

Automatic spatial association for luminance

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Abstract In the present study, we investigated whether luminance and the side of response execution are associated, showing a SNARC-like effect (faster responses with the left hand for dark stimuli, and vice versa for light stimuli). A total of 30 participants were tested in two experiments. In Experiment 1, the association between space and the luminance of chromatic stimuli was directly tested (brightness discrimination). In Experiment 2, the same spatial association was tested indirectly (hue discrimination). The results showed that participants responded faster with their left hand to hues with lower luminance, and with their right hand to hues with higher luminance, in either the direct or the indirect task. The consistency of this association in both tasks demonstrates the automaticity of the SNARC-like effect for luminance.

Keywords SNARC · Luminance · Hue · Spatial association

The spatial numerical association of response codes (SNARC) effect is a well-known phenomenon showing a spatial relation between number magnitude and the side of response execution (Dehaene, Bossini, and Giroux 1993). The original study showed that, in a parity judgment task, participants were faster at processing the parity of large one-digit numbers (e.g., 9 presented in the center of the screen) when responses were

executed in the right hemispace, whereas they were faster at judging the parity of smaller numbers (e.g., 1 presented in the center of the screen) when responses were executed in the left hemispace. The SNARC effect suggests that the representations of relatively small magnitudes are spatially compatible with the left hemispace, and those of relatively large magnitudes are spatially compatible with the right hemispace. Traditionally, this effect has been explained in terms of a left-to-right-oriented mental number line, even though other authors have proposed alternative explanations (see Gevers, Verguts, Reynvoet, Caessens, and Fias 2006; Proctor and Cho 2006).

This effect has been shown not only for number magnitude, but also for nonnumerical ordered sequences. Gevers, Reynvoet, and Fias (2003) investigated the spatial organization of two nonnumerical ordered sequences: months of the year and letters of the alphabet. The authors asked participants to judge whether months presented in the center of a screen came before or after “June,” and to judge whether letters presented in the center of a screen came before or after the letter “O.” The results showed that the mental representation of these ordinal sequences could be spatially coded, because the first months of the year were processed faster with responses executed in the left hemispace, whereas the reverse pattern was obtained for the last months of the year. Similar findings were reported in a task employing letters of the alphabet instead months.

SNARC-like effects have been found not only in the visual domain, but also in the auditory domain. For instance, Rusconi et al. (2006) explored the spatial representation of pitch height, using both horizontal and vertical response positions, in both direct and indirect tasks. In the direct task, nonmusicians were asked to judge whether a probe tone was higher or lower than a fixed reference tone, by pressing one of two keys with their left or right hand. In the indirect task, participants (nonmusicians and musicians) were exposed to relatively high or low tones, but were asked to classify the

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sounds as being produced by wind or percussion instruments, instead of judging the pitch. The results evidenced a SNARC-like effect, showing that the internal representation of pitch height is spatially organized, especially in participants with a formal musical education. This effect has been named the *spatial musical association of response codes* (SMARC) effect.

Summarizing, the SNARC effect can be found in different domains, suggesting a common mechanism for representing quantities in the spatial dominion. One of the most relevant attempts to group empirical evidence on magnitude processing was proposed by Walsh (2003) in his “A Theory of Magnitude” (ATOM). Walsh hypothesized the existence of a common code system that processes magnitude through three dimensions: time, space, and numerosity. Considering the more general concept of magnitude, relatively independent from the specific domain, the ATOM model can also explain the SNARC effect for nonnumerical ordered sequences. For this reason, instead of SNARC, Walsh suggested the name SQARC (spatial quantity association of response codes).

The ATOM model has many implications regarding the magnitude processing of both spatial and nonspatial dimensions. For instance, according to ATOM, the processing of numerical information and both spatial dimensions (e.g., size) and nonspatial dimensions (e.g., luminance) should cause mutual interference. In their review, Cohen Kadosh, Lammertyn, and Izard (2008; see also Bonato, Zorzi, and Umiltà 2012) described similar effect patterns (such as distance, size, and SNARC effects) with different kinds of quantities. In particular, they reviewed converging evidence in different domains, such as digit magnitude, geometrical shapes, lines length, pitch height, and luminance, consistent with the ATOM model.

Among the above-mentioned dimensions, only a few studies have investigated the magnitude representation of luminance and its interactions with other magnitudes. In these studies, luminance was mainly investigated in association with digits, by using a congruity paradigm (Algom, Dekel, and Pansky 1996; Henik and Tzelgov 1982). This paradigm assumes that an irrelevant variable (e.g., number magnitude) can affect the performance on a cognitive task (e.g., physical size judgments). Therefore, if pairs of digits are compared with respect to physical size, the irrelevant variable (e.g., number magnitude) would facilitate performance in congruent pairs (e.g., 5–8) and impair it in incongruent pairs (e.g., 5–8).

The first study to examine the association between luminance and other magnitudes was performed by Pinel, Piazza, Le Bihan, and Dehaene (2004). The authors, by using a congruity task, manipulated number, physical size, and luminance within a single stimulus. They asked participants to judge each of the above-mentioned dimensions in separate blocks, and found a significant interference between size and luminance, but little or no interference was observed between

number and luminance. However, the simultaneous manipulation of number, physical size, and luminance might have masked the association between number and luminance, as was suggested by Cohen Kadosh, Cohen Kadosh, and Henik (2008). Indeed, it has been reported that when manipulating only number and luminance, an association does emerge between these dimensions at both behavioral level and neuronal levels (Cohen Kadosh et al. 2008a; Cohen Kadosh and Henik 2006).

As concerns the latter two works (Cohen Kadosh et al. 2008a; Cohen Kadosh and Henik 2006), Gebuis and van der Smagt (2011) noted contrasting results in the direction of the association. Indeed, Cohen Kadosh and Henik (2006) found faster responses for stimuli that were numerically larger and darker, whereas Cohen Kadosh, Cohen Kadosh, and Henik (2008) found faster responses for numerically larger and brighter stimuli. Gebuis and van der Smagt hypothesized that this effect could be due to either luminance or luminance contrast, because in previous studies faster responses for numerically larger and darker stimuli had been found with a bright background (relative to all of the stimuli), and faster responses for numerically larger and brighter stimuli had been found with a dark background (relative to all of the stimuli). In their study, they used a congruity task, comparing either numbers or luminance. In the first case, they found that the luminance contrast hypothesis fitted the results better, whereas in the second case, they found confirmation for the luminance hypothesis.

In general, it seems that an association exists between luminance, numbers, and physical size, but the association between luminance and side of response execution is a phenomenon that has been rarely examined. As of now, only two studies have investigated the existence of a SNARC-like effect for luminance. However, these studies found apparently contrasting results, rendering this effect quite elusive. For this reason, we decided to further investigate this phenomenon.

The first study that addressed this issue, even though this was not its primary aim, was the above-mentioned one by Cohen Kadosh, Cohen Kadosh, and Henik (2008). They failed to report an association between luminance and side of response execution, whereas they confirmed an association between number magnitude and side of response execution (the classical SNARC effect). However, Cohen Kadosh, Cohen Kadosh, and Henik manipulated number magnitude and luminance within a single stimulus, and this could have masked a SNARC-like effect for luminance.

The second study, conducted by Ren, Nicholls, Ma, and Chen (2011), investigated SNARC-like effects for different types of magnitudes (numerical, physical, luminance, conceptual, and sound intensity magnitudes). This is the only study that has reported a SNARC-like effect for luminance. Indeed, whereas the previously described studies manipulated luminance in association with other variables (magnitude and/or

physical size) in congruity tasks, Ren et al. asked participants to perform a direct luminance comparison in their third experiment. The participants were exposed to a reference gray disk, followed by a second disk that was brighter or darker than the reference disk, and were asked to judge whether the second disk was darker or brighter than the reference by pressing a left or a right key. It is important to highlight that both disks were always darker than the gray background. The results evidenced that responses with the right hand were faster to darker stimuli, and responses with the left hand were faster to brighter stimuli.

On the basis of our review of the available literature, we came to the conclusion that two points need to be taken into consideration. The most important one is that Ren et al. (2011) reported a SNARC-like effect by adopting a direct task (luminance comparison), which does not allow us ascertain whether the luminance spatial association is due to an automatic process, as in the classic SNARC effect obtained with an indirect task (parity judgment; Dehaene et al. 1993). The second concerns the hue of the stimuli. All of the previous experiments have used achromatic stimuli; however, it is not known whether the effect found by Ren and colleagues could be replicated with chromatic stimuli. Indeed, Fias, Lauwereyns, and Lammertyn (2001) failed to find the SNARC effect in an indirect task based on hue judgment. However, whereas the task-relevant information (hue) was a preattentive feature (Treisman and Gelade 1980), the irrelevant information (number) was not. Such difference between relevant and irrelevant information may have affected the results.

The first of the above-mentioned considerations is of crucial importance for the present study. Indeed, our purpose was to verify the existence of a relation between luminance and the side of response execution, in both direct and indirect SNARC-like tasks. Unlike all of the above-mentioned studies, we used chromatic instead of achromatic stimuli. This methodological innovation allowed us to introduce a task-irrelevant dimension (hue discrimination) in the indirect task. Because we adopted chromatic stimuli, in a first experiment we investigated the effect reported by Ren et al. (2011) by using an analogous direct-comparison task for luminance. In a second experiment, we made use of the same chromatic stimuli to explore the automaticity of the association with an indirect task. Unlike in Fias, Lauwereyns, and Lammertyn (2001), in our case the relevant and irrelevant forms of information (hue and brightness) were both preattentive features.

Experiment 1: Direct task

Method

Participants A group of 30 students participated in Experiment 1: 15 males ($M = 25.7$ years, $SD = 2.34$)

and 15 females ($M = 25.4$ years, $SD = 2.87$). All of the participants were right-handed and had normal or corrected-to-normal vision.

Apparatus and stimuli We used the E-Prime software, version 1.2, to create and control Experiment 1 (www.pstnet.com/eprime.cfm). The stimuli were colors, mostly different in hue but similar in luminance (seven unique reds and seven unique greens; see Fig. 1). Because our task was to investigate whether reaction times (RTs) to the hue of a color would depend on its luminance, the luminances of the seven colors of a series were different, but the luminance was the same for paired hues in the two series. Equiluminance was determined, in a first step colorimetrically, in a second step it was corrected following the minimum distinct border method, as was proposed by Boynton (1973). On the basis of this procedure, the two colors of each pair, in alternating stripes side by side, were visually compared, and the luminance of one of them was changed until the border dividing the two colors appeared to be minimally distinct to the observer. The final versions of the colors were specified in the CIELUV 2° space (suitable to describe self-luminous colors), for a luminance close to D65 (see Table 1 and Fig. 2).

Colors were presented on a calibrated monitor (Quato Intelli Proof 242 excellence). Each trial encompassed the following stimuli: a fixation cross measuring $1\text{ cm} \times 1\text{ cm}$, and a square (red or green) measuring $12.50\text{ cm} \times 12.50\text{ cm}$. All stimuli were presented in the center of the screen against a black background.

Procedure Experiment 1 took place in a quiet, dimly lit room without environmental distractions. Participants sat in front of the monitor and were asked to put their left index finger on the “A” key and their right index finger on the “L” key. The viewing distance was 57 cm. Each trial started with a fixation cross displayed at the center of the screen for 300 ms, followed by a black screen for 130 ms. Afterward, the reference hue was presented for 1,000 ms, followed by an interstimulus interval (ISI) of 700 ms. Then, the target square appeared in the center of the screen for 1,000 ms or until the response was executed. The intertrial interval (ITI) was 1,500 ms (see Fig. 3). Participants had to judge whether the displayed hue was more or less bright than the reference hue (Luminance Level 4; see Fig. 1). Half of the hue stimuli were green, and the other half were red.

Experiment 1 comprised two sessions. In the first, participants were asked to press the rightmost key with their right index finger when the hue was brighter than the reference hue, and to press the leftmost key with their left index finger when the hue was darker than the reference hue. In the second session, the instruction was the opposite (right–darker, left–brighter). A short break was interposed between sessions, and the order of session presentation was counterbalanced across

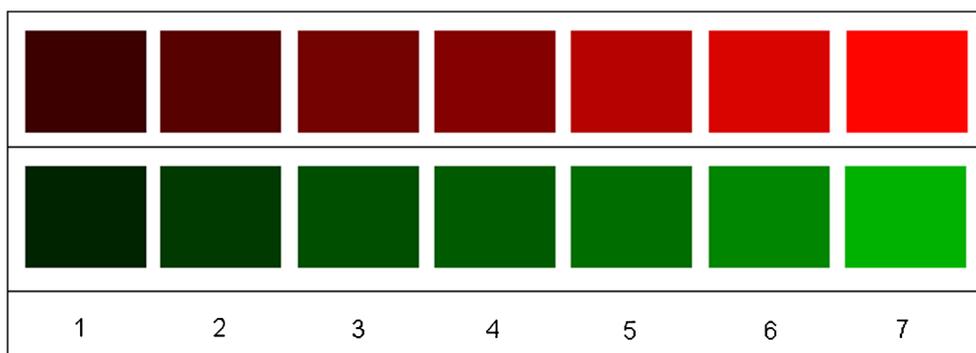


Fig. 1 Stimuli

participants. Each session comprised two blocks of trials (training block and experimental block). Each session started with the training block (12 trials), and after that the experimental block was presented. Each hue was compared five times with the reference hue in the experimental block (60 trials). This resulted in a total of 144 trials. Finally, the order of Experiments 1 and 2 was counterbalanced across participants.

Results

The data were analyzed with a regression analysis for repeated measures (Fias et al. 1996; Lorch and Myers 1990). The independent variable was the hue luminance, and the dependent variable was the difference between the median RTs of the left and right hands: $dRT = RT(\text{right hand}) - RT(\text{left hand})$. A total of 13% of the trials were excluded from the analysis due to incorrect responses.

In the first step, for each participant the median RT of correct responses was computed across all levels of luminance, separately for left- and right-hand responses. Then, dRT was computed by subtracting the median RT of left-hand responses from the median RT of right-hand responses. In the second step, a regression equation was computed across all levels of luminance for each participant. In the third step,

Table 1 $L^*u^*v^*$ values of the seven red and seven green colors used in Experiments 1 and 2 (illuminant close to D65)

Color	L^*	Reds u^*	v^*	Greens u^*	v^*
1	59	170.52	35.08	-50.35	78.68
2	50	146.25	30.09	-44.36	69.32
3	44	121.99	25.10	-38.37	59.95
4	38	97.72	20.11	-32.37	50.59
5	32	73.46	15.11	-26.38	41.22
6	24	49.19	10.12	-20.39	31.86
7	14	24.93	5.13	-14.39	22.49

Unit of $L^* = \text{cd/m}^2$. The value of white was 120 cd/m^2

one-sample t tests were performed in order to test whether the regression beta weights of the group deviated significantly from zero.

The analysis revealed that the regression slopes (regression beta coefficients) were significantly different from zero, $t(29) = 8.220$, $p < .001$. More precisely, participants were faster to process lower-luminance stimuli with their left effector, and to process higher-luminance stimuli with their right effector (see Fig. 4).

Discussion

Our results confirm that the spatial luminance association obtained by Ren et al. (2011) is also present for chromatic stimuli. However, we found that the spatial luminance association was reversed as compared with the findings of Ren et al., probably because we used a background darker, rather than brighter, than the stimuli. Indeed, our results showed that luminance is spatially represented as dark–left and bright–right (as hypothesized also by Cohen Kadosh, Cohen Kadosh, & Henik 2008). Moreover, these results were obtained with a direct task, in which participants were explicitly required to judge luminance. However, it is not clear whether the spatial quantity association for luminance is automatic or was induced by the direct task. To further investigate this phenomenon, we ran a second experiment using an indirect method.

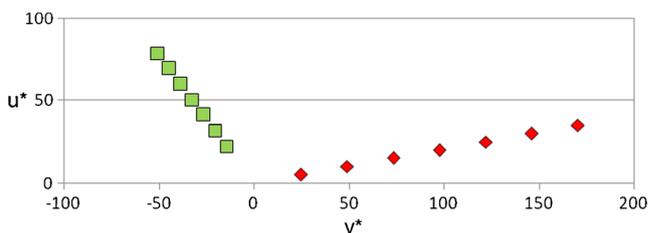


Fig. 2 u^* and v^* coordinates of the experimental colors in a CIELUV 2° diagram. Diamonds represent the series of red stimuli and squares represent the series of green stimuli

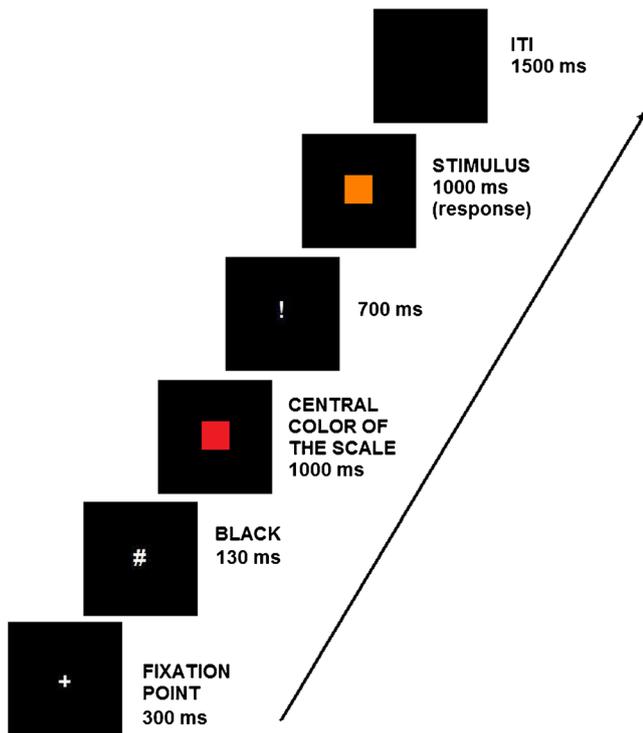


Fig. 3 Direct task: Example of trial sequence and timing

Experiment 2: Indirect task

Method

Participants The participants were the same as in Experiment 1.

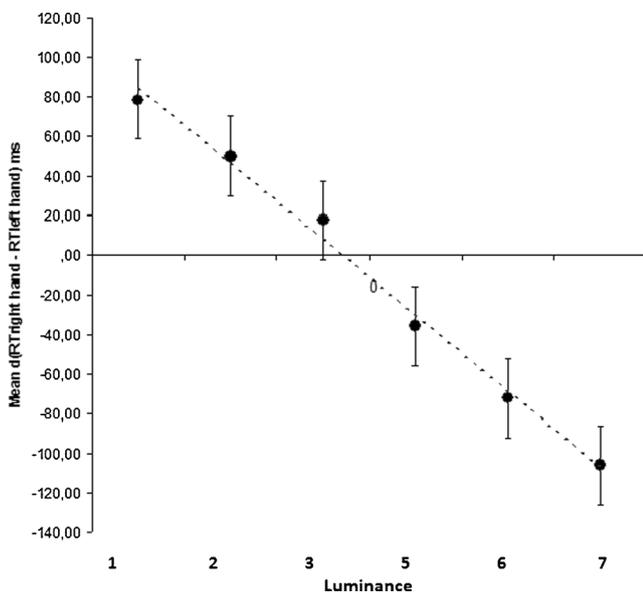


Fig. 4 Mean differences (± 2 SEMs) of the median right-hand RT–median left-hand RT for the direct task. Positive values indicate faster left-hand responses; negative values indicate faster right-hand responses

Apparatus and stimuli The apparatus and the stimuli were the same as those of Experiment 1.

Procedure The procedure was similar to that adopted in Experiment 1. Each trial started with a fixation cross displayed for 300 ms, followed by a black screen for 130 ms. Then the target square appeared in the center of the screen for 1,000 ms or until the response was executed (see Fig. 5). Participants were asked to judge, by pressing one of two keys (“A” or “L”), whether the hue of the square was red or green. The ITI was 1,500 ms.

Experiment 2 comprised two sessions. In the first session, participants were asked to press the rightmost key (“L”) with their right index finger when the square was red, and the leftmost key (“A”) with their left index finger when the square was green. In the second session, the instruction was the opposite (right–green, left–red). A short break was interposed between sessions, and the order of sessions was counterbalanced across participants. Each session comprised two blocks of trials (training block and experimental block). Each session started with the training block of 12 trials, followed by the experimental block, in which each of the 12 hues (six green and six red) was presented five times in random order (60 trials). This resulted in a total of 144 trials.

Results

The data analyses were the same as those carried out in Experiment 1. A total of 6% of the trials were excluded from the analysis due to the incorrect responses. The analyses revealed that the regression slopes (regression beta coefficients) were significantly different from zero, $t(29) = 7.771, p < .001$. We found a left-effector advantage in processing hues with smaller luminance, and a right-effector advantage in processing hues with greater luminance (see Fig. 6).

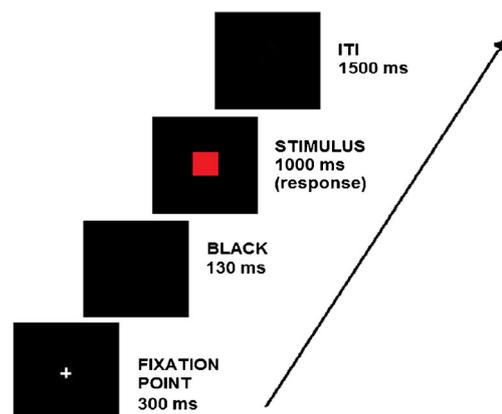


Fig. 5 Indirect task: Example of trial sequence and timing

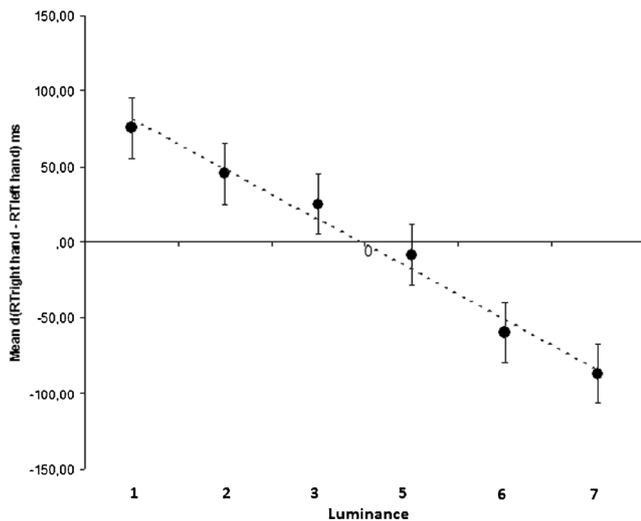


Fig. 6 Mean differences (± 2 SEMs) of the median right-hand RT–median left-hand RT for the indirect task. Positive values indicate faster left-hand responses; negative values indicate faster right-hand responses

Discussion

The results of the second experiment confirmed those obtained in the first one. Indeed, using the same stimuli and background as in the first experiment, the spatial luminance association (dark–left and bright–right) was verified with the indirect task, as well. This result proves the automaticity of smaller luminance–left hemispace and larger luminance–right hemispace associations when the background is darker than the stimuli.

General discussion

The aim of the present study was to investigate the existence of a relation between luminance and the side of response execution, in both direct and indirect tasks. We tested this hypothesis using a SNARC-like paradigm, in which participants had to directly judge the luminance in a comparison task (Exp. 1) and to discriminate the stimulus hue in an indirect task (Exp. 2). Consistent with our expectations, we found a spatial–luminance association. In particular, participants showed a left-hand advantage in processing low luminance and a right-hand advantage in processing higher luminance, in both direct and indirect tasks.

The most important result of the present study is the evidence of the automatic association between luminance and space. Indeed, even when the task did not require a direct discrimination between luminance quantities, we found a bias in participants' response times between the left and right hands. This means that the effect is not due to the mere instructions given to the participants, as might have been the case in the first experiment of the present work and the third

experiment of Ren et al. (2011); instead, we proved that this effect is automatic and task-independent. However, the direction of this association seems to be influenced by factors other than the requirements of the direct and indirect tasks.

Indeed, the direction of the association described in both of our experiments was the opposite of that found by Ren et al. (2011), and is apparently contradictory with their results. However, as Gebuis and van der Smagt (2011) noted, background luminance can play a role in reversing the direction of a number–luminance association. Thus, this is likely to be the most plausible explanation for the different directions of our and Ren et al.'s results. Indeed, whereas Ren and colleagues used a background brighter than the stimuli, in the present study we used a background darker than the stimuli. In any case, we cannot be certain that, by reversing the luminance of the background, the direction of the spatial luminance association would be the opposite. In fact, we did not explore such a possible reversal of the effect.

A second point that we addressed in this study concerns the hue of the stimuli. Indeed, whereas previous experiments had used achromatic stimuli, for the first time we introduced chromatic stimuli, allowing us to indirectly study a SNARC-like association for luminance. Unlike Fias, Lauwereyns, and Lammertyn (2001), we found a SNARC-like effect using a hue judgment task. We can speculate that these different outcomes may be due to the different processing levels of the relevant and irrelevant information (preattentive and semantic in the earlier study, but both preattentive in the present study). However, further research will be needed to better investigate our hypothesis.

With regard to the theoretical aspects, our findings demonstrate that luminance is spatially coded, as are other types of magnitudes (such as numbers, physical size, pitch, etc.). For this reason, the outcome of the present study provides empirical evidence supporting the ATOM model and is in line with the idea that spatial representation might be the most suitable form for representing various types of magnitudes (Walsh 2003). Therefore, our empirical evidence confirms the idea of a general mechanism, independent of magnitude type, and is consistent with the SQUARC (“spatial quantity association of response codes”) effect proposed by Walsh.

In conclusion, we further confirmed the spatial association of response codes for luminance, extending knowledge in the dominion of the SNARC-like effects. In particular, the innovations of the present study regarded the demonstration that this association is automatic and task-independent, and that it is not limited to achromatic colors. Indeed, for the first time a spatial luminance association has been consistently demonstrated in both direct and indirect tasks, confirming the strength of this effect.

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