasping-task mapping on the mapping in the size discrimination task. Second, although there was a significant main effect of the grasping-task mapping in the color discrimination task, the group difference in RTs should have increased, rather than decreased, the expected interaction. Nevertheless, future research should be sensitive to such

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[5] In an exploratory analysis, we compared the size of the SSARC effects after a grasping task with compatible or incompatible mapping with the size of the SSARC effect without a preceding grasping task (Seegelke et al., 2023, Experiment 1, parallel-arms condition). We observed a significant reduction of the SSARC effect after an incompatible mapping in the grasping task relative to the condition without grasping task, $t(172) = 2.609$, $p = .010$, $d = 0.497$, but no difference between the SSARC effect after a compatible mapping in the grasping task relative to the condition without grasping task, $t(172) = 0.244$, $p = .808$, $d = 0.047$.

group differences in performance that might increase or decrease the effects of interest.

The role of strength differences between hands

One of the reviewers argued that the SSARC effect might not be due to different grasping habits of the two hands, but to the online evaluation of the force of the hands. According to this account, the participants know that they have more power in their right (dominant) hand than in their left (non-dominant) hand, and therefore associate each hand to a corresponding size. The main difference to our account is that, on our account, strength differences between dominant and non-dominant hands were initially important for developing different grasping habits of the two hands. Yet, after years of practice, the associations between small-left and large-right have become the driving force behind the SSARC effect, whereas strength (difference) has lost a direct impact. According to the alternative account, when using the two hands for responding, each hand is associated with a strength tag that, in turn, is associated with a corresponding size tag. According to this alternative account, the grasping task in our experiment should have little effect on the hand-strength-size associations because the grasping task most likely did not change the force of the two hands to a significant degree. Hence, the failure to observe an effect of the mapping in the grasping task on the size of the SSARC effect in the color discrimination task might be seen as consistent with this alternative account.

On the other hand, however, the observed effect of the mapping in the grasping task on the size of the SSARC effect in the size discrimination task could be seen as inconsistent with the alternative account. Moreover, an account assuming that the activation of strength differences between hands or responses plays an important role for the SSARC effect also has difficulties with explaining the observation of the SSARC effect in vocal responses (e.g., Wühr et al., 2024). Nevertheless, at present, we cannot fully rule out the possibility that the response categories "left" and "right" activate different force codes that are in turn associated with different size codes, and may therefore play a role in the generation of the SSARC effect.

Conclusion

Our study revealed that manipulating grasping habits in a preceding object-grasping task affected the SSARC effect in a following SSARC task. In particular, a short period of practice with different size-location mappings modulated size-location links used for controlled S–R translation, but not links underlying automatic S–R translation. This supports several conclusions. Firstly, spatial-size associations seem to be modifiable by current experiences such as grasping activities, which demonstrates the flexibility and adaptability of spatial-size associations. Secondly, if spatial-size associations are once activated, they seem to be transferable from one task to another. Thirdly, grasping habits seem to play a causal role in the formation of spatial-size associations thus supporting the CORE principle (Pitt & Casasanto, 2020) and its application to the SSARC effect by Wühr et al. (2024).

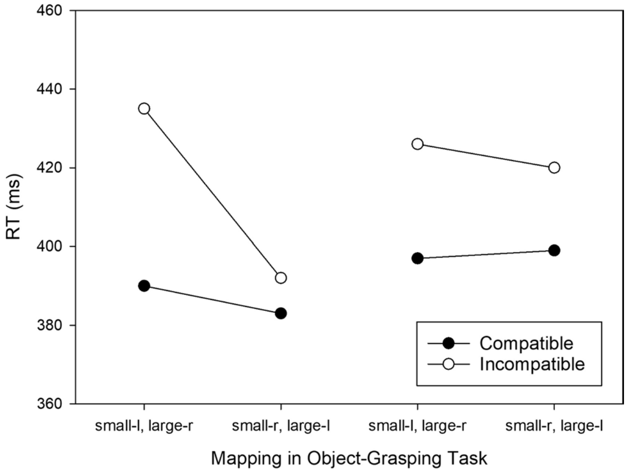

Fig. 4 RTs observed in the size-discrimination task as a function of mapping in the preceding grasping task, mapping in the size-discrimination task, and task order (left: size-discrimination task first, right: size-discrimination task second).

Appendix

Impact of task order on performance in the size discrimination task

We first conducted a three-way ANOVA with Mapping in size discrimination task as within-subjects factor, Mapping in grasping task and Task Order (i.e., choice-response task with relevant or irrelevant size first) as between-subjects factors, and RT as dependent variable. The two-way interactions of Task Order with Mapping in grasping task, $F(1, 65) = 1.336$, $MSE = 3{,}317.335$, $p = 0.252$, $\eta^2_p = 0.020$, and with Mapping in size discrimination task, $F(1, 65) = 0.096$, $MSE = 714.788$, $p = 0.758$, $\eta^2_p = 0.001$, were not significant. Similarly, the three-way interaction was non-significant, too, $F(1, 65) = 2.258$, $MSE = 714.788$, $p = 0.138$, $\eta^2_p = 0.034$. The marginal means of this analysis are shown in Fig. 4.

Next, we conducted a three-way ANOVA with error percentages as dependent variable. Again, the two-way interactions of Task Order with Mapping in grasping task, $F(1, 65) = 0.034$, $MSE = 7.245$, $p = 0.854$, $\eta^2_p = 0.001$, and with Mapping in size discrimination task, $F(1, 65) = 0.538$,

Table 3 Error percentages observed in the size-discrimination task as a function of mapping in the grasping task, mapping in the size-discrimination task, and task order

Order	Mapping in grasping task	Mapping in size-discrimination task	
		Compatible	Incompatible
Size-discrimination task first	Small-left, large-right	2.194	2.604
	Small-right, large-left	1.960	2.744
Size-discrimination task second	Small-left, large-right	2.003	3.447
	Small-right, large-left	2.441	3.254

$MSE = 4.522$, $p = 0.466$, $\eta^2_p = 0.008$, were not significant. Similarly, the three-way interaction was non-significant, too, $F(1, 65) = 0.479$, $MSE = 4.522$, $p = 0.491$, $\eta^2_p = 0.007$. The marginal means of this analysis are shown in Table 3.

Impact of task order on performance in the color discrimination task

We conducted a three-way ANOVA with S–R correspondence in color discrimination task as within-subjects factor, Mapping in grasping task and Task Order (i.e., choice-response task with relevant or irrelevant size first) as between-subjects factors, and *RT* as dependent variable. The two-way interactions of Task Order with Mapping in grasping task, $F(1, 65) = 0.143$, $MSE = 3{,}678.726$, $p = .707$, $\eta^2_p = .002$, and with Correspondence in color discrimination task, $F(1, 65) = 0.060$, $MSE = 304.115$, $p = .807$, $\eta^2_p = .001$, were not significant. Similarly, the three-way interaction was non-significant, too, $F(1, 65) = 0.002$, $MSE = 304.115$, $p = .962$, $\eta^2_p < .001$. The marginal means of this analysis are shown in Fig. 5.

Finally, we conducted a three-way ANOVA with error percentages as dependent variable. Again, the two-way interactions of Task Order with Mapping in grasping task, $F\ (1, 65) = 0.009$, $MSE = 7.675$, $p = .923$, $\eta^2_p < .001$, and with Correspondence in color discrimination task, $F\ (1, 65) = 2.451$, $MSE = 4.743$, $p = .122$, $\eta^2_p = .036$, were not significant. Similarly, the three-way interaction was non-significant, too, $F(1, 65) = 3.812$, $MSE = 4.743$, $p = .055$, $\eta^2_p = .055$. The almost significant three-way interaction reflects the fact that, when the color discrimination task was performed second, the SSARC effect was larger with a compatible mapping (difference = 1.60%) relative to an incompatible mapping (difference = 0.20%) in the object-grasping task, whereas, when the color discrimination task was performed first, the SSARC effect was smaller with a compatible mapping (difference = -1.01%) relative to an incompatible mapping (difference = 0.49%) in the object-grasping task. The marginal means of this analysis are shown in Table 4.

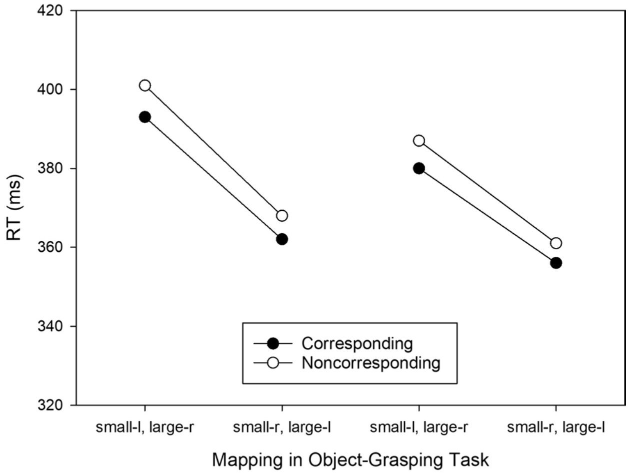

Fig. 5 RTs observed in the color-discrimination task as a function of mapping in the preceding grasping task, S–R correspondence in the color-discrimination task, and task order (left: color-discrimination task second, right: color-discrimination task first)

Table 4 Error percentages observed in the color-discrimination task as a function of the mapping in the grasping task, S–R Correspondence in the color-discrimination task, and task order

Order	Mapping in grasping task	S–R correspondence	
		Corresponding	Non-corresponding
Color-discrimination task first	Small-left, large-right	2.770	1.755
	Small-right, large-left	1.620	2.107
Color-discrimination task second	Small-left, large-right	1.593	3.192
	Small-right, large-left	1.802	2.002

Acknowledgements The authors thank Sarah Behrendt and Delal Can for testing the participants.

Author contributions M.R.: Conceptualization, Methodology, Software, Validation, Formal analysis, Data Curation, Writing–Original Draft, Writing–Review and Editing, Visualization. P.W.: Conceptualization, Methodology, Software, Validation, Formal analysis, Resources, Writing–Original Draft, Writing–Review and Editing, Visualization, Project administration

Funding This research did not receive any specific funding from agencies in the public, commercial, or not-for-profit sectors.

Data availability The dataset has been published on the Mendeley Data repository (https://doi.org/10.17632/7387hprrf9.1).

Code availability The experiment's program (E-Prime 3.0) and the R code can be obtained from both authors upon request.

Material availability Materials can be obtained from both authors upon request.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

Ethical approval The local Ethics Committee at TU Dortmund University had approved the experimental protocol for our study (approval no. approval no. 2018-09)

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

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