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Early is left and up: Saccadic responses reveal horizontal and vertical spatial associations of serial order in working memory

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Abstract

Maintaining serial order in working memory is crucial for cognition. Recent theories propose that serial information is achieved by positional coding of items on a spatial frame of reference. In line with this, an early-left and late-right spatial-positional association of response code (SPoARC) effect has been established. Various theoretical accounts have been put forward to explain the SPoARC effect (the mental whiteboard hypothesis, conceptual metaphor theory, polarity correspondence, or the indirect spatial-numerical association effect). Crucially, while all these accounts predict a left-to-right orientation of the SPoARC effect, they make different predictions regarding the direction of a possible vertical SPoARC effect. In this study, we therefore investigated SPoARC effects along the horizontal and vertical spatial dimension by means of saccadic responses. We replicated the left-to-right horizontal SPoARC effect and established for the first time an up-to-down vertical SPoARC effect. The direction of the vertical SPoARC effect was in contrast to that predicted by metaphor theory, polarity correspondence, or by the indirect spatial-numerical association effect. Rather, our results support the mental whiteboard-hypothesis, according to which positions can be flexibly coded on an internal space depending on the task demands. We also found that the strengths of the horizontal and vertical SPoARC effects were correlated, showing that some people are more prone than others to use spatial references for position coding. Our results therefore suggest that context templates used for position marking are not necessarily spatial in nature but depend on individual strategy preferences.

Keywords: working memory; serial position; spatial association; SPoARC effect; ordinal position effect; mental whiteboard hypothesis

1. Introduction

1.1 Serial ordering in working memory

The concept of working memory assumes that a limited capacity system enables us to hold and manipulate information in mind, which is a fundamental prerequisite for human cognition (e.g., Alloway & Alloway, 2010; Murray et al., 2017; Wilhelm et al., 2013). A crucial aspect of working memory is the serial ordering of information (e.g., Lashley, 1951). Holding in mind what happened before and relating it to what happens next allows us for example to make sense of language or to see relations between items or ideas, which is fundamental for comprehension, reasoning and decision making (e.g., Baddeley, 2003; Daneman & Merikle, 1996; Diamond, 2013). Various models have been proposed to account for how serial order in working memory is created. Chaining models assume that each item is a cue for the next item (pairwise binding), whereas contextual models assume that successive items are associated with a contextual cue, such as the serial position of the item in the list (Baddeley, 2003). While chaining models have been rejected as exclusive mechanism of serial order (especially for short lists of items; Burgess & Hitch, 2006; Farrell et al., 2013; Hurlstone et al., 2014), most current models of working memory assume some form of positional coding of items (Botvinick & Watanabe, 2007; Brown et al., 2000; Henson, 1998; Lewandowsky & Farrell, 2008; Majerus & Oberauer, 2019).

Since a position is always embedded in a context, serial position coding inevitably relies on some form of reference system, such as start vs. end (Henson, 1998), encoding strength (Page & Norris, 1998), oscillatory response (Brown et al., 2000), or rank (Botvinick & Watanabe, 2007). More recent studies have pointed to a *spatial* reference system as possible mechanism for serial position coding, with early items associated with the left side, and late items with the right side of space (e.g., Abrahamse et al., 2014; Belder et al., 2015; Botvinick & Watanabe, 2007; Ginsburg et al., 2017; Oberauer, 2009; Rasoulzadeh et al., 2020). Initial evidence for this hypothesis has been shown in seminal studies by Previtali et al. (2010) and by van Dijck and Fias (2011). Van Dijck and Fias asked participants to memorize arbitrary sequences of numbers (e.g., 4-8-6-1-3) in correct order and to reproduce these sequences after a retention interval. Critically, during the retention interval, participants performed a brief number classification task (parity judgment), whereby responding only to those numbers that were part of the memorized sequence (this ensured that working memory retrieval was needed during the classification task). They found that participants in general responded faster with left-sided responses to early (vs. late) items, and faster with right-sided responses to late (vs. early) items of the memorized sequence. A similar interaction between serial order and lateralized spatial processing has now been replicated in several studies (Antoine et al., 2017; Belder et al., 2015; Ginsburg et al., 2014, 2017; Ginsburg & Gevers, 2015; Guida et al., 2016; Huber et al., 2016; van Dijck et al., 2013, 2014b; Zhou et al., 2020). The association between space and serial position in working memory has been termed the *ordinal position effect* (Ginsburg et al., 2014), or also the *spatial-positional association of response codes* (SPoARC) effect (e.g., Guida et al., 2016). The latter term is borrowed from the well-known spatial-numerical association of response code (SNARC) effect, showing faster left-sided responses to small, and faster right-sided responses to large numbers (e.g., Dehaene et al., 1993; Fischer & Shaki, 2014). The SPoARC and the SNARC effects are conceptually related since they both reflect a spatial association between stimuli and response, although the exact relationship between these two effects is still under discussion (Abrahamse et al., 2016; Belder et al., 2015; Ginsburg et al., 2014; Ginsburg & Gevers, 2015; Guida & Campitelli, 2019; Huber et al., 2016; van Dijck & Fias, 2011; van Dijck et al., 2014b).

1.2 Theoretical accounts of the SPoARC effect and their predictions regarding spatial associations

The question about the nature of the spatial association of serial positions in working memory has received much attention in recent years, and its origin is still debated (for a discussion see Guida et al., 2018). The most common theoretical accounts are the *mental whiteboard hypothesis*, the *conceptual metaphor theory*, the *polarity correspondence account,* and the *indirect spatial-numerical association effect*. To anticipate, all these accounts have in common that they predict a left-to-right direction of the horizontal SPoARC effect. However, they make different predictions regarding the direction of a *vertical* SPoARC effect (from up-to-down vs. from down-to-up). Previous research about the SPoARC effect has almost exclusively focused on horizontal spatial associations, and we argue that investigating both horizontal *and* vertical spatial associations is important for further evaluating the possible contribution of the different theoretical accounts. To make this point clear, we briefly summarize the different theoretical accounts and their predictions regarding horizontal and vertical spatial associations of serial position in working memory.

1.2.1 The mental whiteboard hypothesis

The most prominent explanation of the SPoARC effect is that items of a sequence are mentally represented within an internal space (a “mental whiteboard”), and that the filling direction on this internal space is determined by cultural habits, such as reading/writing direction (Abrahamse et al., 2014, 2016; see also Oberauer, 2009). Evidence for this assumption comes from Guida, Megreya et al. (2018) who found a left-to-right orientation for Western readers, a reversed (right-to-left) orientation for Arabic readers, and no reliable orientation of the SPoARC effect for illiterate people. These results confirm that reading/writing direction drives the direction of the SPoARC effect, although more recent research also showed that the direction of the SPoARC effect can be reversed *within* Western readers depending on specific experimental manipulations (Guida, Abrahamse, et al., 2020; Guida, Mosinski, et al., 2020). Nevertheless, the mental whiteboard hypothesis points to a default left-to-right direction of the horizontal SPoARC effect for wester cultures.

Although the mental whiteboard hypothesis relies primarily on the horizontal dimension of space (Abrahamse et al., 2016; Rinaldi et al., 2015), Abrahamse et al. (2014) theorized the possibility of a vertical arrangement of working memory contents, but this hypothesis has not yet been tested empirically. Following the mental whiteboard hypothesis, the direction of such a possible vertical association would be determined by our most dominant experience with information processing, which is from *up-to-down* (Abrahamse et al., 2014). Thus, the mental whiteboard hypothesis predicts an early-up and late-down spatial association of the vertical SPoARC effect.

1.2.2 Conceptual metaphor theory

Another potential mechanism underlying the spatial association of serial position has been proposed by Zhou et al. (2019). Based on Lakoff and Johnson’s assumption that the human conceptual system is fundamentally metaphorical in nature, Zhou et al. (2019) hypothesized that the spatial association of serial position may emerge from a general application of orientational/spatial metaphors that we use in daily life (Lakoff & Johnson, 2003). Specifically, it has been proposed that magnitudes are conceptualized metaphorically as a location on a path (Lakoff & Nunez, 2000), and the concept of *more* is associated with *right* (the MORE IS RIGHT metaphor; cf. Lakoff & Johnson, 2003). For example, more of something, such as higher number magnitudes in a graph, or citizens with more financial resources in a demographic illustration, are typically illustrated *to the right* of their lower-magnitude counterparts. Consequently, *more,* in the sense of a *higher/further position* in a sequence, is associated with the right side of space, leading to the left-to-right orientation of the horizontal SPoARC effect (Zhou et al., 2019).

Regarding the vertical spatial association, conceptual metaphor theory suggests that the direction of the spatial association is determined by the “MORE IS UP” metaphor (Lakoff & Johnson, 2003; Winter, Marghetis, et al., 2015). This metaphor describes the fact that *more* is typically associated with the *upper space.* For example, bigger buildings occupy more of the upper space than smaller buildings, and we often observe an increase in the vertical level when we put *more* items together (e.g., adding water in a glass vertically increases the water level). The MORE IS UP metaphor is also reflected in language: we use the spatial terms *high* or *low* in order to express large and small magnitudes (e.g., a *high* number). By considering *more* as a *higher/further* position in a sequence, conceptual metaphor theory predicts a down-to-up orientation of the vertical SPoARC effect (Zhou et al., 2019).

1.2.3 The polarity correspondence principle

A further possible mechanism for the spatial association of serial position is the polarity correspondence principle (Proctor & Cho, 2006). According to this principle, stimuli and response dimensions are coded in terms of a positive [+] or a negative [-] polar, and processing is facilitated when the polarities between the stimulus and the response correspond. Many congruity effects from binary response classification tasks can potentially be explained in this way (Proctor & Cho, 2006). For example in the case of numbers, it is assumed that small numbers have a [-] polar, and large numbers a [+] polar (Proctor & Cho, 2006; Santens & Gevers, 2008). A possible explanation for such a polar association is the asymmetric use of magnitude dimensions: We tend to ask "How large/big/much is it?" rather than "How small/tiny/less is it?". Thus, the [+] polar is attributed to the more dominant (or sometimes called "unmarked") stimulus dimension (Nuerk et al., 2004). Regarding the response dimension, right is considered as [+] because right is the more dominant response for most people, and the word *right* is more frequent than *left* (Winter, Matlock, et al., 2015). Thus, polarity correspondence between numbers and space can potentially explain the SNARC effect (Proctor & Cho, 2006). In the case of time, we tend to ask: "How late is it?" rather than "How early is it?". One could therefore assume that early items would be coded by means of [-], and late items by means of [+] polarity, leading to the left-to-right orientation of the horizontal SPoARC effect (Antoine et al., 2017; Zhou et al., 2020).

Regarding the vertical response dimension, downward responses are considered as [-], and upward responses as [+] polars, because up is the more dominant response, and the word *up* is more frequent than *down* (Winter, Matlock, et al., 2015). Thus, if the vertical SPoARC effect is the result of polarity correspondence, an early-down [both -] and late-up [both +] association is expected.

1.2.4 The indirect spatial-numerical association effect

It has also been proposed that the spatial association of serial order might be the indirect result of the link between numbers and space (i.e., „numerical tagging“; see Belder et al., 2015; Botvinick & Watanabe, 2007; Guida, Abrahamse, et al., 2020). Accordingly, serially presented items may be tagged to number codes to maintain serial order (e.g., the first item is tagged as „1“, the second as „2“ and so on; cf. Marshuetz, 2005). These order tags then drive spatial processing in line with the well-established small-left and large-right SNARC effect (although such an indirect spatial tagging hypothesis has recently been rejected for the horizontal SPoARC effect by Guida, Abrahamse, et al., 2020).

Regarding the vertical spatial association of numbers, a small-down and large-up vertical SNARC effect has been established (Aleotti et al., 2020; Hartmann et al., 2012; Holmes & Lourenco, 2012; e.g., Schwarz & Keus, 2004; Winter, Matlock, et al., 2015; Winter & Matlock, 2013). Thus, if the spatial association of serial positions in working memory is the indirect result of spatial-numerical associations of the number tags (Antoine et al., 2017; Botvinick & Watanabe, 2007), then a small-down and large-up vertical SPoARC effect is expected.

1.3 The present study

The different theoretical accounts presented above have in common that they all predict a left-to-right direction of the horizontal SPoARC effect. Conversely, they make different predictions regarding the direction of a vertical SPoARC effect. Thus, the horizontal SPoARC effect alone is not diagnostic when assessing the potential contribution of these different accounts. We therefore argue that studying the SPoARC effect along the vertical spatial dimension is of theoretical relevance for the understanding of its origin. In the light of the theoretical implications of vertical spatial associations of serial positions, it is striking that previous studies almost exclusively focused on the horizontal SPoARC effect (Antoine et al., 2017; Belder et al., 2015; Ginsburg et al., 2014, 2017; Ginsburg & Gevers, 2015; Guida et al., 2016; van Dijck et al., 2013, 2014b). This is insofar surprising as the potential of involving different spatial dimensions as a means to understand the origin and characteristics of mental spatialization mechanisms has formerly been highlighted and applied for the conceptually related SNARC effect (for a review see Winter, Matlock, et al., 2015). Regarding the spatial association of serial position, only one study so far assessed a "pseudo"-vertical SPoARC effect using the established dichotomous response setting (i.e., comparing response time differences between two lateralized responses; Zhou et al., 2019). We consider it as "pseudo" because Zhou et al. (2019) did not isolate the response positions along the true vertical spatial dimension. Instead, they rotated an ordinary keyboard counterclockwise by 90° on the table and used the nearer key ("D") as proxy for "down", and the further key ("L") as proxy for "up" responses (for a discussion of this issue see Winter, Matlock, et al., 2015). In line with the theoretical accounts of *metaphor theory*, *polarity correspondence*, and *the indirect spatial-numerical association effect*, they found evidence for a "down-to-up" oriented SPoARC effect in a Chinese sample, but only when the "up" response key was pressed by the right hand, and the "down" response key by the left hand. When they controlled for this left/right hand confound, there was no evidence in favor of a pseudo-vertical SPoARC effect anymore, suggesting that their finding was driven by an early-left and late-right association of response hands.

Moreover, Rinaldi et al. (2015) investigated whether spontaneous eye movements on a blank screen would reveal horizontal and vertical spatial associations of serial position during recognition of single items of a memorized sequence and during verbal free recall thereof. They found left-to-right shifts in gaze positions only during verbal free recall, and there was no evidence for a vertical association of serial position. However, the fact that Rinaldi et al. (2015) were not able to replicate the left-to-right association of serial position during recognition may suggest that the assessment of spontaneous eye movements is less sensitive in detecting spatial associations when compared to the more established assessment of RT differences between lateralized responses, since the manifestation of internal representations into detectable shifts in gaze positions also depends on individual scaling of time and space (e.g., Anderson et al., 2015; Gurtner et al., 2021). Moreover, in the recognition phase of Rinaldi et al.'s study, participants indicated whether the item did or did not belong to the memorized sequence. It has been suggested in other studies that a semantic processing of items, as it occurs for example during classification tasks, leads to stronger spatial associations when compared to recognition alone (Ginsburg et al., 2017; however see also Abrahamse & Guida, 2018). There are therefore several possible explanations for the absence of vertical shifts in spontaneous eye movements in Rinaldi et al.'s study (e.g., because the vertical association was simply not manifested in spontaneous eye movements, because the vertical association was trumped by the more dominant horizontal association, because of the methodological reasons described above, or because a vertical association does not emerge in a task that does not require vertical responses). However, even if no vertical spatial association of serial position develops on a spontaneous basis, it is still important to further explore the vertical SPoARC effect in order to better understand the flexibility and association principles of working memory. No study has so far investigated whether a vertical SPoARC effect would emerge when responses are given along the true vertical axis, and it remains unknown which direction it may have (down-to-up vs. up-to-down). The aim of this study was to fill this gap. Specifically, we assessed the existence and direction of the horizontal and vertical SPoARC effects by means of saccadic responses. Leftward/rightward and upward/downward saccadic responses were collected for the critical classification task of items from the memorized sequence. We used saccadic responses because they allow to separate the responses along the true horizontal and vertical spatial axes by placing gaze trigger keys to the left and right, and also below and above the centre of the screen. Moreover, saccadic responses do not induce a near-far dimension (as it is the case for manual responses along the sagittal axis, or for up/down keys located below the screen), and they do not induce a left/right hand confound for the up/down responses, all of which can bias spatial associations (Chen et al., 2015; Hartmann, Gashaj, et al., 2014; Santens & Gevers, 2008; Wiemers et al., 2017; Zhou et al., 2019, 2020). Thus, saccadic responses overcome critical issues that were observed in previous studies that used manual responses. Previous studies established that spatial congruity effects, such as the SNARC effect, can also be found with saccadic responses (Fischer et al., 2004; Hesse et al., 2016; Hesse & Bremmer, 2017; Schwarz & Keus, 2004). We therefore expected to find a horizontal and possibly a vertical SPoARC effect with saccadic responses in this study. Moreover, we will correlate the strength of the horizontal and vertical SPoARC effects in order to explore whether these associations reflect individual proneness to use a spatial reference system for internal coding, or respectively whether the mechanisms underlying the horizontal and vertical spatial associations are independent of each other (Bogdanova et al., 2008; Gevers et al., 2006; Winter & Matlock, 2013). This study thus further sheds light on the nature and flexibility of the spatialization of working memory.

2. Method

2.1 Participants

Thirty-two undergraduate students participated in return for course credit (mean age = 21.6, ranging from 19 to 35; 28 female). Participants gave informed consent prior to the study. The study protocol was approved by the local Ethics Committee.

Based on an a-priori power analysis with a frequentist approach of testing dRT values against zero by means of a one-sample *t*-test (see 2.5.3), we would need a sample size of $n = 34$ to reliably (with probability greater than 0.8) detect an effect size of $d \geq .5$, assuming a two-sided criterion for detection that allows for a maximum Type I error of $\alpha = .05$. Since our design requires that the number of participants is divisible by 4 (counterbalancing of order and response setting), we included 32 participants into the sample. Such a sample size is in the same range as in previous studies on the SPoARC effect (e.g., Ginsburg et al., 2014; Huber et al., 2016; van Dijck & Fias, 2011).

2.2 Apparatus and Experimental Setting

We used an EyeLink 1000 eye tracker (SR Research Ltd., Ontarion, Canada) with a sampling rate of 1000 Hz. Eye-tracking data was parsed into saccades using the manufacturer's default parameters. Participants placed their heads on a chin- and forehead rest. The head-to-screen distance was 800 mm. Stimuli were presented on a 520 x 300 mm monitor (1920 x 1080 px; 36 x 21.24°).

2.3 Stimuli

We used four-letter sequences for this study (cf. De Belder et al., 2017). We used letters instead of numbers because letters typically show a less pronounced inherent long-term spatial association, allowing for a "purer" (i.e., working memory determined) spatial association of serial positions (see discussion for a further elaboration on this issue). We used the four vowels "a", "e", "i", "u" and the four consonants "c", "n", "r", "s" for creating the to-be-memorized sequences and for the consonant-vowel-classification task. For the creation of four-letter sequences, we first created all possible four-letter combinations consisting of two vowels and two consonants. Eighteen of these combinations were chosen at random. For these 18 unique combinations, the four letters were ordered pseudo-randomly, so that all serial positions (1, 2, 3, 4) were filled an equal number of times by vowels and consonants across all sequences. We also ensured that all of the six possible vowel-consonant-orders (e.g., consonant-vowel-consonant-vowel) were used equally often. This procedure resulted in a set of 18 unique sequences consisting of two vowels and two consonants (Set A). Following the same procedure, we created a second set (Set B) of 18 different sequences, consisting of the same 18 letter combinations as in Set A but with different orders of letters. For half of participants, Set A was used to study the horizontal SPoARC effect, and Set B to study the vertical SPoARC effect, and vice versa for the other half of participants. An additional sequence was randomly chosen that was used as a practice block.

2.4 Procedure

Participants were seated in front of the eye-tracker. Following the 9-point calibration procedure, task instructions appeared on the screen. Participants were informed that the task involves several loops of the three steps described below (see Fig. 1). They were also informed that they needed to respond by executing leftward and rightward eye movements for half of the experiment, and by executing upward and downward eye movements for the other half of the experiment. The order of spatial dimension (horizontal, vertical) was counterbalanced across participants.

The experiment followed the typical three-phase procedure that has been established for the SPoARC effect (e.g., Ginsburg et al., 2017; van Dijck & Fias, 2011). In the first phase (*memorizing the sequence*), participants were asked to memorize one of the 18 four-letter sequences so that they will be able to recall the sequence later in the correct order. The four letters were presented sequentially in the center of the screen (26 pt. Arial). Each letter was presented for 1000 ms, separated by a blank screen for 10 ms. After the four letters have been presented, participants decided whether they wanted to see the sequence again (button "j" for "yes"), or continue to the next phase (button "n" for "no"). They could repeat the sequence for as many times as they wanted. Participants memorized the sequences in their minds (without speaking out loud).

In the second phase (*consonant-vowel-classification task*), participants were asked to classify each letter as vowel or consonant as quickly and correctly as possible. Prior to the start of the classification task, a fixation dot was presented in the centre of the screen that served as a drift correction for the eye-tracker. In the classification task, each of the eight letters from the stimulus set (cf. 2.3) was presented twice in the centre of the screen (26 pt. Arial) in random order, resulting in a total of 16 trials for each iteration of the second phase. Each letter was preceded by a fixation cross that was presented in the centre of the screen with a duration of 500 ms (see Fig. 1). The letter stimuli were accompanied by two saccade trigger response boxes (100 x 100 px; ~ 2.0 x 2.0°) that were located either at the left and right side of the screen (horizontal spatial dimension, see Fig. 1), or at the top and bottom of the screen (vertical spatial dimension). The distance from the center of each of the boxes to the center of the screen was 440 px (~8.6°). One box contained the capital "V" for vowel (Vokal in German), and the other the capital "K" for consonant (Konsonant in German) (26 pt. Arial). The allocation of "V" and "K" to the left and right (or respectively up and down) box was counterbalanced across participants.

Importantly, participants were asked to respond only to those letters that were part of the memorized sequence ("go"-trials). This ensured that the memorized sequence was held in working memory during the classification task. In this case, participants classified the letter as vowel or consonant by looking to the corresponding box ("V" or "K"). For letters that were not part of the memorized sequence ("no-go"-trials), participants were asked to keep their eyes fixated at the center of the screen, and the next trial started automatically after 3000 ms. The word "Falsch" ("wrong") appeared in red at the centre of the screen if participants (1) looked at the wrong box in a "go"-trial, or (2) did not look at one of the boxes in a "go"-trial within 3000 ms after letter onset, or (3) looked at any of the boxes in a "no-go"-trial. A blank screen of 500 ms appeared before the next trial started.

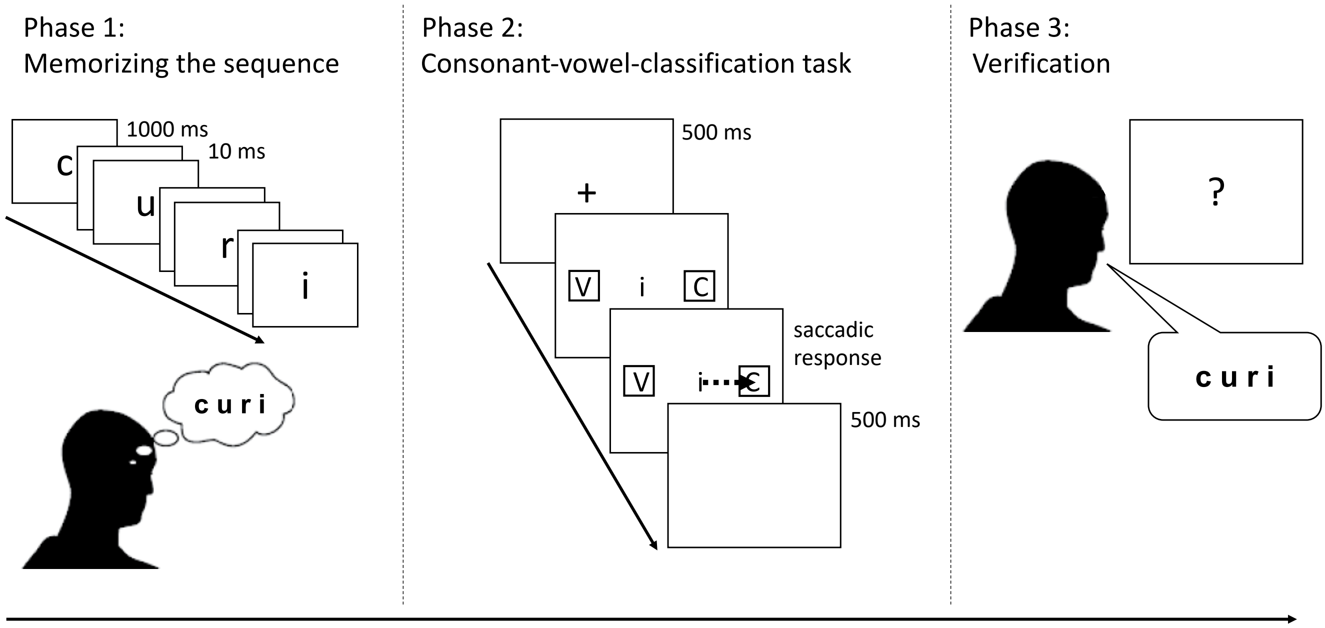
In the final phase (*verification*), participants were asked to name the previously memorized sequence aloud. To this end, a question mark was presented in the center of the screen after the completion of the classification task. The experimenter verified whether the sequence was correct. If correct, the experimenter pressed a corresponding key to proceed with the task. If the sequence was recalled incorrectly, the sequence (and the corresponding classification and verification task) was presented again at the end of the experiment. Following the experimenter's key press, the word "Richtig!" ("Correct!"; in green) or "Falsch!" ("Wrong!"; in red) appeared in the center of the screen. Participants were informed at the beginning of the experiment that incorrectly recalled sequences were repeated at the end of the task.

The entire procedure (phase 1-3) was repeated until all 18 sequences (plus the repetition of the incorrectly recalled sequences) were completed. Following this, a short break was provided, and then the same procedure started again with the second set of 18 sequences for the other spatial dimension (horizontal or vertical). Thus, without the repetition of incorrectly recalled sequences, each participant performed a total of 576 experimental trials (18 sequences x 16 trials per sequence x 2 spatial dimensions), whereby only half of the trials ("go"-trials; $n = 288$) were relevant for the analyses.

At the beginning of the experiment, participants performed two practice tasks. The first practice task consisted of a consonant-vowel-classification task (without having to memorize any sequence beforehand). Each of the eight letters was presented three times, resulting in 24 practice trials. The aim of this practice task was to familiarize participants with the saccade response setting. The second practice task was identical to the main procedure of the experiment, consisting of all three phases. The sequence used for this practice task was different from the 36 experimental sequences. The entire experimental session lasted about 1.5 hours.

Fig. 1

Illustration of the three Phases of the Task (Example of the Horizontal Response Condition)



2.5 Data analysis

2.5.1 Data processing

An effect of serial position can only be expected when participants actively represent the four-item-sequence in working memory during the classification task (Ginsburg et al., 2014). Participants incorrectly recalled the sequence for a total of 14 blocks (1.2%). These blocks were removed and repeated at the end of the experiment. We also removed blocks for which participants responded to 50% or more no-go trials (4 blocks; 0.3%), since such a behavior likely reflects temporarily loss of working memory content or inattention. Incorrect go-trials (50 no response and 530 incorrect classification) were removed from the analysis (total 580 trials; 6.3% of go-trials). There was no tradeoff between errors and reaction times for the go-trials ($p > .05$). Another 139 trials (1.6% of remaining go-trials) were removed because participants did not look at the center of the screen during target onset (central letter) or due to loss of the eye-tracking signal.

Saccade latency was defined as the time between the onset of the central letter and the start of the saccade that landed in the correct response box in go-trials. Latency values were log-transformed in order to account for the typical skewed distribution of saccade latencies, and values above or below 3 standard deviations from the individual means were excluded from analysis (54 trials; 0.6% of remaining go-trials). Thus, from the total of 9216 go-trials (288 x 32 participants), a total of 805 trials (8.7%) were excluded for the different reasons explained above. No participant was excluded from the analyses. Finally, the mean log-latency for each serial position, spatial dimension (horizontal, vertical), and response direction (leftward/rightward, upward/downward) was computed for each participant.

The SPoARC effect was analyzed by means of a Bayesian repeated measure regression analysis as well as by the frequentist dRT-approach.

2.5.2 Bayesian analysis

A Bayesian repeated measure linear regression analysis was performed using the brms-package in R (Bürkner, 2017). We used *serial position* (1-4; continuous predictor, centered for analysis), *response direction* (1 = leftward/upward, -1 = rightward/downward), and *spatial dimension* (1 = horizontal, -1 = vertical), as well as all higher order interactions between these three variables as fixed effects predictors. A random intercept effect for participants was added in order to account for the repeated measurement design. Since we used sum-coding, the intercept reflects the grand mean, and the estimates of the predictors reflect the deviation from the grand mean (i.e., the effects of interest). Most importantly, the interaction between serial position and response direction indicates the SPoARC effect, and the three-way-interaction indicates whether the SPoARC effect depends on the spatial dimension (horizontal vs. vertical). Specifically, in the way we combined the horizontal and vertical response directions (leftward/upward, rightward/downward), a significant three-way interaction can be expected in case there is a left-to-right horizontal, and a down-to-up vertical association. Analogously, the absence of a three-way interaction in combination with a significant two-way interaction between serial position and response direction indicates a left-to-right and up-do-down SPoARC effect. In any case, separate analyses for the horizontal and vertical responses will be performed to further assess the SPoARC effects.

Fixed effects predictors are summarized using the mean estimate, the estimation error, and the two-sided 95% Credible Intervals (CI) of the posterior distribution. The posterior distribution reflects the relative plausibility of the parameter values after prior knowledge has been updated by means of the observed data. In the Bayesian framework, there is evidence for the existence of an effect when zero is not included in the 95% CI. The Bayesian repeated measure linear regression analysis was performed on the mean log saccade latency values (averaged by participants, serial position, response direction and spatial dimension). We used four independent Markov chains, each using 10000 iterations to sample from the posterior distribution (and 5000 additional warm-up samples) with a Gaussian link function. Weakly informative student-t priors were used (df = 3, $SD_{\text{Errors}} = 2.5$). Graphical posterior predictive checks and MCMC diagnostics confirmed good model fit and convergence of the chains. The potential scale reduction factor on split chains also confirmed convergence (all Rhat values were below 1.01).

2.5.3 dRT approach

In previous studies, the SPoARC effect is typically assessed by computing the individual regression coefficients (betas) of the dRT values (rightward – leftward responses) as a function of serial position and then testing the beta values against zero by means of a one-sample *t*-test (Fias et al., 1996). For the sake of comparability of our results to previous studies, we also followed this approach (dRT = rightward-leftward responses for the horizontal spatial dimension, and dRT = downward-upward responses for the vertical spatial dimension). We also computed the correlation between the horizontal and vertical beta values. For all beta-related *t*-tests, we additionally reported the Bayes Factor using the BayesFactor package in R (Morey et al., 2018). Specifically, we reported the Bayes Factor_{10}, which quantifies the relative plausibility of the alternative hypothesis (H1) over the null hypothesis (H0). A BF_{10} between 1/3 and 3 is considered as inconclusive, whereas values above 3 are considered as evidence in favor of H1, and values below 1/3 as evidence in favor of H0 (Jeffreys, 1939).

3. Results

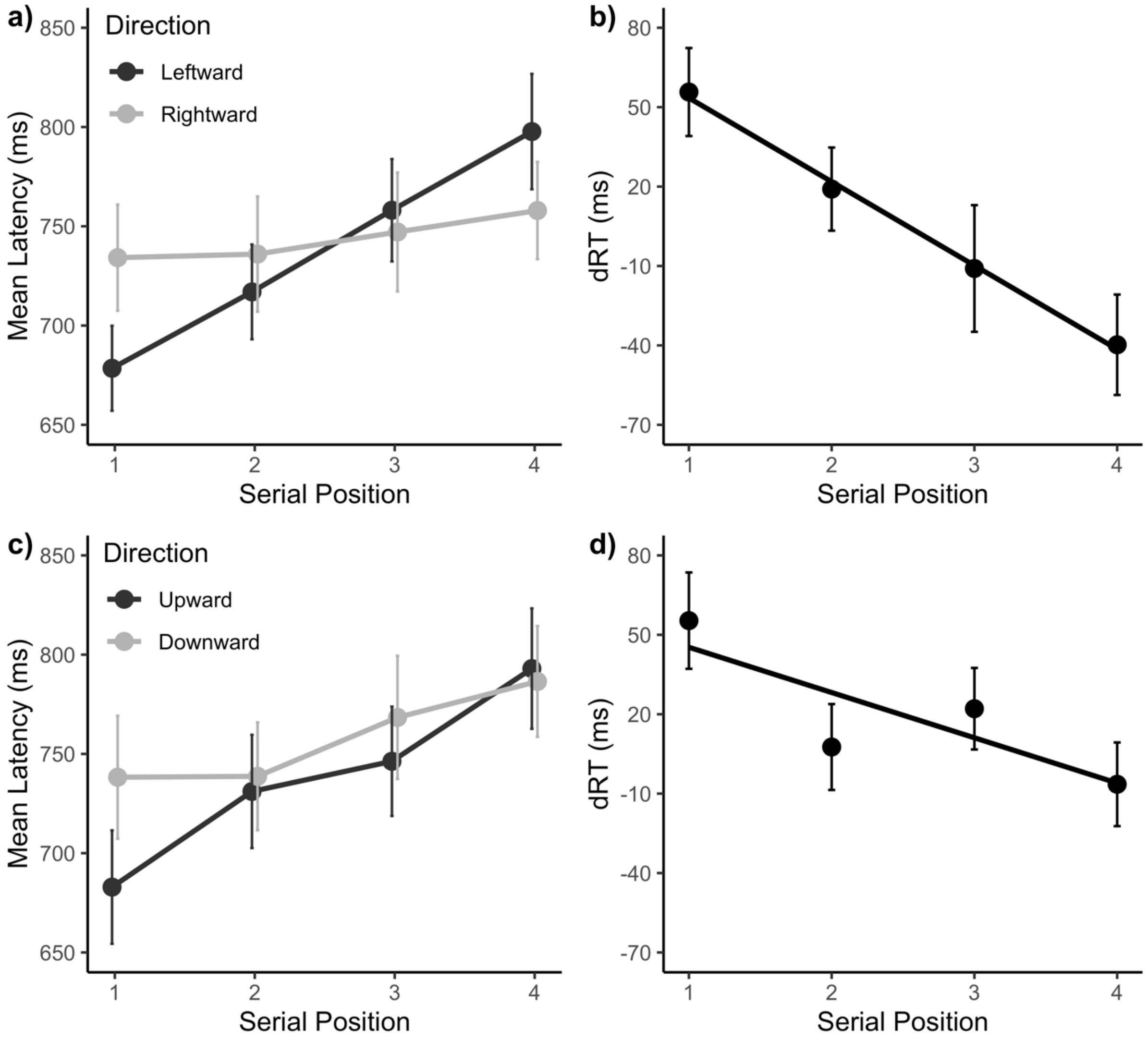
The data from this study are available at https://osf.io/nma7f.

3.1 Descriptive statistics

Mean saccade latency values (back-transformed log means) for each serial position, response direction, and spatial dimension, as well as the dRT values are summarized in Fig. 2.

Fig. 2

Mean Saccadic Onset Latencies



Note. Mean saccadic onset latencies (ms) for the horizontal (a) and vertical (c) spatial dimension as a function of the serial position in working memory. The right panel shows the linear fits of dRT values. dRT values express rightward-leftward responses for (b), and downward-upward responses for (d). Error bars depict +/- 1 *SEM*.

3.2 Bayesian regression analysis

The mean estimate, standard deviation, and the two-sided 95% CI of the posterior distribution are summarized in Table 1. Since the intercept reflects the grand mean (exponential function of $6.59 \approx 728$ ms), it was expected that zero was not included in the 95% CI. Moreover, the estimate of serial position indicates a significant linear increase in saccade latency with increasing serial positions. This effect was also expected and confirms that participants held the sequence in working memory during the classification task and performed a serial search when activating the item. There was also an effect of response direction, with faster leftward and upward (vs. rightward and downward) responses. Most importantly, zero was not included in the 95% CI for the interaction between serial position and response direction, indicating a SPoARC effect. The SPoARC effect was not moderated by spatial dimension (horizontal, vertical), as indicated by the inclusion of zero in the 95% CI of the three-way interaction.

In the next step, we further assessed the SPoARC effect separately for the horizontal and vertical spatial dimension by running the same analysis with the predictors serial position, response direction (leftward, rightward; or upward, downward, respectively), and the two-way interaction (SPoARC effect).

Table 1

Results of the Bayesian Repeated Measure Linear Regression Analysis for the Log Saccade Latency Values

	Estimate	Error	95% CI [l, u]
Intercept	6.591*	0.036	[6.523, 6.663]
SP	0.034*	0.004	[0.027, 0.042]
RD	-0.009*	0.004	[-0.017, -0.001]
SD	-0.004	0.004	[-0.012, 0.004]
SPoARC effect (SP x RD)	0.016*	0.004	[0.009, 0.023]
SP x SD	-0.002	0.004	[-0.009, 0.005]
RD x SD	0.005	0.004	[-0.003, 0.014]
SP x RD x SD	0.004	0.004	[-0.003, 0.011]

Note. SP = Serial Position; RD = Response Direction (leftward and rightward for the horizontal, and upward and downward for the vertical spatial dimension); SD = Spatial Dimension. The estimate of the intercept reflects the grand mean, and the other estimates reflect the deviation to the grand mean (in log-space). In the Bayesian framework, there is evidence for an effect when zero is not included in the 95% CI [l = lower, u = upper], as indicated by asterisks.

The results of the separate analyses are reported in Table 2. Importantly, the separate analyses clarify that there was a significant SPoARC effect for both the horizontal and the vertical spatial dimension (zero was not included in the 95% CI for the interaction between serial position and response direction). The analysis for the vertical spatial axis also revealed a significant effect of response direction, indicating that upward responses were faster than downward responses (see Fig. 2 c). This is a common finding for vertical saccadic responses that has also been found in other saccade response tasks (e.g., Dudschig et al., 2013; Goldring & Fischer, 1997; Hesse & Bremmer, 2017; Honda & Findlay, 1992; Schwarz & Keus, 2004).

Table 2

Results of the Separate Bayesian Repeated Measure Linear Regression Analysis for the Horizontal and Vertical Spatial Dimension

Effect	Horizontal			Vertical		
	Estimate	Error	95% CI [l, u]	Estimate	Error	95% CI [l, u]
Intercept	6.587*	0.036	[6.516, 6.658]	6.594*	0.037	[6.522, 6.665]
SP	0.032*	0.005	[0.023, 0.042]	0.036*	0.005	[0.027, 0.045]
RD	-0.004	0.005	[-0.014, 0.007]	-0.014*	0.005	[-0.025, -0.004]
SPoARC effect (SP x RD)	0.020*	0.005	[0.011, 0.029]	0.012*	0.005	[0.003, 0.021]

Note. SP = Serial Position; RD = Response Direction (leftward and rightward for the horizontal, and upward and downward for the vertical spatial dimension; leftward and upward were coded as 1, and rightward and downward as -1). The estimate of the intercept reflects the grand mean, and the other estimates reflect the deviation to the grand mean (in log-space). In the Bayesian framework, there is evidence for an effect when zero is not included in the 95% CI [l = lower, u = upper], as indicated by asterisks.

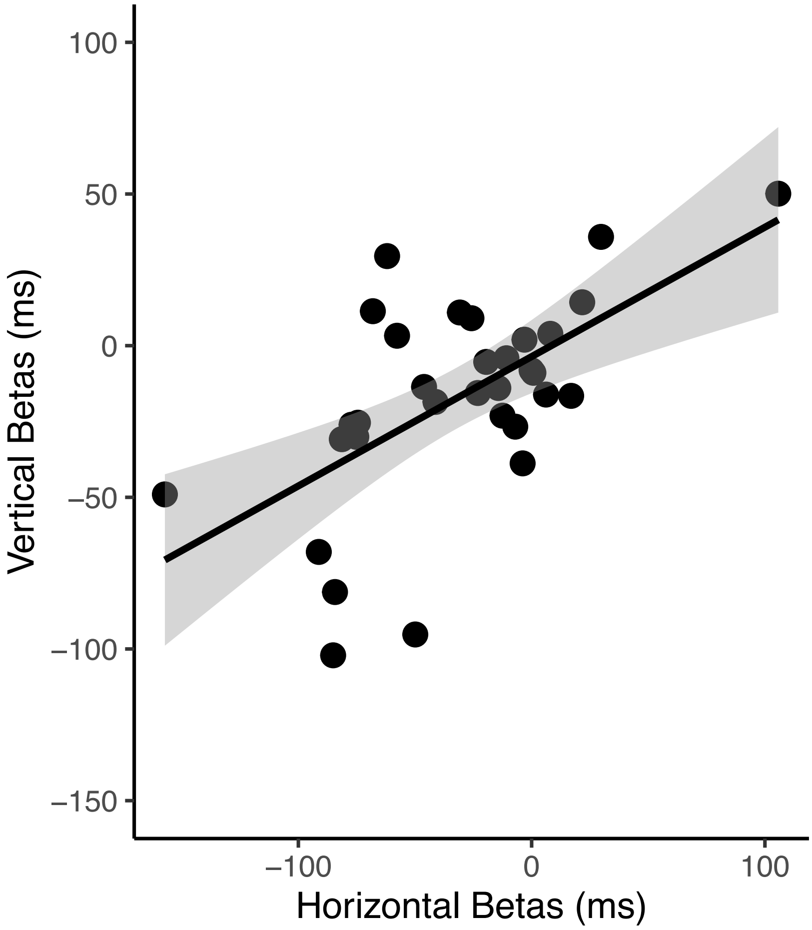
3.3 dRT analyses

We also illustrated and quantified the SPoARC effect in both spatial dimensions (horizontal, vertical) by means of the frequentist dRT approach by computing the individual regression coefficients (betas) for dRT values (rightward-leftward responses for the horizontal, and downward-upward responses for the vertical spatial dimension) as a function of serial positions, see Fig. 2 b and d. For the horizontal spatial dimension, the one-sample *t*-test of the betas confirmed a significant difference from zero (*M* = -32, *SEM* = 9), *t*(31) = -3.68, *p* < .001, Cohen's *d* = 0.65, Bayes Factor$_{10}$ = 36.68. The same was true for the vertical spatial dimension (*M* = -17, *SEM* = 6), *t*(31) = -2.81, *p* = .008, Cohen's *d* = 0.50, Bayes Factor$_{10}$ = 5.12.

The dRT analysis confirmed the SPoARC effects in both spatial dimensions. At the individual level, there were 25 participants (78.1%) with a negative beta value for the horizontal dRTs (indicating a left-to-right direction), and 22 participants (68.8%) with a negative beta value for the vertical dRTs (indicating an up-to-down direction). These proportions are in the same range as those typically reported for the SNARC effect (Cipora et al., 2016; Wood et al., 2008; for a critical discussion of this approach see Cipora et al., 2019). Crucially, there was a significant correlation between the horizontal and vertical beta values, Pearson's *r* = .603, *p* = < .001; Spearman's rho = .570, *p* = .002; Bayes Factor$_{10}$ = 130.00 (see Figure 3). From the 25 participants who showed a left-to-right direction of the horizontal SPoARC effect, 21 also showed an up-to-down direction of the vertical SPoARC effect.

Fig. 3

Scatterplot and Correlation between Horizontal and Vertical Betas



Note. Scatterplot of the horizontal (x-axis) and vertical (y-axis) individual regression coefficients (betas). Beta coefficients are obtained by individual linear regressions of dRT values as a function of serial position. Negative values indicate a left-to-right orientation of the horizontal SPoARC effect, and an up-to-down orientation of the vertical SPoARC effect, while positive values indicate the opposite spatial associations. The positive correlation indicates that participants showing a left-to-right horizontal SPoARC effect tend to show also an up-to-down vertical SPoARC effect.

In a final analysis, we assessed to what extend the vertical SPoARC might potentially be driven by the horizontal SPoARC effect. Specifically, it is conceivable that that the vertical SPoARC effect only emerged because of the participants who first performed the task in the horizontal spatial dimension, and then transferred the spatial association of serial positions to the vertical spatial dimension. In this case, the order of task condition (horizontal spatial dimension first vs. vertical spatial dimension first) would have an impact on the strength of the vertical SPoARC effect. To rule out this possible mechanism, we computed an independent *t*-test on the individual regression coefficients (betas) with the grouping variable *task order* (horizontal first, vertical first). There was no effect of task order, $t(30) = -0.22$, $p = .827$, Cohen's $d = 0.08$, Bayes $\text{Factor}_{10} = 0.34$.

As an interesting side note, visual inspection of our data shows that the horizontal SPoARC effect was mainly driven by a linear dependency of leftward responses on serial position (2a), and the vertical SPoARC effect by a linear dependency of upward responses (2c). Such an asymmetry in the emergence of spatial association effects (both SPoARC and SNARC) has recently been highlighted by Zhou et al. (2020). They concluded that left-hand responses are more sensitive to spatial-positional associations. Since we found the same pattern with saccadic responses, our results suggest that this asymmetry does not depend on hands but is rather effector-independent. Given that this effect is outside of the scope of the present study and given that there is currently no comprehensive explanation for such asymmetries (for a discussion see Zhou et al., 2020), we do not further elaborate on this issue.

4. Discussion

In this study, we assessed the horizontal and vertical spatial association of serial position in working memory by means of saccadic responses. We found that latencies for leftward and upward (vs. rightward and downward) saccades were relatively shorter when classifying early (vs. late) items from a sequence held in working memory. We thus replicated the well-established early-left and late-right horizontal SPoARC effect with saccadic responses, showing that this effect generalizes across different effectors (i.e., hands, eyes). Crucially, we provide first evidence that serial positions can also be associated along the vertical spatial axis. Previous research almost exclusively focused on the horizontal spatial dimension (Antoine et al., 2017; Belder et al., 2015; Ginsburg et al., 2014, 2017; Ginsburg & Gevers, 2015; Guida et al., 2016; van Dijck et al., 2013, 2014b), and theoretical work typically considers only the horizontal, left-to-right orientation of position coding (Abrahamse et al., 2016). Our results show that position coding is not restricted to the horizontal spatial dimension but rather suggest a flexible use of spatial frames of references for position coding. Specifically, when the task requires horizontal responses, a horizontal association of serial position codes is employed, and when the task requires vertical responses, a vertical arrangement is employed. Accordingly, the SPoARC effect seems to reflect how a specific serial order is mentally represented in working memory, and the spatial format of this representation is determined by specific task demands (Guida, Abrahamse, et al., 2020; Guida, Mosinski, et al., 2020).

Interpreting congruity effects as evidence for how people mentally represent concepts has been criticized in the past (Hutchinson & Louwerse, 2014; Santens & Gevers, 2008). Specifically, the polarity correspondence principle suggests that congruity effects in binary classification tasks can emerge based on purely structural features of response and stimuli (Proctor & Cho, 2006). Accordingly, the correspondence of the polarities between “left” and “early” [both -], and between “right” and “late” [both +] might account for the horizontal SPoARC effect we observed (Antoine et al., 2017; Zhou et al., 2020). In a similar vein, metaphor theory suggest that the spatial association of serial order can emerge from a general application of orientational/spatial metaphors that we use in daily life in order to describe quantities, such as MORE IS RIGHT (Lakoff & Johnson, 2003; Zhou et al., 2019). Thus, the horizontal SPoARC effect can be explained without assuming a spatial representation of serial order in working memory but rather by a structural (e.g., polarity) or conceptual (e.g., metaphorical) link between stimuli and response. However, we argue that the direction of the vertical association found in this study (up-to-down) is opposite to the direction predicted by polarity correspondence or metaphor theory, which both would favor a down-to-up direction, as it is also found for the vertical SNARC effect (Aleotti et al., 2020; Hartmann et al., 2012; Holmes & Lourenco, 2012; e.g., Schwarz & Keus, 2004; Winter, Matlock, et al., 2015; Winter & Matlock, 2013). Since the direction of the vertical SPoARC effect (up-to-down) was opposite to that typically found for the vertical SNARC effect (down-to-up), our results also rule out that the spatial association of serial position is the indirect result of spatial associations with numerical markers used for coding of serial order (Antoine et al., 2017; Belder et al., 2015; Botvinick & Watanabe, 2007; Guida, Abrahamse, et al., 2020).

Thus, none of these accounts (polarity correspondence principle, metaphor theory, indirect spatial-numerical association effect) provides an adequate explanation of the vertical SPoARC effect found in this study. Although we cannot rule out a role of these accounts for the horizontal SPoARC effect, our results nevertheless rather support the mental whiteboard hypothesis, according to which items in working memory are spatially represented (Abrahamse et al., 2014; Rasoulzadeh et al., 2020; van Dijck et al., 2013). Specifically, Abrahamse et al. (2014) assumed that a series of items is represented in an internal space, in analogy to writing the items down on a physical whiteboard. Our finding that spatial associations of serial positions can be found in both spatial dimensions (horizontal and vertical) is in line with such a whiteboard analogy, since we can also write in a flexible way on a physical whiteboard when required by the task (i.e., writing along the horizontal and vertical axis).

A central assumption of the mental whiteboard hypothesis is that whenever an item of a sequence held in working memory becomes relevant for a task (such as in the classification task in this study), a search-through of the set and selection/activation of the relevant item takes place, and that this process is related to spatial attention mechanisms (Abrahamse et al., 2014; Belder et al., 2015; Rasoulzadeh et al., 2020; van Dijck et al., 2013, 2014b). Specifically, the retrieval of an item in working memory engages the spatial attention system in a position-dependent way, following the format of the internal spatial representation of the sequence (in our case early-left/up, late-right/down). Spatial mechanisms are also involved in the effectors' response selection process. For example, it has been shown that eye movements and spatial attention are closely linked (e.g., Corbetta et al., 1998; Engbert & Kliegl, 2003). The SPoARC effects found in this study can be explained with such an attention framework: if the direction of the shift in spatial attention that is induced by the activation of the position code of the item is congruent to the direction of the response, then the programming of the saccade is facilitated.

Another assumption of the mental whiteboard hypothesis is that the "default" spatial arrangement of the serial positions is determined by reading/writing habits (Abrahamse et al., 2014, 2016; Guida et al., 2018). The direction of the horizontal SPoARC effect found in this study is in line with this assumption. Since we typically start reading on top of a page and move down, also the up-to-down direction of the vertical SPoARC effect can be considered as congruent to this assumption, at least in a broader sense (i.e., the flow of information is generally directed downwards). Thus, since our participants were all "expert" readers, it is possible that they used knowledge structures from reading when retrieving items from memory (see Guida & Campitelli, 2019 for a discussion of an expertise account). However, when taking a closer look at the reading/writing behaviour, it becomes evident that the downward movements during reading do not involve a "pure" downward displacement along the vertical axis but rather have a much stronger horizontal component: we jump from the right side to the left side of the page when reading the next line. Moreover, a short sequence of four letters, as used in this study, is typically arranged in a line and not in a colon. Reading such stimuli would therefore not involve any vertical eye movements. Thus, there is not much overlap between the "pure" vertical saccadic responses required in this study and the actual sensorimotor experience during reading/writing, neither for reading/writing in general nor for reading the specific stimuli at hand. This further strengthens the view that spatial reference systems can be flexibly used depending on the task demands and are not strictly determined by exact sensorimotor experiences during reading/writing (Guida, Abrahamse, et al., 2020; Guida, Mosinski, et al., 2020; Zhou et al., 2019).

Yet another assumption of the mental whiteboard hypothesis is that the context templates used for position marking are spatial in nature (Abrahamse et al., 2016). Our finding that spatial associations of serial position can also be found along the vertical spatial axis when vertical responses are required generally confirms this assumption. However, it is also interesting to point out that some of the participants did not show a spatial association (e.g., the dots around zero in Fig. 3). Do these individuals not use a spatial reference frame for positional coding? This question is difficult to assess based on the task used in this study, since it is also possible that these individuals formed spatial associations other than horizontal or vertical. Nevertheless, the correlation between the horizontal and vertical SPoARC effects shows at least that some individuals are more prone than others to recruit a Cartesian spatial frame of reference. The spatial coding of serial positions might therefore be considered as an individual strategy adopted by the majority of individuals rather than being an obligatory mechanism. Future research could explore these individual differences in more detail and assess whether the strength of the SPoARC effect can account for the diversity in specific cognitive abilities. Regarding the spatial association of numbers, there is a fruitful discussion as to whether the strength of the SNARC effect is related to math skills (for recent reviews see Cipora et al., 2020; He et al., 2020). In a similar vein, it would be interesting to assess whether the strength of the SPoARC effect is for instance related to specific memory capacities.

The correlation between the horizontal and vertical SPoARC effects can be considered as a strong effect but it is also evident that there is a substantial part of unexplained variance when predicting the spatial association from one axis by the other ($1\text{-}r^2 = 64\%$). One possible source of this unexplained variance may come from the slightly different shape of the horizontal and vertical SPoARC effects. First, although the strength of the SPoARC effect was not significantly moderated by spatial dimension (horizontal, vertical), the separate analysis showed that the horizontal SPoARC effect was somewhat more pronounced than the vertical SPoARC effect (as indicated by a higher effect size and a higher Bayes Factor). Secondly, while the horizontal SPoARC was remarkably linear (e.g., dRT values lie closely on the linear fit line, see Fig. 2b), the vertical SPoARC effect seems to be mainly driven by the first serial position (see Fig. 2d). There are several possible reasons for these slightly different patterns. First, as elaborated above, horizontal responses match more closely the actual sensoritmotor experiences during reading/writing when compared to vertical responses, which could strengthen the horizontal spatial association. Secondly, unlike for the horizontal SPoARC effect, the potential contribution of polarity correspondence, metaphor theory, and the indirect spatial-numerical association effect favor an opposite (down-to-up) direction for the vertical SPoARC effect. Although the resulting direction was from up-to-down, these alternative accounts might nevertheless induce some conflicting (down-to-up) tendencies that weaken the resulting up-to-down direction. Beside this, it is also possible that differences in terms of the visual field and in terms of exploration preferences between the two spatial axes might contribute to these slightly different patterns. Specifically, the visual field is typically of larger horizontal than of vertical extent, and people tend to scan the visual field more extensively along the horizontal than along the vertical spatial axis (Chaikin et al., 1962; Haith, 1980; Pelz et al., 2001; Previc & Blume, 1993). Moreover, rooms and computer screens (such as the one used in the current study) typically have a larger horizontal than vertical extent. All these asymmetries might bias participants to use a stronger horizontal than vertical spatial mapping (Winter, Matlock, et al., 2015). Furthermore, when facing a computer screen that is placed on a desk (as in the present study), the lower part of the vertical space is restricted by the desk (see also Figure 2 in Winter, Matlock, et al., 2015). One could speculate that such a restriction of the lower part of the vertical visual space might lead to a restriction (e.g., compression or distortion) of the lower part of the representational space, consequently leading to a less linear position mapping of items along the vertical spatial axis.

4.1 Implications for future research

In the present study, participants were forced to use responses along the horizontal and vertical spatial dimensions. Our results therefore leave open to what extent these different spatial dimensions are employed on a spontaneous basis. Future studies could use response settings that give participants free choice how to map serial positions onto space, for example by measuring spontaneous eye movements (e.g., Hartmann et al., 2016; Hartmann, Martarelli, et al., 2014; Loetscher et al., 2010; Martarelli et al., 2017; Rinaldi et al., 2015), or by assessing free placing of items in space (Fischer & Campens, 2009; Leone et al., 2018; Woodin & Winter, 2018). As mentioned earlier, first insights into preferences for different spatial reference frames for position coding in working memory was provided by Rinaldi et al. (2015) who found that eyes spontaneously move from left-to-right, but not vertically, during recall of memory items. It remains to be determined to what extend such preferences depend on individual predispositions and/or specific task demands.

Since we showed here for the first time that the spatial association can be found along the horizontal and vertical spatial dimensions, this opens the question whether serial positions might be represented along a frontal plane (or in a diagonal shape) rather than along the strict cardinal spatial axes. Research in the domain of spatial-numerical associations has shown that it can be problematic to generalize from the presence of purely horizontal and vertical associations (Schwarz & Keus, 2014) to a diagonal or grid-like mapping (Winter, Matlock, et al., 2015). Although there is some evidence for a frontoparallel mental number line (Hesse & Bremmer, 2017), it has been concluded that associations between numbers and space are primarily oriented along distinct cardinal axes (horizontal, vertical), rather than being map-like (for a recent review see Winter, Matlock, et al., 2015). This might be related to the observation that numbers are generally represented horizontally or vertically in our culture (Tversky, 2011) rather than diagonal, and children first learn numbers on a number line before they learn the Cartesian coordinate system. Taking the mental whiteboard-analogy for working memory in a literal sense, then a frontoparallel spatialization of serial position is certainly possible. Future research could therefore pit strictly cardinal (horizontal, vertical) and diagonal arrangements against each other in order to further explore the spatial nature of working memory.

According to recent dual process models, the spatial format of serial position coding might ultimately be determined by both short-term and long-term associations (e.g., Abrahamse et al., 2016). Our study sets the stage for using the vertical spatial dimension as means to disentangle short-and long-term associations. In this study we aimed to reduce the possible effect of long-term spatial associations by using letters instead of numbers as stimuli, thus investigating a “purer” (i.e., short-term determined) spatial coding of serial position in working memory. Although a SNARC-like effect (i.e., faster leftward responses for early letters of the alphabet) has also been demonstrated (Gevers et al., 2003), letters typically show no (or weaker) spatial associations (Dehaene et al., 1993; Dodd et al., 2008; Fischer, 2003; Goffin et al., 2020; Hoffmann et al., 2016). This might be related to the fact that it takes longer to search for a specific letter throughout the entire alphabet (and therefore to activate a spatial code) when compared to search through a number interval from 1-9 (Nakhai et al., 2012). Additionally, letters have not only a position in the alphabet but also on the computer keyboard, which can lead to conflicting long-term associations with space (Kozlik et al., 2013). Since we have established an up-down direction of the vertical SPoARC effect with letters, it might now be interesting to further study the vertical spatial axis with number stimuli. According to Abrahamse et al. (2016), the mental whiteboard is filled according to the most dominant experience with the content at hand. In the case of numbers, the most dominant experience with vertical arrangements would result in a down-small and large-up association, as found for the vertical SNARC effect (Aleotti et al., 2020; Hartmann et al., 2012; Holmes & Lourenco, 2012; e.g., Schwarz & Keus, 2004; Winter, Matlock, et al., 2015; Winter & Matlock, 2013). It would therefore be interesting to explore whether the direction of the long-term spatial-numerical association (from down-to-up) would influence the direction of serial position coding (from up-to-down, as shown in this study). Although it should be noted that for the horizontal spatial association, an additive effect of spatial association of magnitudes (small-left, large-right) on top of the SPoARC effect is typically not reported (Ginsburg et al., 2014; van Dijck et al., 2013, 2014a), suggesting that the default short-term coding (up-to-down) might trump the long-term association (down-to-up).

This study further established that the oculomotor system is a valid alternative to manual responses when exploring the link between space and serial order (Rinaldi et al., 2015). In this study, we used saccadic responses in order to avoid problems that are typically induced by manual responses along the vertical axis, such as the close-far dimension or the left-right hand association (e.g., Chen et al., 2015; Hartmann, Gashaj, et al., 2014; Wiemers et al., 2017; Zhou et al., 2020). Besides these rather technical aspects, eye movements might generally play a special role in exploring the spatial nature of thoughts (e.g., Hartmann, 2015; Loetscher et al., 2010; Mast & Kosslyn, 2002; Rinaldi et al., 2015). Mental imagery and memory recall are often accompanied by eye movements that follow the pattern of the imagined/recalled contents, as if the eyes would “act out” the spatial relationship of thoughts (e.g., Grant & Spivey, 2003; Gurtner et al., 2021; Johansson & Johansson, 2014; Laeng & Teodorescu, 2002; Spivey & Geng, 2001). Eye movements might also play a role for the binding of elements of an episode together into an integrated episodic memory representation (Kumaran & Wagner, 2009; Pathman & Ghetti, 2015). Along this line, eye movements might be involved in the transformation of the internal representation of serial order into a spatial code, and thus be an important element for positional coding in working memory. Moreover, eye movements are directly involved in reading and writing, and the oculomotor system is therefore a prime candidate for assessing signatures of culturally shaped sensorimotor routines as ground for cognition (e.g., Barsalou, 2008; Fischer, 2012; Winter, Marghetis, et al., 2015). For these reasons, we propose that eye movements might be informative for future research on the spatialization of working memory.

4.2 Conclusions

To conclude, this study provides further evidence that memorizing a sequence in working memory engages spatial reference frames. We extended previous work by showing that position coding is not restricted to the horizontal frame of reference but can also be found along the vertical spatial dimension, suggesting a flexible adaptation of spatial reference frames to the task. Such flexibility is in line with the idea that the spatial coding of positions on an internal space (mental whiteboard) developed in order to facilitate the coordination of and the operation on items in working memory (Abrahamse et al., 2014). Our results also suggest that some people are more prone than others to use spatial references for position coding. The question therefore remains open whether the SPoARC effect is the result of strategic use of space, or rather the result of an automatic and inescapable way of how people maintain serial orders in working memory.

Declarations

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Conflicts of interest/Competing interests

The authors have no conflicts of interest to declare.

Availability of data and material

A link to the datasets is included in the results section of this study.

Code availability (software application or custom code)

Not applicable (no software application or custom code).

Authors' contributions

All authors contributed to the study conception. Preparation of experiment and data collection was performed by Nils Sommer. Matthias Hartmann performed data analysis and wrote the first draft of the manuscript. Corinna Martarelli and Nils Sommer commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Ethics approval

The study was approved by the Ethical Committee of UniDistance Suisse and has been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments.

Consent to participate

All participants gave informed consent prior to the study.

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