SERIAL POSITION AND DISTANCE EFFECTS IN VISUAL WORKING MEMORY

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Abstract: Numerous studies have identified and explored the factors that affect order information processing in verbal working memory (WM), whereas little is known about order maintenance in visual WM. To gain better insight into the possible mechanisms of representing order in visual WM, we assessed the extent of serial position and item distance effects on visual WM. 20 students performed a visual WM task. They were asked to encode and maintain either the identity or temporal order of four visual stimuli. The results revealed recency and distance effects congruent with previous studies of verbal WM, however, no primacy effect in accuracy results was detected. Distance was revealed to be closely intertwined with recency, making it difficult to estimate their separate effects on order recognition. These results suggest that order coding in visual WM involves the use of a magnitude of codes similar to those employed in number processing and verbal WM.

Key words: visual working memory, temporal order memory, primacy, recency, distance effect

Working memory (WM) is a key component of human cognition, enabling maintenance of information relevant for the execution of the ongoing task. WM consists of short-term memory stores that can temporarily hold a limited amount of information in an easy accessible state (Atkinson, Shiffrin, 1968; Baddeley, Hitch, 1974) and processing mechanisms that help make use of the short-term memory (Cowan, 2008). WM should therefore be distinguished from short-term memory as it refers to structures and processes used not only for temporary storage of the information but also for manipulation of the stored information. A key feature of WM that enables formation and control of goal-oriented plans is coding and maintenance of order information.

WM, as most researchers agree, is not a unitary system. The multicomponent model of WM (Baddeley, 2000; Baddeley, Hitch, 1974) - probably the most influential cognitive model of WM - identifies four separate components: a phonological loop that enables storage of verbal information; a visuo-spatial sketch-pad dedicated to maintenance of visual and spatial information; an episodic buffer storing integrated multimodal information and providing link to long-term memory; and a central executive, controlling access to and manipulation of information within WM. Each of the components may

DOI: 10.21909/sp.2013.01.622

depend on separate mechanisms and processes for encoding and maintenance of information. Of these, much attention has been paid to representations and processes that enable maintenance of order information in verbal WM, however, surprisingly little is known about how order is coded and maintained in visual WM.

Identifying the factors that affect and shape cognitive abilities is a necessary step towards proposing and validating specific models and theories about mechanisms and representations that enable them. In the study of verbal WM three empirical findings seemed to be particularly influential (Marshuetz, 2005): serial position effects, distance effect and error types in serial recall. The focus of this paper will be the serial position and distance effects.

Serial Position Effect

Shortly after learning a list of items, the subjects' recall or recognition performance usually depends on the serial position of the item in a predictable way. Items in the first and the last positions are often better remembered than the ones in the middle of the list, as indicated by higher accuracies and shorter reaction times (e.g., Golob, Starr, 2004; Jones, Polk, 2002; Lange, Cerella, Verhaeghen, 2011; McElree, Dosher, 1989; Sederberg et al., 2006; Stephane et al., 2010; Talmi, Goshen-Gottstein, 2006; Williams, McCoy, Kuczaj, 2000; Zhang et al., 2003). The superior memory for the first item has been termed the primacy effect, and for the last item, the recency effect.

Some authors (e.g., Baddeley, 1986; Rundus, 1971) have suggested that the first few items from the to-be-remembered list represented the benefit from the greatest rehearsal, thus increasing their probability of recall. Craik and Lockhart (1972) hypothesized that items at the beginning of the list are subject to elaborative processing in order to allow rehearsal of items presented subsequently. Another account claims that early list items simply receive enhanced attention resources and, consequently, are better encoded regardless of how many additional rehearsals they receive (Neath, Crowder, 1990). Recency effects, in contrast, occur because the words at the end of the list are still being held in short-term memory (Rundus, 1971). This view is consistent with the dual-store models, in which late list items are retrieved from a highly accessible short-term memory store (Raaijmakers, Shiffrin, 1981). Both, primacy and recency can be explained with the feature of distinctiveness, the degree to which a given item stands out among the other items in the set (Neath, 1993). This view of distinctiveness can predict the shape of the serial position function: the most recent to-be-remembered items and the first few items in a uniformly spaced list are temporally more distinct than the middle items.

Distance Effect

Distance effects are typically noted in tasks requiring subjects to make relative judgments about an aspect of two stimuli that are definable along some dimension, such as physical size. For example, the time to judge the distance between items in perceived spatial arrays is shorter for items that are farther apart (Holyoak, 1977). The same effect is observed in judgments about imagined real-world objects, for which, for example, a subject's response to the question of which object is larger is faster the more disparate their sizes (Moyer, 1973). Distance effect is also observed in the order of letters (e.g., Angiolillo-Bent, Rips, 1982; Proctor, Healy, 1987) and in numerical comparisons (Buckley, Gillman, 1974; Dehaene, Dupoux, Mehler, 1990; Milosavljevic et al., 2011). Size and distance effects in numerical cognition have inspired the proposal that we cognitively represent numbers on a mental number line (Restle, 1970). In this view, numerical distance is expressed as spatial distance, and similarity in number size is captured as representational overlap (Göbel, Shaki, Fischer, 2011). This phenomenon implies that representation of size and quantity are stored as magnitudes that are easier to discriminate from one another if more disparate (Chochon et al., 1999; Marshuetz et al., 2000).

Coding of Order in Visual WM

Whereas order effects have been extensively studied in verbal WM, studies of visual WM are few and far between. In humans, primacy and recency effects are observed in various studies using verbal stimuli, such as numbers (e.g., Golob, Starr, 2004; Zhang et al., 2003), letters (e.g., Henson et al., 2003) or words (e.g., Jones, Polk, 2002; Murdock, 1962; Rushby, Barry, Johnstone, 2002; Sederberg et al., 2006; Stephane et al., 2010; Talmi et al., 2005). Studies of primacy and recency effect in visual WM (Roberts, Kraemer, 1981; Woodman, Vogel, Luck, 2012; Wright et al., 1985) are rare and mostly involve animal subjects. The studies report of no primacy and substantial recency effect with short retention intervals, however, as the retention interval increased, the magnitude of primacy effect increased while that of the recency effect decreased (Wright et al., 1985).

As for the distance effect, all previous studies were done on pairs of strings of letters (Angiolillo-Bent, Rips, 1982; Proctor, Healy, 1987) or numbers (Buckley, Gillman, 1974; Dehaene et al., 1990; Milosavljevic et al., 2011), whereas, to our knowledge no such studies exist on visual stimuli nor on visual WM.

Based on verbal WM empirical findings, several possible mechanisms of representing order information have been proposed. The first possibility is that items are coded with respect to other items on the list via inter-item associations (e.g., Henson, 1999; Marshuetz, 2005). When probed with two items that were on the list and asked to make a judgment about whether the items appear in the same order as they were presented in the list, this inter-item associative mechanism predicts that reaction time will increase with the number of intervening items (Marshuetz et al., 2000). The second possible mechanism for coding order information is an explicit association of temporal or ordinate position to each item (e.g., Anderson, Matessa, 1997). We refer to this possibility as direct coding. The behavioral prediction for a direct coding model differs from that of an inter-item association model: If response time is measured to a pair of probes it should not vary with the distance between the items in the list because subjects can access the associated position for each item and then compare which of those position codes is larger (Marshuetz, 2005). The third possible order-coding mechanism is one in which the temporal position of an item is represented on a continuous scale of a variable, such as an index of item recency, familiarity, or some other code that can be expressed in magnitudes (e.g., Brown, Preece, Hulme, 2000; Neath, Crowder, 1990). To the extent that items in memory are coded according to magnitude information, the behavioral data should parallel psychophysical functions for other perceptual judgments, such as size discriminations, which are also thought to be coded in terms of magnitude. That is, the more the items are separated in time, the easier the judgment of their temporal order should be (Marshuetz, 2005).

To our knowledge, no study exists that would relate the proposed mechanisms of order coding to visual WM and explicitly test them. That is what our study aimed to address. Our goal was to explore the presence and extent of order related effects - serial position and distance - on visual WM, compare them to verbal WM findings, and test the predictions of the three proposed mechanisms of order coding. Three possibilities were explored. First, an increase in reaction times of order judgments with increased inter-item distance would support the predictions of inter-item association coding. Second, no effect of inter-item distance on order judgment reaction times would best fit the direct coding of order in visual WM. Third, a decrease of reaction time and increase in accuracy of order judgments with increase of inter-item distance would suggest that order information in visual WM is represented using magnitude coding.

METHODS

Participants

20 students from University of Ljubljana participated in the study (15 females, 5 males). Mean age of participants was 23.71 years (SD = 2.14 years). All the participants had normal or corrected to normal vision. All participants gave written informed consent prior to participation in the experiment.

Materials and Design

The participants completed a visual WM task in which their task was to remember either the identity or the order of four sequentially presented items. The length of the sequence was chosen, as empirical evidence suggests that visual WM is limited to approximately four items (Luck, Vogel, 1997; Pashler, 1988). Using four items allowed us the study of order effects and, at the same time, ensured that the participants were able to encode and remember the items on most trials. Sequential rather than simultaneous presentation was used, as previous studies (Blalock, Clegg, 2010; Jiang, Olson, Chun, 2000) suggest that sequential presentation isolates each item during the encoding, whereas simultaneous presentation encourages the use of spatial configuration over an item-focused representation. Using sequential presentation we ensured that the items were encoded individually in visual WM. In addition, presenting them at the same location prevented recoding an order task into a spatial position task.

To enable additional analyses that are not the focus of this paper, in each trial two sequences of stimuli were presented, one to the left and one to the right visual hemifield with the participant having to attend to and remember only one of them. The laterality of the stimuli to remember was varied randomly within each block of trials.

The progression of the task is illustrated in Figure 1. Each trial started with a cue stimulus indicating the type of the trial and the side of the display that the participant should attend to. The participants were asked to encode and maintain either the identity (Item condition) or temporal order (Order condition) of the items that were presented in the indicated hemifield. The cue was presented for 700ms and followed by a 300ms presentation of the fixation cross. In the encoding phase of the trial four pairs of stimuli were presented sequentially. In each pair, one stimulus was presented on the left and the other on the right side of the fixation point. Each pair was presented for 800 ms with 300 ms inter-stimulus interval (ISI). During the presentation the participants were asked to look at the fixation cross while observing the stimuli in their lateral visual field. According to previous studies (e.g., Phillips, 1974), with ISI of 100 ms or longer, stimuli sensory traces decay to the point of being unusable. Stimuli traces were additionally attenuated by lower contrast between the letter and background (dark blue on medium gray). The timing structure therefore enabled the participants to individually encode each presented item, with no or minimal sensory trace interference.

After the encoding phase, a 3500 ms delay (maintenance phase) followed before a probe appeared on the screen. Subjects were instructed to look at the fixation point on the screen during the delay phase. After the delay the probe consisting of two stimuli appeared. In the order condition, participants had to indicate by pressing a button, which

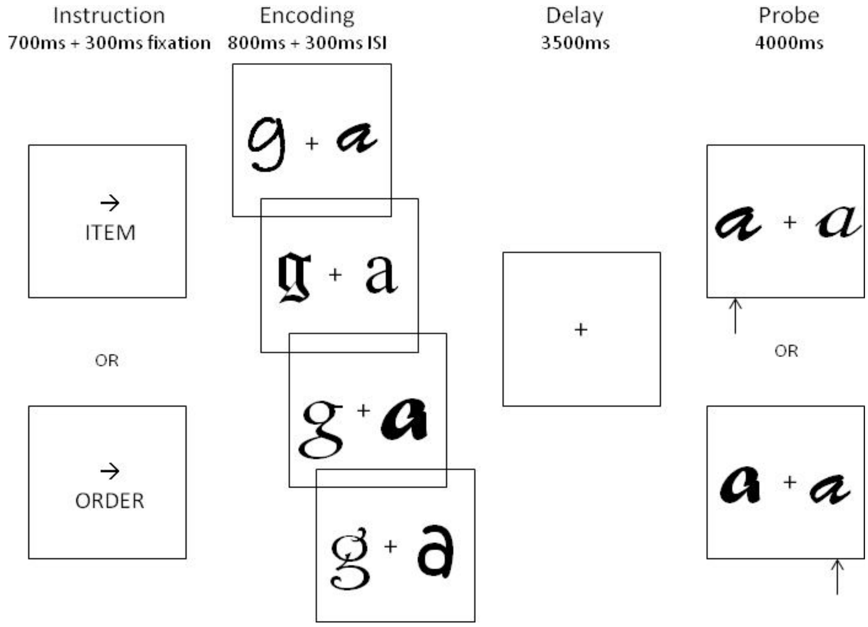

Figure 1. Schematic diagram of the visual WM paradigm. Each trial started with a cue indicating the task and the hemifield to attend to. Four visual stimuli were then sequentially presented in each hemifield. After a delay, a probe was presented to which participants responded by pressing a key indicating the stimulus that appeared in the original set (item condition) or the stimulus that appeared first in the original set (order condition). Arrows indicate the correct response for each of the conditions.

of the two items was shown earlier in the sequence. In the item memory trials, the test display consisted of one item from the memory set, along with a visually similar foil item. Participants had to indicate by pressing a button, which of the presented items was a part of the initial set. Each trial was followed by 1700 ms inter-trial interval (ITI). During the ITI the subjects were instructed to look at the fixation cross until the cue for the next trial appeared.

Visual stimuli were letters of 129 different font types. The stimuli were carefully chosen based on prior piloting with the aim to reduce the possibility of verbal recoding. As the identity of the letters within a sequence remained the same, their verbalization did not provide any task relevant information to the participant. Additionally, the letters differed in a number of nonpredictable features that were difficult to verbalize, which further reduced the possibility of successful use of verbal recoding strategies. By making sure that on each trial the identity of the letters used in the target hemifield differed from the letters in the opposite visual hemifield as well as letters used in the previous trial, the choice of stimuli enabled us to minimize the potential of interference from either set of stimuli.

The different types of each letter were grouped in 12 different clusters based on their visual similarity. To ensure the distinctiveness between items, the letters for the memory set were chosen from four different randomly selected clusters. Conversely, to make the Item condition more challenging, the foil probe in the Item condition was selected from the same cluster as the probe from the initial set.

On Item trials, the probe had an equal chance of occurring at any serial position (first, second, third or fourth). To allow for the examination of distance effects, target probes in Order condition were either 0 items apart (adjacent items, distance 1), 1 item apart (one intervening item between probes, distance 2) or 2 items apart (two intervening items between probes, distance 3). All three distances occurred with equal frequency.

The stimuli were presented on a 19" CRT screen. At a distance of 100 cm they were approximately 3.4° in size and were presented with 8.1° eccentricity. The task was controlled by E-Prime (Psychology Software Tool, Pittsburgh, PA) running on a Windows XP operating system. The participants provided their responses by pressing either left of right mouse button using their dominant hand.

Procedure

Participants were comfortably seated, viewing the computer screen at a distance of 100 cm. The task started with presentation of written instructions. First, participants carried out a practice block to familiarize themselves with the experiment. Participants continued with the task only after the experimenter made sure that they understood the instructions.

The task was organized in 10 blocks of 40 trials each. Each block consisted of 20 Item and 20 Order trials presented in random sequence in order to reduce the possibility of developing task specific strategies. Similarly, the side of the target stimuli as well as the stimuli (letters) used changed randomly from trial to trial and were balanced across both Item and Order trials. Each block took approximately 9 minutes to complete. Blocks were separated by short breaks to give participants the opportunity to rest before continuing with the task. In sum, each participant completed 200 Item and 200 Order trials. In each trial reaction times and accuracy of responses were recorded. Participants were asked to focus on the visual details of the letters and avoid trying to verbalize their features. Post-test debriefing indicated that the participants were not able to and did not try to use verbal recoding strategies.

Differences in accuracy and reaction times between different serial positions and item distances were analyzed using one-way ANOVA for repeated measures and η_p^2 effect size was computed. When significant, the effects were further explored using post-hoc analyses with Bonferroni correction for multiple comparison and computation of Cohen's *d* effect size.

RESULTS

Serial Position

To explore the effect of serial position on accuracy in Item condition we computed repeated-measure one-way ANOVA with item position (1, 2, 3 or 4) as the single factor. The results (see Figure 2) confirmed a significant effect of serial position ($F(3, 16) = 11.63$; $p < .001$; $\eta_p^2 = 0.45$). Post-hoc analyses revealed significantly better accuracy when the probed item was presented last in comparison with position 1 ($t(19) = -5.05$; $p < .001$; $d = -1.34$), position 2 ($t(19) = -3.34$; $p = .005$; $d = -1.06$) and position 3 ($t(19) = -4.58$; $p <$

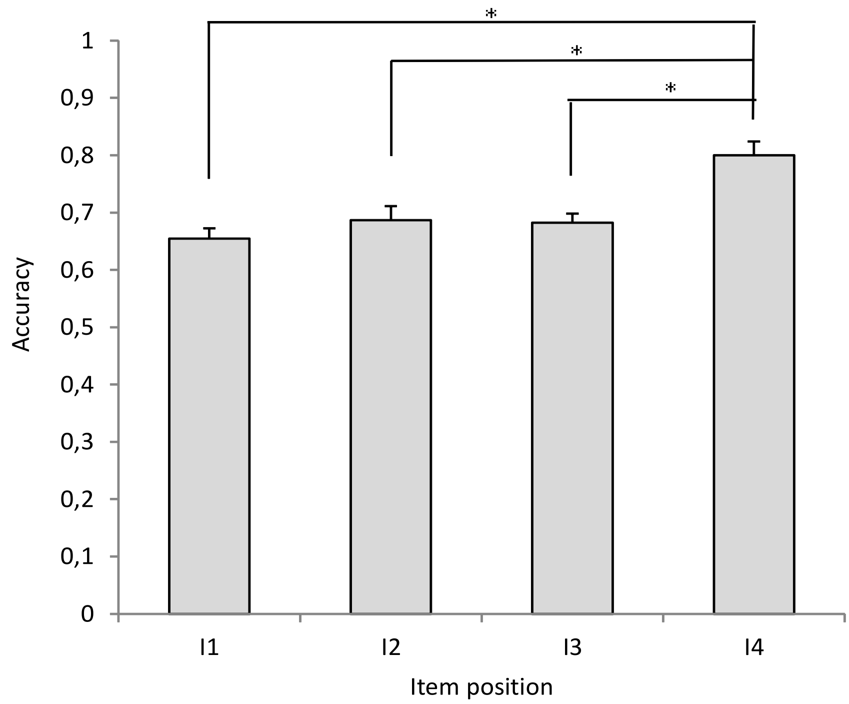

Figure 2. Accuracy as the function of serial position of the target item in Item condition. Error bars represent standard errors. * $p < .0125$

.001; d = -1.22). No other effects passed statistical significance.

Next, we also tested the effect of serial position on reaction times in correct trials. To avoid outliers, all reaction times that differed more than 2 standard deviations from the mean in each condition were excluded from the analysis prior to computing each subject's averages. Repeated-measures one-way ANOVA revealed a significant effect of serial position ($F(3, 16) = 6.83$; $p = .001$; $\eta_p^2 = 0.33$). Post-hoc analyses revealed slower reaction times when probed item was presented in position 3 in comparison with position 1 ($t(19) = -3.30$; $p = .005$; $d = -0.24$) and with position 4 ($t(19) = 3.53$; $p = .003$; $d = 0.61$). Results are presented in Figure 3.

Distance

To assess the effect of distance on accuracy of order judgments we computed repeated-measure one-way ANOVA with item distance (1, 2 or 3) as the single factor. ANOVA showed a significant effect of distance on accuracy ($F(2, 16) = 27.13$; $p < .001$; $\eta_p^2 = 0.66$). Post-hoc analyses revealed that subjects performed significantly worse with adjacent items than when items were one ($t(19) = -3.93$; $p = .002$; $d = -1.04$) or two ($t(19) = -2.44$; $p < .001$; $d = -1.44$) items apart, however, differences between the latter two cases did not reach significance ($t(19) = -2.44$; $p = .028$; $d = -0.64$). For results see Figure 4.

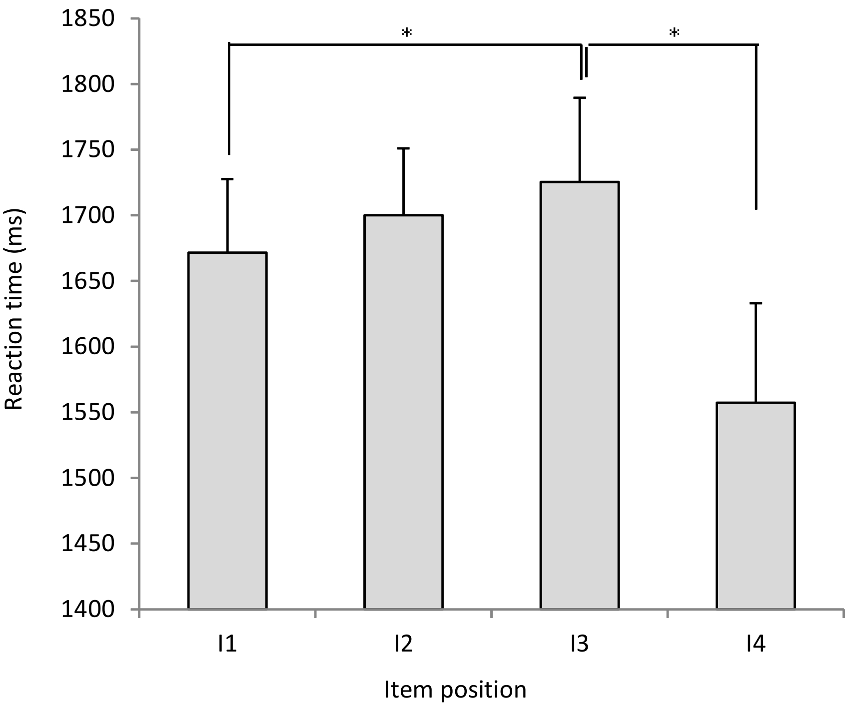

Figure 3. Reaction time as the function of serial position of the target item for correct responses in Item condition. Error bars represent standard errors. * p < .0125

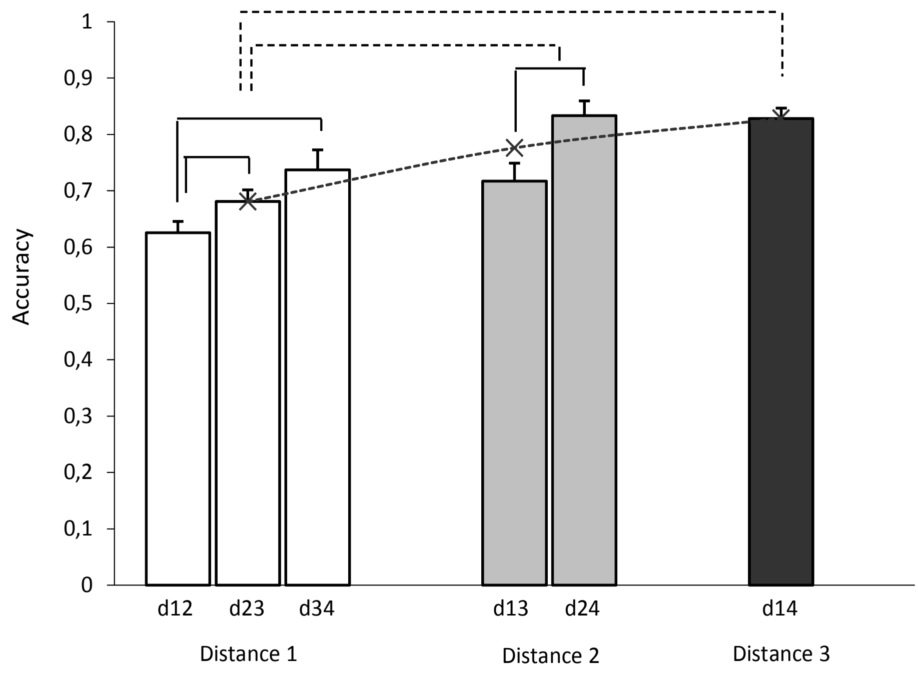

Figure 4. Accuracy as the function of distance of target items and serial position within specific distance in Order condition. Lines connect mean accuracy at each of the distances. Error bars represent standard errors. Dashed lines represent statistical significance for the main effect of distance, whereas filled lines represent statistical significance within specific distance. * p < .0167

To identify the possible mediating effect of serial position we also analyzed the effect of serial position on accuracy in order judgment. A repeated-measure one-way ANOVA with positions within distance 1 as a single factor (positions 12, 23, and 34) confirmed a significant serial position effect on accuracy for order judgment on adjacent items ($F(2, 16) = 6.73$; $p = .004$; $\eta_p^2 = 0.33$). Post-hoc analyses revealed that accuracy was significantly worse when probes in Order condition were in serial positions 1 and 2 compared to positions 2 and 3 ($t(19) = -2.68$; $p = .018$; $d = -0.68$), and 3 and 4 ($t(19) = -3.37$; $p = .005$; $d = -0.93$). The difference between the later two did not reach significance ($t(19) = -1.60$; $p = .133$; $d = -0.51$). Similarly, when probes were spaced one item apart (distance 2) accuracy was significantly worse when probes were shown in serial positions 1 and 3 in comparison with positions 2 and 4 ($t(19) = -3.16$; $p = .007$; $d = -0.94$).

To control for the effect of serial position, we then compared accuracy across distances only for those cases when one of the probed items was presented in the most memorable, last position (items 3, 4 vs. items 2, 4 vs. items 1, 4). The results showed significant main effect of distance on accuracy ($F(2, 16) = 6.20$; $p = .006$; $\eta_p^2 = 0.31$). Post-hoc analyses revealed better accuracy for distance 3 in comparison to distance 1 ($t(19) = 3.78$; $p = .002$; $d = 0.79$). The same trend was observed for the difference between distances 1 and 2, however, the effect did not reach the more stringent statistical threshold ($t(19) = 2.52$; $p = .025$; $d = 0.77$). There was practically no difference between distances 2 and 3 ($t(19) = -0.18$; $p = .86$; $d = -0.06$).

Next, we tested the effect of item distance on reaction times. Again, only reaction times for correct responses that did not deviate more than two standard deviations from the mean in each condition were used to compute subjects' averages. Repeated-measures one-way ANOVA again confirmed a significant effect of item distance (1, 2 or 3) on reaction times ($F(2, 16) = 42.87$; $p < .001$; $\eta_p^2 = 0.75$, see Figure 5). Post-hoc analyses revealed that reaction times were significantly shorter with larger distances for all cases, comparing distances 1 and 2 ($t(19) = 3.12$; $p = .008$; $d = -1.04$), distances 1 and 3 ($t(19) = 7.45$; $p < .001$; $d = -1.44$) as well as distances 2 and 3 ($t(19) = 6.97$; $p < .001$; $d = -0.64$).

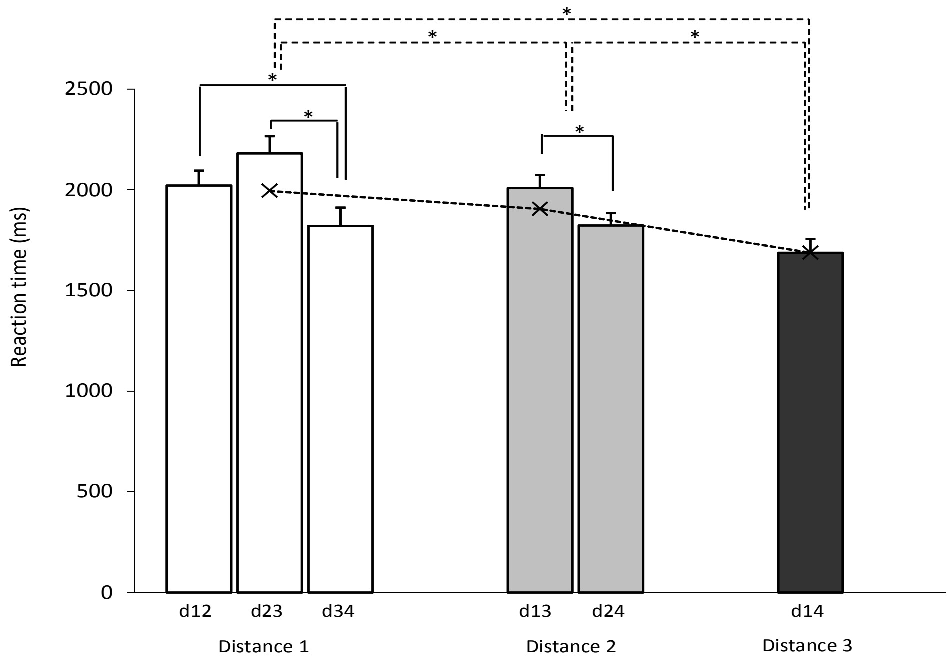

Figure 5. Reaction times for correct responses as the function of distance of target items and serial position within specific distance. Lines connect mean reaction times within each distance. Error bars represent standard errors. Dashed lines represent statistical significance for the main effect of distance, whereas filled lines represent statistical significance within specific distance. * $p < .0167$

Again we tested for possible serial position effects. Repeated-measures one-way ANOVA indeed revealed significant effect of serial position on reaction times for adjacent probes ($F(2, 16) = 18.98$; $p < .001$; $\eta_p^2 = 0.58$). Post-hoc analyses revealed that the items in position 3 and 4 required shorter reaction times than items in positions 1 and 2 ($t(19) = 3.43$; $p = .004$; $d = 0.61$) and position 2 and 3 ($t(19) = 6.13$; $p < .001$; $d = 0.96$), whereas the difference in reaction times between position 1 and 2 vs. position 2 and 3 did not reach significance when Bonferroni correction was applied ($t(19) = -2.73$; $p = .016$; $d = -0.52$). Similarly, when items were 2 positions apart, the reaction times were shorter when the probes were shown on positions 2 and 4 in comparison with positions 1 and 3 ($t(19) = 3.44$; $p = .004$; $d = 0.73$).

To control for the effect of serial position we again compared distances on only those cases that included the most memorable fourth item. Repeated-measures one-way ANOVA with factor distance (3 and 4 vs. 2 and 4 vs. 1 and 4) showed significant main effect of distance on the reaction times ($F(2, 16) = 8.03$; $p = .002$; $\eta_p^2 = 0.36$). Post-hoc analysis revealed faster reaction times for distance 3 in comparison with distance 2 ($t(19) = -5.07$; $p < .001$; $d = -0.54$) and distance 1 ($t(19) = -3.09$; $p = .008$; $d = -0.43$). However, there was no significant difference between distance 1 (item position 3 and 4) and distance 2 (item position 2 and 4) ($t(19) = -0.05$; $p = .960$; $d = 0.01$).

DISCUSSION

The aim of our study was to determine to what extent visual WM exhibits similar order related effects as verbal WM, and more specifically, to test which of the proposed order coding mechanisms (inter-item association, direct coding and magnitude coding) best describes maintenance of order information in visual WM. We focused specifically on serial position and distance effects.

Serial Position Effect

The results from the Item condition revealed different patterns of accuracy and reaction times as a function of probe position with the domination of recency effect. The results demonstrated significantly better accuracy and faster reaction times when the probe was from the end of the initial set in comparison with all other positions (see Figures 2 and 3), which is consistent with the recency effect. According to the distinctiveness theory (Neath, 1993) it seems that the most recent to-be-remembered items stand out among the other items in the set and are temporally more distinct in comparison with items from the middle and, in our case, also from the beginning of the list. Our accuracy results did not reveal any primacy effect, as the stimuli from the beginning of the list were not better recognized. However, reaction times for the first three items did increase with the position, congruent with the primacy effect.

The observed pattern of strong recency and absent primacy effect in accuracy data differs from findings reported in studies of verbal WM, which show the influence of both recency (e.g., Golob, Starr, 2004; Stephane et al., 2010; Talmi, Goshen-Gottstein, 2006; Talmi et al., 2005), as well as primacy effect of serial position on recall accuracy (e.g., Jones, Polk, 2002; Sederberg et al., 2006; Stephane et al., 2010; Williams et al., 2000). A number of possible explanations of the observed discrepancy can be considered.

First, significant primacy effect is usually found in intentional learning tasks, and likely reflects the subjects' use of elaborative rehearsal strategies to help associate items and encode them into memory (Craik, Tulving, 1975). Such elaborative rehearsal strategies (e.g., making a story out of the list items) result in increased rehearsal of early list items during later item presentations (Tan, Ward, 2000), and consequently relatively poorer encoding of items later in the list. One possible reason for the lack of primacy effect in our study could be due to the differences in the rehearsal mechanism between verbal and visual WM, the latter not allowing for the same kind of elaborative strategies as the former. The dependence of primacy effect on rehearsal strategies afforded by phonological loop was demonstrated in a verbal WM study by Baddeley and Hitch (1974), showing that a concurrent task engaging the phonological loop significantly impairs recall accuracy for earlier serial positions, however, it does not reduce the recency effect.

Second, the few existing studies of visual WM that explored the serial position effect in visual WM (Roberts, Kraemer, 1981; Wright et al., 1985) report significant effect of delay period on serial position curve. The effect was most convincingly shown in the study by Wright et al. (1985), in which only recency effect was observed in the shortest delays (0 and 1s) and only primacy effect remained at the longest delay (100s), whereas both were present in the medium delay lengths. The authors attributed the findings to differential time courses of fast decaying retroactive interference and slow growth of proactive interference. From that perspective, it could be argued that the 3.5s delay used in our study was too short to elicit primacy effect.

Third, as no visual masking was used between trials, a week primacy effect could also be explained by interference between the trace of the probe from the previous trial and the first target stimulus of the following trial. As visual WM is limited in capacity and is quickly updated with new visual input, it would be advantageous to maintain only currently relevant information (Makovski, Jiang, 2007). However, recent studies report that one cannot fully eliminate unwanted visual information from the current WM tasks (Makovski, Jiang, 2008). The use of different letters in the consecutive trials makes the stimuli clearly distinct and should significantly reduce the possibility of such interference, its possible effect, however, should still be addressed in future studies.

Last, a number of studies have demonstrated a capacity limit of visual WM of only about three to four items (e.g., Alvarez, Cavanagh, 2004; Luck, Vogel, 1997; Pashler, 1988). Taking that into account, it seems likely that better recall of the last items in a series is a consequence of overwriting the memory for prior items by subsequent items (Glanzer, Cunitz, 1966). As suggested by Woodman et al. (2012) who obtained a similar pattern of results, these might reflect the capability to dynamically update the content of visual WM and displace earlier items once the capacity limit was exceeded.

The last interpretation is also most congruent with the obtained reaction time results that show both recency and primacy effect. Namely, when the items from the beginning of the list do remain in memory, the earlier ones do have the distinctiveness advantage over the following ones, leading to faster reaction times for accurate responses.

Distance Effect

To differentiate between different possible mechanisms of order coding in visual WM, we also investigated the presence and characteristics of distance effect in order judgments. Our results demonstrated a strong distance effect (see Figures 4 and 5). Specifically, accuracy increased and reaction times decreased as a function of distance between two probe stimuli. This implies that the representation of position for adjacent items overlap more and might result in more difficult relative position judgments than in the case of nonadjacent items (Göbel et al., 2011).

These results closely match observations in studies of verbal WM reporting strong distance effect (Angiolillo-Bent, Rips, 1982; Buckley, Gillman, 1974; Dehaene et al., 1990; Holyoak, 1977; Moyer, 1973; Proctor, Healy, 1987), suggesting that similar mechanisms of order coding might be employed for both modalities. The specific pattern of results is most congruent with magnitude coding of order information similar to the one proposed for numerical cognition (e.g., Restle, 1970). Specifically, the order in visual WM could be represented using a continuous scale serving as a mental measure of spatial or temporal distance from a common reference point (Brown et al., 2000; Marshuetz, 2005). Ordinal position in such a system is not coded explicitly, so adjacent items will have similar representations and their order is more likely to be confused than in the situation of more widely separated items that have less similar representations, are easier to tell apart, and thus will be responded to more accurately and quickly (Göbel et al., 2011; Jahnke, Davis, Bower, 1989; Marshuetz, 2005). This is exactly what has been observed in our results, which therefore support the hypothesis that temporal position of items in visual WM is represented using a magnitude code, similarly to representation of size and quantity (Chochon et al., 1999; Marshuetz et al., 2000).

Caveats

The biggest challenge to making a strong conclusion in regards to a specific mechanism of order coding based on the presented results is the separation of the distance effect from the serial position effects. Namely, to be able to identify the correct order of items, one depends, to a large extent, on the items being remembered in the first place. The task should be easier in the case where the items to be compared are better remembered. In the case of accuracy, there were no differences in item recall for positions 1 through 3, so better accuracy for order comparison of items 1 and 4 than for items 3 and 4 cannot be explained by position effects alone. With the reaction time results, however, the effects are not so clear, as responses were fastest when comparing items that showed reaction time advantage already present in the item recognition task. It is therefore difficult to assess whether the observed differences in reaction times in order judgments can be fully explained by position effects or do they reveal additional contribution of distance effects, supporting the magnitude-coding hypothesis.

To provide more robust evidence in support of the magnitude coding hypothesis further studies are needed that will either validate the independent influence of order distance on reaction times or test the hypothesis of magnitude temporal position coding more directly. fMRI studies of verbal WM have already shown the existence of overlap in recruitment of areas in maintenance of order memory and number processing (Marshuetz et al., 2000). Additionally, electrophysiological data could give us more insight into the temporal processing of items in different serial positions. A number of studies have already identified different neural mechanisms that could underpin primacy and recency in verbal WM (Stephane et al., 2010; Zhang et al., 2003), however, neural mechanisms of order coding in visual WM still need to be addressed appropriately.

CONCLUSIONS

By combining item recognition and order judgment tasks and focusing on both response accuracy as well as reaction time, the present study provides novel information about position effects and order coding in visual WM. Whereas strong recency effect in item recognition accuracy indicates dynamic updating of visual WM and displacement of previous items, the presence of primacy effect evident in reaction times provides simultaneous evidence of distinctiveness advantage for earlier items. Furthermore, increased accuracy for order judgment of temporally distant items coupled with similar accuracy for those items in item recognition task suggests that maintenance of order information in visual WM is best explained by magnitude coding. These results demonstrate that visual WM employs order-coding mechanisms similar to those enabling number processing (e.g., Chochon et al., 1999) and verbal WM (Marshuetz et al., 2000).

Received May 11, 2012

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SÉRIOVÝ POLOHOVÝ A VZDIALENOSTNÝ EFEKT PRI VIZUÁLNEJ PRACOVNEJ PAMÄTI

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Súhrn: Faktory ovplyvňujúce poradie spracovania informácií vo verbálnej pracovnej pamäti (PP) identifikovali a skúmali početné štúdie, zatiaľ čo o udržiavaní poradia vo vizuálnej pracovnej pamäti sa vie len málo. Aby sme lepšie pochopili možné mechanizmy, ktoré reprezentujú poradie vo vizuálnej PP, hodnotili sme rozsah sériového polohového efektu a efektu vzdialenosti položiek pri vizuálnej PP. Testu vizuálnej PP sa zúčastnilo 20 študentov. Ich úlohou bolo kódovať a pamätať si identitu alebo časové poradie štyroch vizuálnych podnetov. Výsledky ukázali, že efekt novosti a vzdialenosti sú v súlade s výsledkami predchádzajúcich štúdií verbálnej PP, nezistil sa však žiaden efekt prvotnosti v presnosti. Vzdialenosť úzko súvisela s novosťou, čo sťažovalo určenie ich samostatného vplyvu na znovupoznávanie poradia. Z výsledkov teda vyplýva, že kódovanie poradia vo vizuálnej PP zahŕňa aj použitie množstva kódov podobných tým, ktoré sa používajú v PP spracúvajúcej čísla a vo verbálnej PP.