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Processing directional information in stimuli inhibits the spatial association of luminance levels

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Abstract

Previous studies have found that the spatial-numerical association of the response codes (SNARC) effect automatically occurred when processing both numbers and non-symbolic magnitudes. However, this conclusion was challenged by several recent studies that found no SNARC effect when processing non-symbolic magnitudes with a directional cue. In the present study, we hypothesized that automatic spatial association of non-symbolic magnitudes would be inhibited by directional cues; thus, we utilized left and right arrow stimuli with different luminance levels to systematically investigate the spatial association of luminance. To ensure that participants could effectively discriminate the luminance stimuli, we first replicated the SNARC effect in Experiment 1, by presenting rectangles with different luminance levels. Then, arrows with the same luminance levels as the rectangles were randomly presented to participants on the centre of a screen; participants completed direction classification (Experiment 2), colour classification (Experiment 3), or luminance classification (Experiment 4) tasks with these arrow stimuli. We found that (1) the SNARC effect was present when processing rectangles with different luminance levels (Experiment 1); however, (2) the Simon-like effect rather than the spatial association of luminance was observed when processing arrows with different luminance levels in the luminance-irrelevant classification tasks (Experiments 2 and 3) and the luminance-relevant classification task (Experiment 4). These results indicate that processing of a directional cue inhibited the spatial association of luminance in both luminance-relevant and luminance-irrelevant classification tasks.

Keywords SNARC effect · Nonsymbolic magnitudes · Direction · Luminance

Introduction

When Arabic numerals were randomly presented in the centre of a screen to participants who were asked to classify these numbers according to their numerical magnitude or parity by pressing a left key or a right key, participants responded faster to small numbers with left key presses than right key presses; in contrast, participants responded faster to large numbers with right key presses than left key presses. This phenomenon was first observed by Dehaene and his colleagues, who named it the *spatial-numerical association of response codes* (SNARC) effect (Dehaene et al., 1990; Dehaene et al., 1993). The systematic difference between the latency of responses to small numbers (left < right key presses) and large numbers (right < left key presses) when processing of Arabic numerals was attributed to the spatial representation of numbers along a mental number line, with small numbers represented on the left side, and large numbers represented on the right side.

After the SNARC effect was first identified, many subsequent studies extended this effect to the processing of other types of numbers, such as Chinese and German numbers (Kopiske et al., 2016; Nuerk et al., 2005; Wang et al., 2020), and to non-symbolic magnitudes, such as different numbers of dots or fingers as well as stimuli with different luminance, angles and pitch (Cho et al., 2012; de Hevia et al., 2014; Fumarola et al., 2014; Fumarola et al., 2016; Fumarola et al., 2020; Holmes & Lourenco, 2011; Prete, 2020; Rugani et al., 2015; Wang, Ma, et al., 2021a). For example, Fumarola et al.

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(2014) utilized rectangles with different levels of luminance to investigate whether luminance was associated with the side of response execution. Their results showed that, similar to numbers, the mental representation of luminance in space was aligned left to right, with lower (darker) luminance levels to the left and higher (brighter) luminance levels to the right, on both luminance-relevant and luminance-irrelevant classification tasks. These systematic left/right differences in responses to numbers and non-symbolic magnitudes imply that both numbers and non-symbolic magnitudes are automatically associated with spatial representations by cognitive agents.

However, this conclusion was challenged by several recent studies in which the authors did not capture a SNARC-like effect when processing non-symbolic magnitudes in magnitude-irrelevant classification tasks (Cleland et al., 2020; Prpic et al., 2020; Wang, Ma, et al., 2021a). For example, Cleland et al. (2020) replaced number stimuli with arrays constructed of one to nine black equilateral triangles with apexes that pointed up or down; these arrays were presented to participants who were asked to perform upwards or downwards decisions based on the direction of the triangles. These authors did not observe a SNARC-like effect in processing these non-symbolic magnitudes when the total surface area was held constant or when the total surface area increased with increases in the number of triangles. Based on their findings, Cleland et al. (2020) suggested that non-symbolic magnitudes were not automatically associated with spatial representations by cognitive agents.

The conclusion that non-symbolic magnitudes are not automatically associated with spatial representations has also been superficially supported by several studies (Prpic et al., 2020; Wang, Ma, et al., 2021a). For example, Prpic et al. (2020) presented Kanizsa illusory triangles and real triangles with different surface areas (the surface area represented the non-symbolic magnitude) to participants who were asked to classify triangles depending on their direction (pointing upwards vs. downwards) and the size of the surface area, respectively. They did not capture a SNARC-like effect for direction classification tasks, regardless of whether the stimuli were Kanizsa illusory triangles or real triangles; in contrast, a SNARC-like effect was observed in surface area classification tasks for both Kanizsa illusory triangles and real triangles. Additionally, Wang, Q. et al. (Wang, Ma, et al., 2021a) replaced Arabic numerals with Chinese number gestures expressed with the left or right hand and asked participants to perform a numerical magnitude-irrelevant classification task. The results also did not capture a SNARC effect during the processing of Chinese number gestures.

Although the SNARC-like effect was absent during magnitude-irrelevant classification tasks involving non-symbolic magnitudes in the above studies, this does not necessarily indicate the absence of automatic activation of spatial associations when viewing non-symbolic magnitudes. These findings may reflect the inhibition of directional information accompanying non-symbolic magnitudes (i.e., through spatial associations of non-symbolic magnitudes) because directional information was present in all of the non-symbolic stimuli discussed above (Cleland et al., 2020; Prpic et al., 2020; Wang, Q. et al., Wang, Ma, et al., 2021a). Specifically, the information on upwards or downwards directions was contained in Cleland et al.'s (2020) study and Prpic et al.'s (2020) study, and information regarding the left or right hand was contained in the Chinese number gestures utilized by Wang, Q. et al.'s (Wang, Ma, et al., 2021a) study.

The possibility that directional information contained in non-symbolic magnitudes inhibits their spatial associations is indirectly supported by several studies that investigated the influence of the Simon effect on SNARC or SNARC-like effects in the processing of numbers or sequence symbols (Jin et al., 2017; Shi et al., 2020; Wang, An, et al., 2021b; Wang et al., 2020); the theory and expert accounts were discussed by Guida et al. (Guida & Campitelli, 2019; Guida et al., 2020). Regarding the influence of the Simon effect on SNARC or SNARC-like effects, previous studies found that the SNARC effect and the Simon effect coexisted (Gevers et al., 2005; Keus & Schwarz, 2005; Mapelli et al., 2003; Rusconi et al., 2007); however, several recent studies found that activating the location of numbers or sequence symbols inhibited SNARC or SNARC-like effects in classification tasks in which number magnitude or sequence symbol sequence was irrelevant (Jin et al., 2017; Shi et al., 2020; Wang, An, et al., 2021b; Wang et al., 2020). For example, Shi et al. (2020) presented sequence symbols, specifically days, to participants and asked them to classify the probe day based on the day's location on the screen or the colour of the day's label; they did not capture a SNARC-like effect in these two classification tasks.

The possibility that directional information contained in non-symbolic magnitudes inhibits their spatial association is also indirectly supported by theoretical explanations. For example, Guida and Campitelli (2019 introduced three parsimonious steps to interpret how symbols, including numbers, non-symbolic magnitudes and sequence symbols, were encoded and therefore resulted in a SNARC or SNARC-like effect. Specifically, the authors claimed that participants first encoded symbols based on the spatial directional information in the environment. If no external spatial directional information is provided, the participants encode symbols depending on their spatial information in long-term memory (e.g., number locations along a mental number line). If both types of spatial information (i.e., external and internal) are not suitable for encoding symbols, the cognitive system uses other situational information (e.g., ordinal information in the sequence of stimuli presented) to encode the symbols (Guida et al., 2020; Guida & Campitelli, 2019). According to this theory, numbers are first encoded based on a directional cue if the numbers contain directional information; in contrast, number encoding based on numerical magnitude is inhibited by the directional cue, leading to the absence of a SNARC effect when processing numbers.

Based on the above empirical and theoretical findings, we believe that the spatial association of non-symbolic magnitudes was automatically activated even in the studies that failed to capture a SNARC-like effect in the processing of non-symbolic magnitudes. We speculate that the absence of SNARC-like effect in the processing of non-symbolic magnitudes containing directional information in a magnitude-irrelevant classification task instead reflected the inhibition of the spatial association of non-symbolic magnitudes by this directional information.

Although our hypothesis concerning the automatic activation of spatial associations for non-symbolic magnitudes is directly supported by several empirical studies and theoretical approaches, it must be verified by additional experimental research. Therefore, the present study used left and right arrows with different luminance levels (varying non-symbolic magnitudes). We designed a series of experiments to systematically investigate the presence of spatial association when processing non-symbolic magnitudes in different cognitive tasks and thus verify our predictions. In addition, to ensure that the luminance levels utilized in this study effectively induced a SNARC effect, Experiment 1 aimed to replicate the SNARC effect using rectangles with the same luminance levels as the arrows used in later experiments. In Experiment 2, left- or right-pointing red probe arrows with different luminance levels were randomly selected and centrally presented on the screen, and the participants were asked to classify whether the arrow pointed left or right as a preliminary verification of our prediction that the arrows provided robust directional cues. Then, in Experiment 3, red or green arrows with different luminance levels that pointed left or right were also randomly selected and centrally presented on the screen, but the participants were asked to perform a colour classification task (based on the colour of the probe arrows) to investigate whether the spatial association of luminance was absent even when both the luminance level and the arrows' directional cue were not directly emphasized. In the last experiment (Experiment 4), red probe arrows with different luminance levels that pointed left or right were randomly selected and centrally presented on the screen; we asked the participants to classify whether the probe arrows were darker or brighter than a reference arrow to investigate how directional cues influenced the spatial association of luminance when the stimuli luminance levels were robustly activated by the luminance classification task. If our hypothesis is correct, the spatial association of luminance would be absent in the direction classification task. If the spatial association of luminance is absent in some tasks but present in others, the inhibition of the spatial association of luminance by directional information is likely moderated by the task demands.

Experiment 1

In this experiment, rectangles with varying luminance levels were randomly presented to participants who were asked to judge whether the probe rectangle was darker or brighter than the reference rectangle. The aim of this experiment was to replicate the spatial association of luminance and demonstrate that the luminance levels utilized as stimuli in this study indeed elicited a SNARC-like effect.

Methods

Participants

G*Power 3.1 indicated that a sample size of 24 participants ensured that a 2 × 2 within-participant design could detect differences with a moderate effect size (f = 0.25) at an adequate power level (80%). Thirty-two university students (22 females) were recruited to participate in this experiment. All participants were right-handed and had normal or corrected-to-normal vision. The mean age was 19.56 years (SD = 2.06), the maximum age was 26 years, and the minimum age was 17 years. Informed consent was obtained prior to starting the experiment. The research protocol was approved by the Ethics Committee of the School of Medicine, Huzhou University.

Stimuli and apparatus

Five rectangles with different luminance levels were utilized as non-symbolic stimuli in this experiment (see Fig. 1). To ensure that participants could correctly identify changes in luminance levels, we shuffled these five rectangles (each with a different luminance level) and asked 40 different university students to rank the five shuffled rectangles in order of luminance, from dark to bright. All 40 university students correctly ranked the rectangles, indicating that the luminance levels used in this study were discernible. All stimuli were presented on a 19-in. computer screen with 1,280 × 1,024-pixel resolution and a 60-Hz refresh rate. The visual angle of each rectangle was approximately 4.3° when the viewing distance was 50 cm.

Design

This experiment adopted a 2 (luminance: darker vs. brighter) × 2 (pressed key: left vs. right) within-participant design. The response time (RT) of participants was the dependent variable.

Procedures

The experiment was conducted using E-prime v. 1.1 software. The procedures of one trial were as follows. First, a fixation

Fig. 1 Rectangles with different luminance levels used as stimuli in Experiment 1. The luminance levels of the rectangles became increasingly bright from left to right. The third rectangle is the reference rectangle, and the other rectangles are probe rectangles

cross was centrally displayed on the screen for 500 ms. Then, the fixation cross disappeared and was replaced by a reference rectangle (the middle rectangle in Fig. 1) for 1,000 ms. Next, the fixation cross was displayed again for 500 ms. Finally, a probe rectangle with a different luminance than the reference rectangle was randomly presented to participants for 3,000 ms. During presentation of the probe rectangle, participants were instructed to indicate whether its luminance level was darker or brighter than that of the reference rectangle by pressing the left key ("F") or right key ("J") on the keyboard as quickly and correctly as possible. The probe rectangle was shown until the participant responded or 3,000 ms had elapsed; subsequently, the probe rectangle disappeared and was replaced by a blank screen for 1,500 ms before the next trial started. Both fixation cross and stimuli were displayed against a white background. The entire experiment included two blocks. In one block, participants were instructed to press the left key if the probe rectangle had a luminance level darker than that of the reference rectangle and to press the right key if the probe rectangle had a luminance level brighter than that of the reference rectangle. In the other block, these key mappings were reversed (e.g., the left key indicated that the probe rectangle had a luminance level brighter than that of the reference rectangle). Across all trials, participants were instructed to place their left index finger on the left key and their right index finger on the right key. The order of the two blocks was balanced across the participants, and the entire experiment included 64 formal trials. In addition, the participants completed eight practice trials (repeated as needed) to become familiar with the procedures of the experiment before each formal block started. The entire experiment lasted approximately 6 min.

Results and discussion

The mean RTs, excluding RTs on incorrect trials and those more than three standard deviations from the mean of each condition (4.35% of all trials), were analysed with a repeated-measures analysis of variance (ANOVA). The results indicated that the main effect of the pressed key was nonsignificant, $F(1, 31) = 1.24$, $p = 0.27$, $\eta^2 = 0.038$. The main effect of luminance was significant, $F(1, 31) = 9.65$, $p = 0.004$, $\eta^2 = 0.237$, with the darker rectangles eliciting a faster response (496 ± 12.06 ms) than the brighter rectangles (520 ± 15.94 ms). The interaction between the pressed key and luminance was significant, $F(1, 31) = 6.31$, $p = 0.017$, $\eta^2 = 0.169$, and simple effect analysis showed that the darker rectangles elicited a faster response (485 ± 9.12 ms) than the brighter rectangles (539 ± 19.27 ms) on the left key, $F(1, 31) = 16.29$, $p < 0.001$, $\eta^2 = 0.344$. The difference in RTs between the brighter rectangles (501 ± 15.50 ms) and the darker rectangles (507 ± 17.24 ms) on the right key was non-significant, $F(1, 31) = 0.12$, $p = 0.74$, $\eta^2 = 0.004$. The reason that the brighter rectangles did not significantly elicit a faster response than the darker rectangles on the right key was due to the faster overall response for darker rectangles. Therefore, the interaction between luminance and the pressed key indicates the presence of a SNARC-like effect in this experiment (Fig. 2).

This experiment utilized rectangle stimuli with different luminance levels to replicate the spatial association of luminance reported by Fumarola et al. (2014); thus, the processing of luminance levels in this study showed that luminance is associated with space by cognitive agents and confirmed the effectiveness of our luminance levels for eliciting SNARC-like effects, indicating that our luminance levels were discriminable and effective.

Experiment 2

In Experiment 2, the rectangles were replaced by left or right arrows with the same luminance levels as the rectangles in Experiment 1 to investigate whether activating a directional

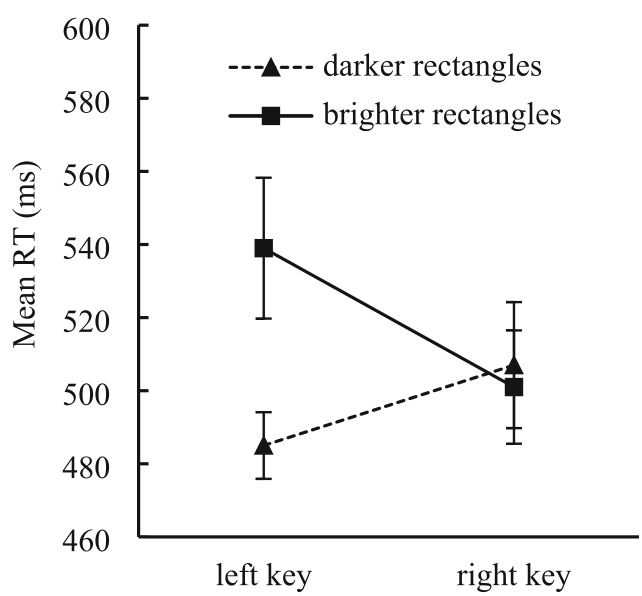

Fig. 2 Participant response times (RTs) to rectangles with different luminance levels by pressing the left or right keys. The error bars represent the standard errors of the mean

cue inhibited the spatial association of luminance. Participants were asked to judge whether the probe arrow pointed left or right.

Methods

Participants

G*Power 3.1 indicated that a sample size of 16 participants could ensure that a 2 × 2 × 2 within-participant design was suitable for detecting differences with a moderate effect size (f = 0.25) at an adequate power level (80%). Experiments 3 and 4 had a similar design and sample size requirement. Thirty-two university students (25 females) were recruited to participate in this experiment. All participants were right-handed and had normal or corrected-to-normal vision. The mean age was 21.38 years (SD = 3.41), the maximum age was 33 years, and the minimum age was 18 years. Informed consent was obtained prior to starting the experiment. The research protocol was approved by the Ethics Committee of the School of Medicine, Huzhou University.

Stimuli and apparatus

Eight red probe arrows with the same luminance levels as the rectangles in Experiment 1 that pointed left or right were used as experimental stimuli (see Fig. 3). All stimuli were presented on a 19-in. computer screen with 1,280 × 1,024-pixel resolution and a 60-Hz refresh rate. The visual angle of each arrow was approximately 4.3° when the viewing distance was 50 cm.

Design

This experiment adopted a 2 (pressed key: left vs. right) × 2 (luminance: darker vs. brighter) × 2 (direction: pointing left vs. pointing right) within-participant experimental design. Participant RTs were used as the dependent variable.

Procedures

The experiment was conducted using E-prime v. 1.1 software. The procedures of one trial were as follows. First, a fixation cross was centrally displayed on the screen for 500 ms. Then, the fixation cross disappeared and was replaced by a left- or right-pointing red probe arrow for 3,000 ms. When the probe arrow was presented, the participants needed to indicate whether it pointed left or right by pressing the left key ("F") or right key ("J") on the keyboard as quickly and correctly as possible. The probe arrow was shown until the participant responded or 3,000 ms had elapsed; subsequently, the probe arrow disappeared and was replaced by a blank screen for 1,500 ms before the next trial started. Both fixation cross and stimuli were displayed against a white background. The entire experiment included two blocks. In one block, the participants were instructed to press the left key to indicate a left arrow and the right key to indicate a right arrow. In the other block, the key mappings were reversed. Across all trials, participants were instructed to place their left index finger on the left key and their right index finger on the right key. The order of the two blocks was balanced across the participants, and the entire experiment included 128 formal trials. In addition, the participants completed eight practice trials (repeated as needed) to become familiar with the procedures of the experiment before each formal block started. The entire experiment lasted approximately 10 min.

Results and discussion

The mean RTs, excluding those on incorrect trials and those more than three standard deviations from the mean of each condition (2.86% of all trials), were analysed with a repeated-measures ANOVA. The results indicated that the main effect of the pressed key was significant, $F(1, 31) = 8.15$, $p = 0.008$, $\eta^2 = 0.208$, with the right key (401 ± 7.71 ms) pressed faster than the left key (414 ± 8.94 ms). This result is consistent with the dominant hand effect. The interaction between the pressed key and arrow direction was significant, $F(1, 31) = 96.17$,

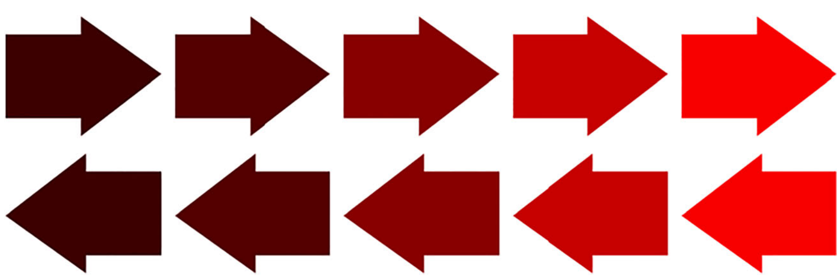

Fig. 3 Left and right red arrows with different luminance levels used in this study. The luminance of the arrows was the same as the luminance of the rectangles in Experiment 1; the arrows became increasingly bright from left to right in each row. The arrows of the third (middle) column were the reference arrows presented in Experiment 4; participants were instructed to compare the luminance of the probe arrows (all other columns) with that of the reference arrows. The other eight arrows were probe arrows and were used in Experiment 2. The arrows pointed to the right on the first row and pointed to the left on the second row

$p < 0.001$, $\eta^2 = 0.756$, and simple effect analysis showed that left arrows elicited a faster response (378 ± 5.71 ms) than right arrows (449 ± 12.79 ms) on the left key, $F(1, 31) = 69.03$, $p < 0.001$, $\eta^2 = 0.69$, whereas right arrows elicited a faster response (367 ± 5.71 ms) than left arrows (435 ± 10.76 ms) on the right key, $F(1, 31) = 78.49$, $p < 0.001$, $\eta^2 = 0.717$. This pattern of results indicates that a Simon-like effect occurred in this experiment (Fig. 4). The other main effects and interaction effects were not significant, $ps > 0.193$, indicating that a SNARC-like effect in the processing of luminance was absent in this experiment.

In Experiment 2, we used arrows whose luminance levels were the same as the rectangles in Experiment 1 to investigate whether directly activating the direction of arrows with different luminance levels inhibited the spatial association of luminance. The results captured a Simon-like effect in the processing of luminance but did not reveal a SNARC-like effect. These results provide a preliminary verification of our hypothesis that the activation of directional cues would inhibit the spatial association of luminance.

Experiment 3

In Experiment 3, the stimuli included red or green arrows pointing left or right that had the same luminance levels as the arrows in Experiment 2. The participants were asked to perform a colour classification task to investigate whether the inhibition of the spatial association of luminance by directional information extended to a context in which neither the luminance or directional information was directly emphasized.

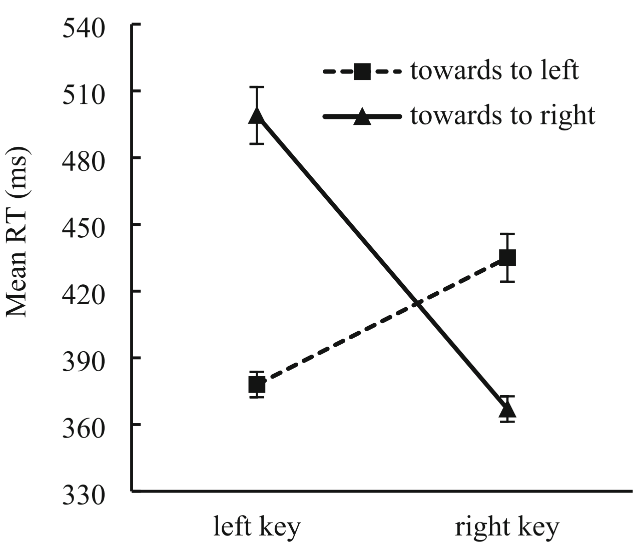

Fig. 4 Participant response times (RTs) to viewing arrows pointing left or right; participants responded by pressing the left key or right key, respectively, in a direction classification task. The error bars indicate the standard error of the mean

Methods

Participants

Thirty-two university students (25 females) were recruited to participate in this experiment. All participants were right-handed and had normal or corrected-to-normal vision. The mean age was 20.06 years (SD = 1.34), the maximum age was 23 years, and the minimum age was 18 years. Informed consent was obtained prior to starting the experiment. The research protocol was approved by the Ethics Committee of the School of Medicine, Huzhou University.

Stimuli and apparatus

The stimuli and apparatus used in Experiment 3 were similar to those used in Experiment 2 except that the arrows were either red or green in Experiment 3.

Design

The experiment implemented a 2 (pressed key: left vs. right) × 2 (luminance: darker vs. brighter) × 2 (direction: pointing left vs. pointing right) within-participant experimental design. Participant RTs served as the dependent variable.

Procedures

The procedures for Experiment 3 were similar to those used in Experiment 2, except that the task in Experiment 3 was different. In Experiment 3, the participants were asked to classify the arrows based on their colour.

Results and discussion

The RTs of incorrect trials and those more than three standard deviations away from the mean of each condition (5.79% of all trials) were excluded. The remaining mean RTs of the participants were analysed with a repeated-measures ANOVA. The results indicated that the main effect of the pressed key was marginally significant, $F(1, 31) = 4.14$, $p = 0.051$, $\eta^2 = 0.118$, and that the participants pressed the right key (482 ± 10.65 ms) faster than the left key (496 ± 10.75 ms). This result is consistent with the dominant hand effect. The main effect of luminance was significant, $F(1, 31) = 43.41$, $p < 0.001$, $\eta^2 = 0.583$; arrows with brighter luminance (472±10.60 ms) elicited faster responses than arrows with darker luminance (506±10.35 ms). The main effect of direction was also significant, $F(1, 31) = 5.27$, $p = 0.03$, $\eta^2 = 0.145$; the right arrows elicited a faster response (484 ± 10.36 ms) than the left arrows (493 ± 10.27 ms). The interaction between the pressed key and direction was significant, $F(1, 31) = 20.32$, $p < 0.001$, $\eta^2 = 0.396$, and the simple effect analysis showed that left arrows elicited a faster response (485 ± 10.41 ms) than right arrows (507 ± 12.56 ms) when the left key was pressed, $F(1, 31) = 7.28$, $p = 0.011$, $\eta^2 = 0.19$. Additionally, right arrows elicited a faster response (462 ± 10.26 ms) than left arrows (502 ± 12.20 ms) when the right key was pressed, $F(1, 31) = 28.99$, $p < 0.001$, $\eta^2 = 0.483$. These findings indicate that a Simon-like effect occurred in this experiment (Fig. 5). The interaction between the pressed key and luminance was not significant, $F(1, 31) = 0.04$, $p = 0.84$, $\eta^2 = 0.041$. The interaction among the pressed key, direction and luminance was also not significant, $F(1, 31) = 0.05$, $p = 0.83$, $\eta^2 = 0.046$. These results indicate that a SNARC-like effect in the processing of luminance was absent in this experiment.

A colour classification task was performed in this experiment to investigate whether the inhibition of the spatial association of luminance by directional information extended to a context in which neither the luminance or directional information was directly emphasized. The results showed that a Simon-like effect occurred, but a SNARC-like effect in the processing of luminance was absent in this experiment. These results imply that the inhibition of the spatial association of luminance by directional information extended to a context in which neither the luminance or directional information was directly emphasized.

Experiment 4

In Experiment 4, the participants were asked to determine whether probe arrows were darker or brighter than the reference arrow to investigate whether the inhibition of the spatial association of luminance by direction would be weakened or

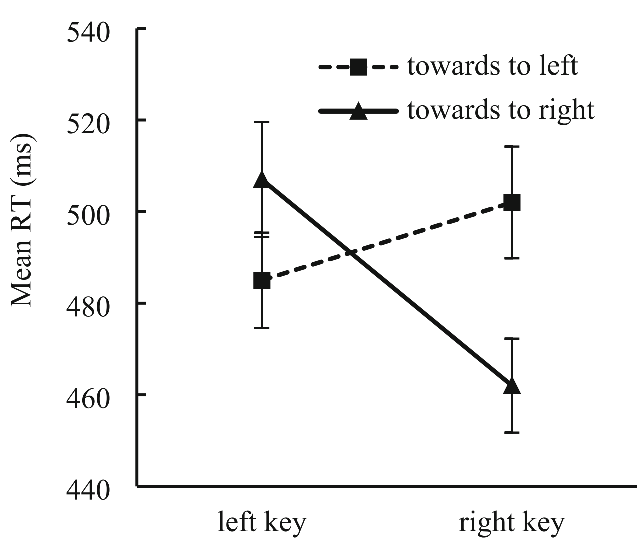

Fig. 5 Participant response times (RTs) in response to viewing arrows pointing left or right; participants responded by pressing the left or right key, respectively, in a colour classification task. The error bars indicate the standard errors of the mean

absent when the luminance information was directly emphasized in a luminance classification task.

Methods

Participants

Thirty-six university students (22 females) were recruited to participate in this experiment. All participants were right-handed and had normal or corrected-to-normal vision. The mean age was 20.03 years (SD = 1.18), the maximum age was 22 years, and the minimum age was 18 years. Informed consent was obtained prior to starting the experiment. The research protocol was approved by the Ethics Committee of the School of Medicine, Huzhou University.

Stimulus and apparatus

Ten red arrows that pointed left or right with the same luminance levels as the rectangles in Experiment 1 were used as the experimental stimuli. Eight of these arrows (used in Experiment 2) served as probe arrows, and the remaining two arrows (those in the third [middle] column in Fig. 2) served as reference arrows (see Fig. 2). The apparatus in Experiment 4 was similar to that in Experiment 1.

Design

he experiment adopted a 2 (pressed key: left vs. right) × 2 (luminance: darker vs. brighter) × 2 (direction: pointing left vs. pointing right) within-participant experimental design. Participant RTs were used as the dependent variable.

Procedure

The procedure for Experiment 4 was similar to that of Experiment 1, except that the rectangles were replaced with left or right arrows. Notably, the two reference arrows in Experiment 4 contained one pointing left and one pointing right. To exclude the influence of differences in direction between the reference arrows and the probe arrows from the experimental result, the reference arrow was chosen to match the direction of the probe arrow presented in all trials. Specifically, when the probe arrow pointed left, the reference arrow that pointed left was presented; likewise, when the probe arrow pointed right, the reference arrow that pointed right was presented. In this experiment, the task also involved luminance classification; participants were asked to judge whether the luminance of the probe arrow was darker or brighter than that of the reference arrow. This experiment also contained two blocks. The response data and the method of balancing the luminance and pressed key between blocks and participants were the same as those in Experiment 1.

Results and discussion

The RTs on incorrect trials and those more than three standard deviations from the mean in each condition (6% of all trials) were excluded. The remaining RTs were analysed with a repeated-measures ANOVA. The results indicated that the main effect of the pressed key was significant, $F(1, 35) = 14.45$, $p = 0.001$, $\eta^2 = 0.292$, with faster responses (529 ± 13.13 ms) elicited when pressing the right key than the left key (560 ± 13.91 ms). This result is consistent with the dominant hand effect. The main effect of direction was significant, $F(1, 35) = 6.58$, $p = 0.02$, $\eta^2 = 0.158$, with right arrows eliciting a faster response (544 ± 13.06 ms) than left arrows (555 ± 12.79 ms). The interaction effect between the pressed key and direction was significant, $F(1, 35) = 38.82$, $p < 0.001$, $\eta^2 = 0.526$, with left arrows eliciting a faster response (553 ± 13.29 ms) than right arrows (567 ± 13.31 ms) when the left key was pressed, $F(1, 35) = 4.23$, $p = 0.047$, $\eta^2 = 0.108$, and right arrows eliciting a faster response (521 ± 13.50 ms) than left arrows (557 ± 13.32 ms) when the right key was pressed, $F(1, 35) = 42.66$, $p < 0.001$, $\eta^2 = 0.549$. These findings indicate that a Simon-like effect occurred in this experiment (Fig. 6). The interaction between the pressed key and luminance was not significant, $F(1, 35) = 0.07$, $p = 0.79$, $\eta^2 = 0.002$. The interaction among the pressed key, direction and luminance was also not significant, $F(1, 35) = 1.57$, $p = 0.218$, $\eta^2 = 0.043$. These results indicate that a SNARC-like effect was absent in the processing of luminance in this experiment.

This experiment investigated whether the inhibition of the spatial association of luminance by directional information would be weakened or absent when the luminance information was directly emphasized in a luminance classification task. The results showed that a Simon-like effect was present but that a SNARC-like effect in the processing of luminance was absent; thus, the inhibition of the spatial association of luminance by directional information extended to a context in which the luminance information was directly emphasized by a luminance classification task.

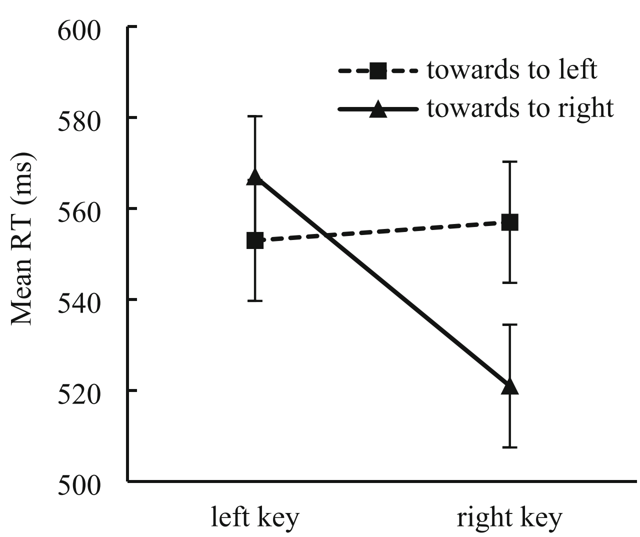

Fig. 6 Participant response times (RTs) to arrows pointing left or right; participants responded by pressing the left or right key, respectively, in a luminance classification task. The error bars indicate the standard errors of the mean

General discussion

Although previous studies have consistently suggested that a SNARC-like effect in the processing of non-symbolic magnitudes is present in both magnitude-relevant and magnitude-irrelevant classification tasks, a few recent studies have shown that the processing of non-symbolic magnitudes did not induce a SNARC-like effect in a magnitude-irrelevant classification task. Based on these results, the authors of these studies even indicated that in the processing of non-symbolic magnitudes, a SNARC-like effect is not automatically activated (Cleland et al., 2020; Wang, Q. et al., 2021). However, after reviewing these studies, we hypothesized that the activation of directional information may inhibit the spatial association effect when processing non-symbolic magnitudes. Therefore, the present study utilized left and right arrows with different luminance levels to test our hypothesis across a series of experiments and investigate the mechanism by which the directional information inhibited the spatial association of non-symbolic magnitudes.

To ensure that the luminance levels utilized as stimuli in this study were discriminable and effectively induced a SNARC-like effect during processing, we first aimed to replicate a SNARC-like effect in the processing of luminance information contained in rectangle stimuli in Experiment 1. As expected, in a luminance classification task, we observed the spatial association of luminance, indicating that the luminance levels utilized in this study were effective and discriminable. In subsequent experiments, we utilized arrows with the same luminance levels as the rectangles in the first experiment to test our hypothesis that activating directional information may inhibit the spatial association effect in the processing of non-symbolic magnitudes.

Experiment 2 adopted a direction classification task in which participants were asked to judge the direction (i.e., left or right) of probe arrows with different luminance levels as a preliminarily examination of a SNARC-like effect when directional information was directly activated. The results of Experiment 2 showed that a Simon-like effect occurred; however, the spatial association of luminance was absent in the direction classification task. Cleland et al. (2020) explored arrays constructed from one to nine black, equilateral triangles with pointing up or down as non-symbolic stimuli to investigate the automatic activation of a SNARC-like effect in the processing of non-symbolic magnitudes when classifying apex angle direction; they found that a SNARC-like effect was absent in the processing of non-symbolic magnitudes both when the total surface area was held constant and when the total surface area increased with increases in the number of triangles presented. Additionally, Prpic et al. (2020) explored Kanizsa illusory triangles and real triangles with different surface areas (i.e., varying in non-symbolic magnitude) and asked participants to classify the probe triangle depending on its direction (upwards vs. downwards). They also did not capture a SNARC-like effect for either Kanizsa illusory triangles or real triangles in a direction classification task.

Although the non-symbolic magnitudes chosen in this study differed from those of Cleland et al. (2020) and Prpic et al. (2020), directional information was contained in both of these non-symbolic magnitudes and was directly stressed in the classification tasks. Experiment 2 verified that the spatial association of luminance was absent when the directional information was directly emphasized. The results of Experiment 2 further replicated the findings of Cleland et al. (2020) and Prpic et al. (2020). This result implies that the direct activation of directional information inhibits the spatial association of luminance. This finding is consistent with our hypothesis and provides a preliminarily verification of our speculation.

Experiment 2 indicated that the activation of directional information inhibited the spatial association of luminance; however, it was unclear whether the inhibition of luminance by directional information occurred automatically. As the directional information was not activated when the participants were asked to determine the colour of arrows, we could investigate the automatic inhibition of the spatial association of luminance by directional information. Therefore, in Experiment 3, we investigated the inhibition of the spatial association of luminance by directional information in a colour classification task. Although the directional cue was not directly emphasized in Experiment 3, the results still showed a Simon-like effect, while a SNARC-like effect was absent. This result further implies that the inhibition of the spatial association of luminance by directional information can be extended to contexts where directional information is not directly activated, i.e., in a direction-irrelevant classification task. In summary, the inhibition of the spatial association of luminance by directional information can occur automatically.

Several previous studies have activated number location and investigated the relationship between the Simon effect and the SNARC effect; although these studies did not determine whether the Simon effect and the SNARC effect could interact, they confirmed that the Simon effect could coexisted with the SNARC effect (Gevers et al., 2005; Keus & Schwarz, 2005; Mapelli et al., 2003; Rusconi et al., 2007). Experiment 3 captured only a Simon-like effect with a colour classification task. Obviously, the results of Experiment 3 differed from those of previous studies in a variety of ways. First, the nature of the experimental stimuli was different; numbers were used in previous studies and non-symbolic magnitudes were used as stimuli in the present study. Second, the spatial information contained within the stimuli differed; in previous studies, a number was used to activate spatial information about the number (i.e., on a mental number line), while in the present study arrow direction was used to activate the spatial information of non-symbolic magnitudes. Therefore, the discrepancy between the results of previous studies and the current study indicates that either the processing of numbers and non-symbolic magnitudes differ or the spatial information of stimuli influences the encoding of numbers and non-symbolic magnitudes. Different ways of conveying spatial information may alter the influence of this information on the encoding of numbers and non-symbolic magnitudes. Further studies are needed to determine which of these possibilities is correct.

Although Experiments 2 and 3 both indicated that the spatial association of luminance was absent in the direction classification task and the colour classification task, neither of these tasks directly emphasized luminance information. Therefore, the inhibition of the spatial association of luminance by directional information indicated in the above two experiments did not predict the interaction between directional information and luminance information when the luminance information was directly emphasized. Thus, in Experiment 4, we adopted a luminance classification task to further investigate whether the direct activation of luminance information would decrease or even eliminate the inhibition of the spatial association of luminance by directional information. The results of Experiment 4 showed that a Simon-like effect was present, but a SNARC-like effect was absent. These findings indicate that the inhibition of the spatial association of luminance by directional information occurred even when luminance information was strongly activated in a luminance classification task. Thus, the inhibition of the spatial association of non-symbolic magnitudes by directional information was very strong and occurred even when the magnitude information of these stimuli is strongly activated.

Although non-symbolic magnitudes elicit weaker and less reliable SNARC-like effects in magnitude-irrelevant classification tasks or do not automatically elicit a SNARC-like effect when processing non-symbolic magnitudes in magnitude-irrelevant classification tasks (Cleland et al., 2020; Macnamara et al., 2018; Prpic et al., 2020), many previous studies have shown that a SNARC-like effect may be present in magnitude classification tasks with non-symbolic magnitudes (Cho et al., 2012; Fumarola et al., 2014; Fumarola et al., 2016; Fumarola et al., 2020; Holmes & Lourenco, 2011; Prete, 2020; Prpic et al., 2020). However, we asked participants to classify the probe arrows according to their luminance. This task (in Experiment 4) directly activated the luminance information; thus, the results suggest that the spatial association may still be absent even in the processing of luminance information. Obviously, the results of Experiment 4 are inconsistent with those of previous studies. The largest difference between the methods of Experiment 4 and those of previous studies is that the stimuli in Experiment 4 included directional information. Therefore, there is sufficient reason to believe that the spatial association (absent in Experiment 4) was inhibited by directional information contained in stimuli with non-symbolic magnitudes.

Surprisingly, the Kanizsa illusory triangles and real triangles used as stimuli by Prpic et al. (2020) contained directional information (i.e., upwards vs. downwards). Prpic et al. still captured a SNARC-like effect in the processing of these triangles on a surface-area magnitude classification task. The arrows used in the present study also included directional information; however, we failed to capture a SNARC-like effect in our magnitude classification task. The differences between Prpic et al.'s study and the present study are as follows: (1) the specific orientation of directional information contained in the stimuli differed (i.e., upwards and downwards vs. left and right in our study) and (2) the nature of the non-symbolic magnitudes differed (i.e., surface area of triangles vs. the luminance of arrows). Prpic et al. captured a SNARC-like effect of processing Kanizsa illusory triangles and real triangles in a surface-area magnitude classification task, but we did not capture a SNARC-like effect of processing arrows in a luminance classification tasks. These results imply that (1) the influence of directional information on the spatial association of non-symbolic stimuli may be moderated by specific orientation (i.e., left and right directions possibly exert a larger influence on the spatial association of non-symbolic stimuli than up and down directions) and (2) the nature of the non-symbolic magnitudes may moderate the influence of directional information on the spatial association of non-symbolic stimuli (i.e., arrows exert a larger influence on the spatial association of non-symbolic magnitudes than triangles or left and right physical locations). Notably, the above two implications are our hypotheses based on the findings of relevant studies, but these hypotheses need to be examined by further research. Additionally, the findings of Experiment 4 provide insight into the spatial association of non-symbolic magnitudes and indicate that the spatial association of non-symbolic magnitudes is not encoded in some contexts.

Guida and Campitelli (2019) regarded the SNARC effect as the result of symbol spatialisation in the brain and suggested that cognitive agents first spatialize symbols depending on the spatial direction information provided in the task. Our study utilized left and right arrows with different luminance levels as stimuli. Obviously, these stimuli included both luminance and directional information. In all three classification tasks, we observed a Simon-like effect, while a SNARC-like effect was absent. The presence of a Simon-like effect and the absence of a SNARC-like effect across these experiments suggest that the left-right directional cue was effectively processed and preferentially used by participants to encode the stimuli in all of these experiments. Thus, the activation of directional information inhibited stimuli spatialisation based on their luminance. Theoretical accounts indicate that spatialisation based on directional information occurs prior to spatialisation based on the magnitude or ordinal symbol sequence of stimuli. The results found here are consistent with the prediction of these theoretical accounts. Therefore, the findings of this study support prior conclusions to a certain extent.

References

Cho, Y. S., Bae, G. Y., & Proctor, R. W. (2012). Referential coding contributes to the horizontal smarc effect. *Journal of Experimental Psychology Human Perception & Performance, 38*(3), 726–734.

Cleland, A. A., Corsico, K., White, K., & Bull, R. (2020). Non-symbolic numerosities do not automatically activate spatial-numerical associations: Evidence from the snarc effect. *Quarterly Journal of Experimental Psychology., 73*(2), 295–308.

Dehaene, S., Dupoux, E., & Mehler, J. (1990). Is numerical comparison digital? analogical and symbolic effects in two-digit number comparison. *Journal of Experimental Psychology: Human Perception and Performance, 16*(3), 626–641.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology General, 122*(3), 371–396.

de Hevia, M. D., Girelli, L., Addabbo, M., & Macchi Cassia, V. (2014). Human infants' preference for left-to-right oriented increasing numerical sequences. *PloS one, 9*(5), e96412.

Fumarola, A., Prpic, V., Da Pos, O., Murgia, M., Umiltà, C., & Agostini, T. (2014). Automatic spatial association for luminance. *Attention, Perception, & Psychophysics, 76*(3), 759–765.

Fumarola, A., Prpic, V., Fornasier, D., Sartoretto, F., Agostini, T., & Umiltà, C. (2016). The Spatial Representation of Angles. *Perception, 45*(11), 1320–1330.

Fumarola, A., Prpic, V., Luccio, R., & Umiltà, C. (2020). A SNARC-like effect for music notation: The role of expertise and musical instrument. *Acta Psychologica, 208*, 103120.

Gevers, W., Caessens, B., & Fias, W. (2005). Towards a common processing architecture underlying Simon and SNARC effects. *European Journal of Cognitive Psychology, 17*(5), 659–673.

Guida, A., Abrahamse, E., & Dijck, J. (2020). About the interplay between internal and external spatial codes in the mind: Implications for serial order. *Annals of the New York Academy of Sciences.* https://doi.org/10.1111/nyas.14341

Guida, A., & Campitelli, G. (2019). Explaining the SPoARC and SNARC effects with knowledge structures: An expertise account. *Psychonomic Bulletin & Review, 26*, 434–451.

Holmes, K. J., & Lourenco, S. F. (2011). Common spatial organization of number and emotional expression: A mental magnitude line. *Brain and Cognition, 77*(2), 315–323.

Jin, G., Wang, Y., & Wang, L. (2017). The Inhibition of Simon Effect for Spatial-Numerical Association of Response Codes Effect. *Studies of Psychology and Behavior, 15*(4), 489–494.

Macnamara, A., Keage, H. A., & Loetscher, T. (2018). Mapping of non-numerical domains on space: a systematic review and meta-analysis. *Experimental brain research, 236*(2), 335–346.

Keus, I. M., & Schwarz, W. (2005). Searching for the functional locus of the SNARC effect: Evidence for a response-related origin. *Memory & Cognition, 33*(4), 681–695.

Kopiske, K. K., Löwenkamp, C., Eloka, O., Schiller, F., Kao, C. S., Wu, C., Gao, X., & Franz, V. H. (2016). The SNARC Effect in Chinese Numerals: Do Visual Properties of Characters and Hand Signs Influence Number Processing? *PLOS ONE, 11*(9), e0163897.

Mapelli, D., Rusconi, E., & Umiltà, C. (2003). The SNARC effect: an instance of the Simon effect? *Cognition, 88*(3), B1–B10.

Nuerk, H.-C., Wood, G., & Willmes, K. (2005). The Universal SNARC Effect. *Experimental Psychology, 52*(3), 187–194.

Prete, G. (2020). Spatializing Emotions Besides Magnitudes: Is There a Left-to-Right Valence or Intensity Mapping? *Symmetry, 12*(5), 1–13.

Prpic, V., Soranzo, A., Santoro, I., Fantoni, C., Galmonte, A., Agostini, T., & Murgia, M. (2020). SNARC-like compatibility effects for physical and phenomenal magnitudes: a study on visual illusions. *Psychological Research, 84*(4), 950–965.

Rugani, R., Vallortigara, G., Priftis, K., & Regolin, L. (2015). Number-space mapping in the newborn chick resembles humans' mental number line. *Science, 347*(6221), 534–536.

Rusconi, E., Turatto, M., & Umiltà, C. (2007). Two orienting mechanisms in posterior parietal lobule: An rTMS study of the Simon and SNARC effects. *Cognitive Neuropsychology, 24*(4), 373–392.

Shi, W., Wang, Q., Deng, M., & Xu, D. (2020). The influence of the location of ordered symbols on the ordinal position effect: The involvement of the task performed. *Acta Psychologica, 202*, 102978.

Wang, Q., Ma, L., Tao, W., Wang, Z., & Jin, G. (2021a). Encoding Numbers in the Context of Multiple Overlapping Cues: Evidence from a Chinese Finger Number Cognition Study. *Perceptual and Motor Skills*. 00315125211044051.

Wang, Q., An, B., Yue, H., Tao, W., & Shi, W. (2021b). Interaction mechanism between location and sequence in letter cognition. *Acta Psychologica, 217*, 103329.

Wang, Z., Zhu, X., & Jiang, Y. (2020). Influence of number location on the SNARC effect: Evidence from the processing of rotated traditional Chinese numerical words. *I-perception, 11*(2), 1–18.

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