Working memory for movements, positions and colors – behavioral studies

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ABSTRACT

A number of behavioral and neurocognitive studies have shown that visuo-spatial and visual-object information in working memory can be dissociated. However, as reflected in the variety of operationalizations, there is no consensus on the definition and delineation of these two types of information. In particular, the role of dynamic aspects in spatial information is not clear. We hypothesize that static-spatial information (i.e. absolute position), dynamic-spatial information (i.e. movement), and visual-object features (e.g. color) are separable features and can be retained selectively in working memory.

We conducted three behavioral studies within the framework of an S1-cue-S2-paradigm. Participants were presented with a first stimulus and were required to compare it to a second stimulus that was presented a few seconds later. In order to enable selective rehearsal, in a part of the trials we presented a cue after S1-offset indicating the specific to-be-evaluated feature. In the unspecific condition the cue specified two features. We expected that specific cues lead to better memory performance than unspecific cues because the former but not the latter allow selective rehearsal. Stimuli were either two moving colored dots or a static layout of four colored dots. Participants' performances were higher in the specific than in the unspecific condition. We take this as evidence that selective rehearsal of movement, position, and color information is possible and that these features are separable in visual working memory.

In two further experiments we modified the perceptual stimulus qualities in order to equate difficulty across tasks and to make the tasks suitable for a planned fMRI study.

Keywords: visuo-spatial working memory, selective rehearsal, movement

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Introduction

In the tripartite working memory model (Baddeley and Hitch, 1974) it is assumed that there are two domain-specific working memory systems that can work independently from one another: the phonological loop for maintenance of verbal material and the visuo-spatial sketch-pad (VSSP) for short-term retention of visuo-spatial information. A central executive is supposed to integrate and supervise the contents of both the verbal and the visuo-spatial slave systems. The aim of the present study is to disclose the characteristics of VSSP and to estimate parameters for an fMRI paradigm.

Logie (1995) specified the structure of VSSP more precisely. Similar to an active rehearsal and a passive storage component in the phonological loop, he postulated that VSSP consists of an active Inner Scribe and a passive Visual Cache. The Inner Scribe is conceptualized as a spatial system, the Visual Cache, in contrast, as a short-term store for visual object information. Both sub-modules interact with each other in that the spatial system provides a rehearsal mechanism for both types of information.

The dissociation of visual-object and spatial information in working memory has been supported both by behavioral and neurocognitive studies (Logie and Marchetti, 1991; Mecklinger and Pfeifer, 1996; Smith and Jonides, 1997; Tresch et al., 1993). However, it remains an open question as to how spatial and object information should be defined and delimited (Zimmer and Speiser, 2002; Zimmer et al., 2003). Logie (1995) emphasizes the dynamic aspect of spatial information. Examples of information types being processed by the Inner Scribe are the mental scanning of a static scene, moving objects that are visually presented, or motor actions. In contrast, the operationalization of spatial and object information in experimental studies diverges from this theoretical approach. Typical object tasks involve short-term retention of color or shape information. On the other hand, there is more variability in the kind of spatial information that is to be retained in working memory experiments – it has been operationalized both as absolute and as relative positions of objects and as spatio-temporal sequences.

For example, the object delayed-match-to-sample (DMS) task of Logie and Marchetti (1991) consisted of four differently colored squares that were displayed sequentially on distinct screen positions. Participants were required to maintain the squares' hues for a short time. In non-match trials, the color nuance of one square was changed in the test stimulus. In the spatial working memory task, squares of the same hue were presented sequentially on six different screen positions. The critical information to be retained in working memory was the spatio-temporal sequence as, in non-match trials, the order in which two of the squares appeared was different from the original sequence. Each primary working memory task was coupled with a visual (irrelevant pictures), a spatial (active movement) or no secondary task during retention. The results suggest separate systems for the temporary retention of visual and spatial material: working memory for spatio-temporal sequences was impaired by active movements during retention but not by the presentation of irrelevant pictures. The reverse pattern emerged for the visual working memory task.

In an ERP study, Mecklinger and Pfeifer (1996) used shape as the feature to be remembered in their visual-object working memory task. Three, four, or five geometrical objects were presented simultaneously in order to manipulate memory load. In the spatial task, again three, four, or five elements were presented at the same time but they were identical in shape and displayed on different positions in a two-dimensional array. In shape non-match trials, the same number of geometrical objects was displayed but one object differed in width when compared with the original display. Non-match trials in the spatial task consisted of a two-dimensional array of the same number of elements that differed only in the position of one element. Specific negative slow wave activity could be observed for short-term retention of spatial and object information differing both in topography and timing. For retention of spatial locations, negative slow wave activity occurred at sites overlying posterior parietal and occipital cortices. Retention of shape information in working memory, on the other hand, was correlated with negative slow wave activity that was obtained 2000 ms later over mid-frontal electrodes. Mecklinger and Pfeifer (1996) concluded from these results that working memory for spatial and object information must be functionally dissociated.

Although both studies claim that visual and spatial information is processed differently in working memory, they have used diverse operationalizations (and maybe concepts) for this purpose. Whereas Logie and Marchetti (1991) used spatio-temporal sequences (involving dynamic aspects) as spatial information, Mecklinger and Pfeifer (1996) considered relative positions of objects as spatial. According to Logie (1995), a corresponding non-match item consisting of an array of objects with only one position shifted would constitute a change in object configuration and should be considered visual object information. “Spatial” working memory tasks using an array of objects have been used in several studies (e.g. Ruchkin et al., 1992; Bosch et al., 2001; Glahn et al., 2002; Postma and deHaan, 1996; Smith and Jonides, 1997). In many of these experiments, spatial tasks could have been solved by retention of configurations rather than absolute positions. Configurations can be considered as virtual shapes defined by interpreting the locations as corners of a polygon (see Zimmer and Lehnert, 2006). In other array studies, however, short-term retention of absolute positions is necessary. Smith and Jonides (1997), for instance, applied a test where a single screen location was circled and participants were required to decide whether the circled location matched one of the object positions from an earlier stimulus retained in working memory.

There is a considerable variety in spatial and object working memory tasks. Some tasks that are theoretically categorized as visual object tasks are empirically applied as spatial tasks. The emphasis on dynamic aspects in spatial information seems to linger in theoretical spheres. An earlier study from our lab (Zimmer et al., 2003) indicated that working memory for object configurations and working memory for spatio-temporal sequences (Corsi task) rely on different memory mechanisms. As a consequence, the notion of "visuo-spatial" information is a very broad category that encompasses different information types.

The purpose of the first behavioral experiment was to show that the three described information types can be retained selectively in working memory. If this is possible, it is likely that there are at least three information types in VSSP. The final two experiments were conducted to adapt the experimental procedure to the affordances of an fMRI study that aimed at identifying posterior cortical activation sites related to these subsystems (Umla-Runge and Zimmer, in preparation).

We applied an S1-Cue-S2 paradigm as exemplified in Figure 1 (see also Bosch, 1999; Bosch et al., 2001; Mecklinger et al., 2004).

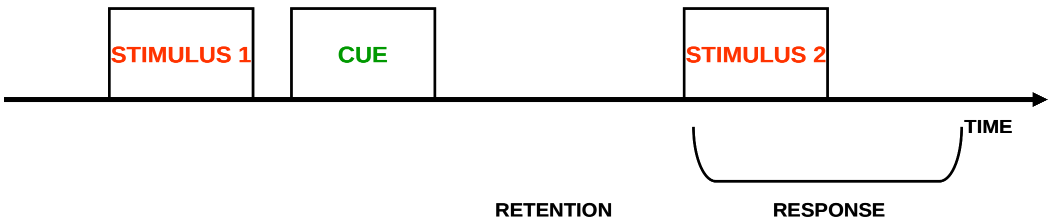

Figure 1. Schematic illustration of a trial in an S1-cue-S2 paradigm. The experimental task is a modified DMS task. Stimulus 1 (S1) is a visual stimulus that is encoded without any knowledge about the feature to be compared with Stimulus 2 (S2). A cue that is presented after S1 offset indicates the feature that participants are required to retain during the retention interval for a match/non-match judgment at S2. Participants are allowed to respond during S2 presentation and a pre-specified additional time interval.

We suggest that short-term retention of dynamic-spatial (movement-related information), static-spatial (locational information), and visual object features (related to object identity) can be distinguished. More generally, we take the position that a visual stimulus consists of separate features that can be attended to selectively rather than being necessarily processed as a whole. Concerning working memory retention systems, it is even more interesting if these different features can also be rehearsed selectively.

Participants were required to compare a second stimulus (S2) with a first stimulus (S1) with respect to a specific feature indicated by a cue. The cue was presented after S1-offset in order to avoid selective encoding of the stimulus feature. S1 could be a static or dynamic visual stimulus. For dynamic S1 stimuli, to-be-retained features were either movement or end position. For static S1 stimuli, possible features were position or color information. The precise nature of the stimuli and the working memory tasks are described in the methods sections of Experiment 1, 2, and 3.

Experiment 1

Participants

32 participants took part in the study (4 male, 28 female). Their mean age was 23.1 years (range 19-42 years). All participants were students from Saarland University and they were paid for participation.

Design & Material

Dynamic and static stimuli (S1) are exemplified in Figure 2.

(a) (b)

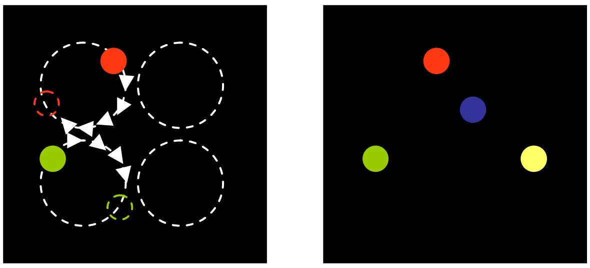

Figure 2. Examples of dynamic and static stimuli in Experiment 1. A dynamic S1 is illustrated in (a). The two colored points moved along a semicircular trajectory as indicated by the arrows. Two speeds were possible. Speed varied between trials but not between points within one trial. The end positions are symbolized by dashed point contours of the same color and size. Circular vectors are displayed for illustrative purposes only and were invisible to the participants. In (b), a static S1 is displayed. Four static colored points were presented on different randomly drawn positions.

A black background was used throughout the experiment. After a fixation cross had been centrally displayed for 250 ms, participants were presented with a visual stimulus (S1) which could be either static or dynamic.

Static stimuli were presented for 2100 ms, duration for dynamic stimuli was 1300 ms and 2100 ms each in 50% of the trials. Different durations for dynamic stimuli were the result of a speed manipulation with identical start and end points. Dynamic S1 consisted of two colored points that moved along two invisible semicircles. The semicircles were part of four circular vectors (diameter: 8 cm) and four start points were possible on each circle (at 45°, 135°, 225° and 315°). Each point moved either clockwise or anti-clockwise and both moved at the same speed. Both speeds occurred with equal probabilities.

For the static block, we included four colored points in each S1 to make working memory tasks of the two blocks more comparable in difficulty. Each point was located on one of four possible positions on each of the four invisible circles also used for dynamic S1.

At encoding, participants were blind to the feature that they would be tested on later. A cue which was displayed 1000 ms after S1-offset could either be specific about the kind of task to be expected or not. The cue was presented in white letters for 500 ms. Participants were instructed to rehearse the feature that had been indicated by the specific cue or both features in the case of an unspecific cue during a retention interval of 6000 ms. In the dynamic block, specific cues were “Bewegung” (movement) and “Position” (i.e. (end) position). Specific cues in the static block were “Position” (position) and “Farbe” (color). “Beides” (both) was used as the unspecific cue because participants were required to rehearse both movement and end position in the dynamic block and both position and color in the static block.

The retention interval could be followed by a static or dynamic visual stimulus (S2) depending on the type of task. Duration was the same as for dynamic and static S1. Participants were required to compare S1 and S2 with respect to a specific feature or feature combination and to respond whether the two matched in that respect or not. 2000 ms after S2-offset, the fixation cross of the next trial was displayed.

The dynamic block consisted in movement and end position trials. In movement trials, S2 was another dynamic stimulus which could either match S1 in movement or not. Movement match and non-match trials occurred with equal probabilities. Furthermore, there were two possible non-match types: either S1 and S2 did not match in speed but in trajectory, or they did match in speed but not in trajectory. In speed non-match trials, the speed of both points was altered. In trajectory non-match trials, a different trajectory was used for one of the two moving points. In these trials, one point moved on the complementary semicircle (relative to S1 trajectory) to get from the same start to the same end point. With this dual operationalization of movement, we wanted to find out which one would be more suitable for the fMRI study.

In end position trials, S2 was a static stimulus with two colored points at specific positions, which were to be evaluated as absolute end position matches or non-matches regarding S1. End position non-matches were converted by a quarter circle position shift for one of the two points either clockwise or anti-clockwise on the respective circular vector.

Participants obtained specific and unspecific cues in 50% of the dynamic block trials, respectively. In unspecific trials, participants were unaware of the type of recognition test until the onset of S2. Only the type of stimulus at S2 (two moving vs. two static points) indicated if it was a movement or end position evaluation.

A static block S2 consisted of four colored points shown simultaneously on specific positions. In position non-match trials, the absolute position of one point was shifted (again a quarter circle either clockwise or anti-clockwise on the circular vector), whereas in color non-match trials, the color of one point was changed. There were no double non-match trials. In position non-match trials, the colors of the points were unaltered. By analogy, the positions remained identical to S1 in color non-match trials. Both non-match cases occurred with equal probabilities. Again, the unspecific cue “Beides” was used in 50% of the trials in the static block. Yet, unlike S2 in the dynamic block, the type of S2 in the static block did not indicate which memory test was to be performed. Therefore, in trials with an unspecific cue, participants were required to evaluate S2 as to its identity with S1.

Participants were either assigned to the static block or the dynamic block (16 participants each). The stimulus material and design of the experiment is summarized in

Figure 3. The dynamic block consisted of 80 movement and 80 end position trials, half of which were administered with a specific or an unspecific cue, respectively. Overall, match and non-match trials as well as speed and trajectory non-match trials in the movement block were uniformly distributed. Likewise, participants of the static block performed 40 position, 40 color, and 80 identity judgment trials. Match and non-match trials and identity non-matches caused by position deviation or by a change in color occurred with equal probabilities.

The experiment was run on a computer

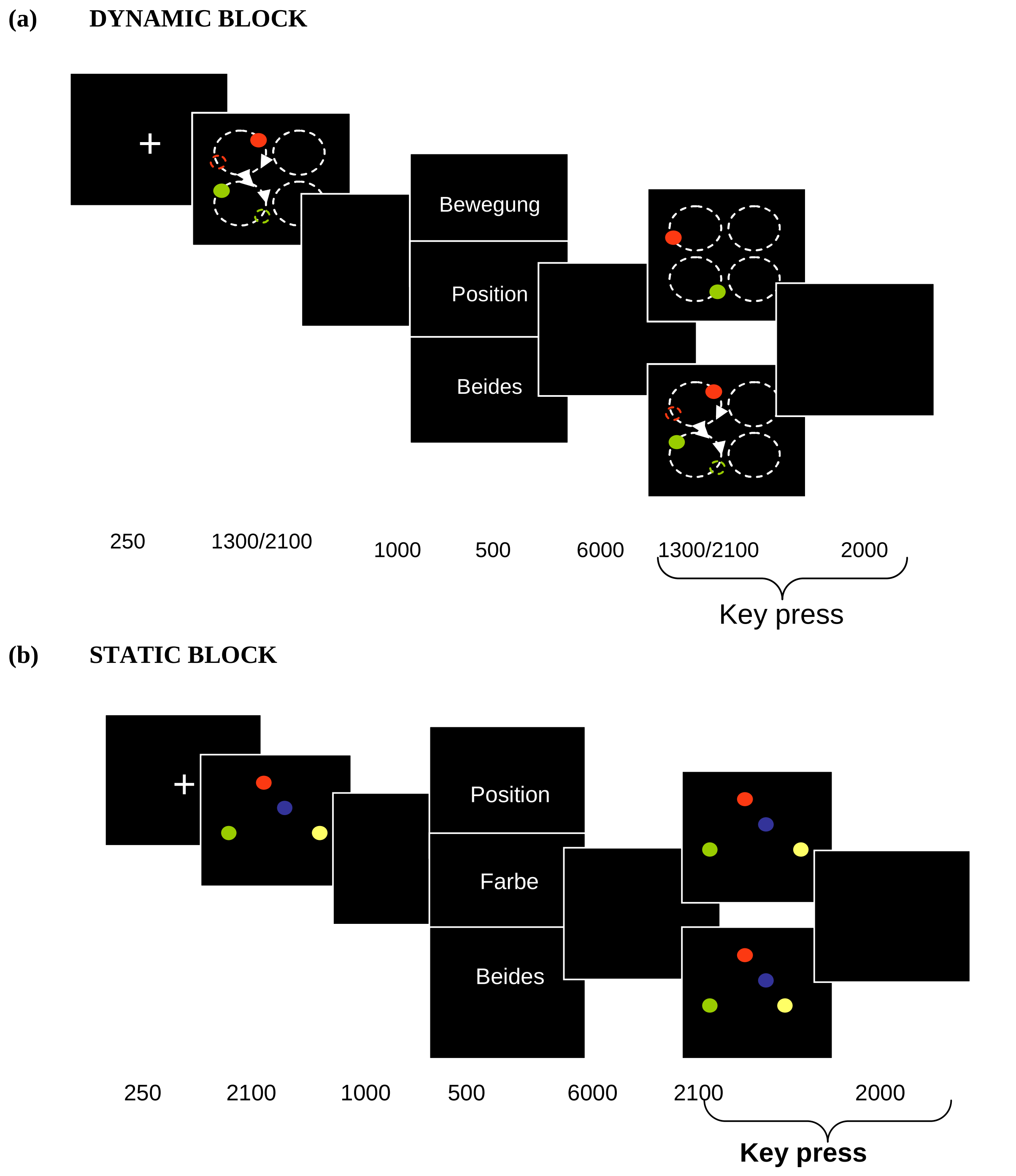

Figure 3. Trial types in the dynamic and static block in Experiment 1. In (a), trial types of the dynamic block are illustrated. Trial types of the static block are displayed in (b). The sequence of trial events can be read from the left to the right. Cues differed within both blocks indicating the type of working memory retention task. The numbers denote time for each trial event in milliseconds. Participants were allowed to respond from S2 onset until the fixation cross of the next trial.

using the experimental run time system software package (ERTS, BeriSoft, Frankfurt, Germany).

Results

We looked at the effect of cue specificity and the type of memory task on response times for hits and correct rejections and on accuracy measures (relative frequencies of hits and correct rejections) separately for the dynamic and static condition. Descriptive statistics are displayed in Table 1.

Table 1. Accuracy measures and response times of Experiment 1. Mean relative frequencies and mean response times for hits and correct rejections are displayed together with corresponding standard deviations. Experimental conditions are defined by the factors task (movement, end position, position, color) and cue specificity (specific, unspecific). With unspecific cues in the static block, participants were required to evaluate S1 and S2 with respect to their identity. Therefore, a distinction between position and color trials is not possible for statistics involving hits. CRs = Correct rejections, SD = Standard deviation.

Task		**Specific cue**				**Unspecific cue**			
		Hit rate	*Correct rejections rate*	*Mean response time in ms (hits)*	*Mean response time in ms (CRs)*	*Hit rate*	*Correct rejections rate*	*Mean response time in ms (hits)*	*Mean response time in ms (CRs)*
					Dynamic block				
Movement	*mean*	.83	.61	2148	2008	.81	.55	2201	2120
	SD	.13	.16	407	494	.10	.14	390	520
End position	*mean*	.78	.79	903	982	.76	.75	1077	1139
	SD	.11	.13	170	201	.14	.11	178	159
					Static block				
Position	*mean*	.76	.83	1358	1090		.76		1257
	SD	.17	.21	406	170	*mean* .78	.21	*mean* 1559	249
Color	*mean*	.85	.82	1486	1431	*SD* .11	.74	*SD* 469	1367
	SD	.07	.10	381	354		.15		315

Dynamic block

We conducted a 2 (cue specificity: specific vs. unspecific) × 2 (working memory task: movement vs. end position) repeated measures ANOVA with mean hit response time as the dependent variable. The analysis yielded significant main effects of cue specificity, $F(1,15) = 12.18$, $MSE = 16898$, $p < .01$ and working memory task, $F(1,15) = 122$, $MSE = 183783$, $p < .001$. Moreover, a significant interaction emerged, $F(1,15) = 8.53$, $MSE = 6845$, $p < .05$. Response times for hits were slower with an unspecific cue compared to a specific cue, but this effect was restricted to the end position task.

An analogous ANOVA was conducted with mean response times for correct rejections. Both a main effect of cue specificity, $F(1,15) = 17.00$, $MSE = 16955$, $p < .001$, and working memory task, $F(1,15) = 83.36$, $MSE = 193310$, $p < .001$ emerged. Response times for correct rejections in trials with specific cues were significantly shorter than in trials with unspecific cues. In addition, response times differed significantly between movement and end position tasks in that it took participants longer to make a correct rejection in a movement task. The interaction did not yield a significant effect, $F(1,15) = 1.01$, $p > 0.33$.

In addition, 2 (cue specificity: specific vs. unspecific) × 2 (working memory task: movement vs. end position) repeated measures ANOVAs were conducted with relative frequencies of hits and correct rejections as dependent variables, respectively. There were no significant main effects or interactions with relative frequencies of hits. With relative frequencies of correct rejections, a significant main effect of cue specificity resulted, $F(1,15) = 5.51$, $MSE = .0067$, $p < .05$. Participants' correct rejections rate in trials with an unspecific cue was significantly lower than in trials with a specific cue. In addition, the analysis yielded a significant main effect of working memory task, $F(1,15) = 30.39$, $MSE = .018$, $p < .001$. There were significantly less correct rejections in the movement task as compared to the end position task. The interaction was not significant, $F < 1$.

In order to find out whether there was a significant difference in the relative frequencies of correct rejections for the two types of non-matches in the movement task, a 2 (cue specificity) × 2 (type of non-match: speed vs. trajectory) repeated measures ANOVA was conducted. A significant main effect for the type of non-match resulted, $F(1,15) = 33.7$, $MSE = .046$, $p < .001$. Participants were more prone to false alarms in speed non-match trials relative to trajectory non-match trials. Moreover, we obtained a marginally significant main effect of cue specificity, $F(1,15) = 4.24$, $MSE = .013$, $p < .07$ in the expected direction. The analysis did not yield a significant interaction effect.[2]

Static block

A repeated measures ANOVA with the factor task (position, color, identity) and mean response times for hits as the dependent variable yielded a significant main effect,

[2] Our movement and end position working memory tasks differed in the duration of S2, which could be either 1300 ms or 2100 ms in the movement task, whereas it was always 2100 ms in the end position task. In order to make responses in movement and position working memory tasks more comparable, we repeated the cue specificity × working memory task ANOVAs for the dynamic block and restricted them to „slow“ S2 (i.e. stimuli presented for 2100 ms). As a result, there were twice as much trials in the position task as compared to the movement task. The analyses yielded comparable results with the exception of the cue specificity main effect for relative frequencies of correct rejections, which no longer reached significance, $F(1,15) = 2.76$, $MSE = .012$, $p < .12$. However, numerically the effect points in the expected direction.

$F(2,30) = 9.64$, $MSE = 17198$, $p < .001$. In planned contrasts (Bonferroni-corrected $\alpha = .017$) between each specific cue task and the unspecific cue task, a significant difference between position and identity in the expected direction resulted ($F(1,15) = 20.19$, $MSE = 16027$, $p < .0005$) but the difference between color and identity did not reach significance ($F(1,15) = 3.87$, $MSE = 11136$, $p = .07$). In addition, response times for hits did not differ significantly between the two working memory tasks with specific cues ($F(1,15) = 5.34$, $MSE = 24432$, $p = .04$).

For the relative frequencies of hits, an analogous repeated measures ANOVA was conducted. Again a significant main effect for the factor task emerged, $F(2,30) = 4.12$, $MSE = .008$, $p < .05$. However, only for the color task did a significant increase in hit rate occur when compared to the identity task, $F(1,15) = 11.11$, $MSE = .003$, $p < .005$. Mean hit rates for position and identity tasks as well as for position and color tasks were not distinguishable (Bonferroni-corrected $\alpha = .017$).

A 2 (cue specificity: specific vs. unspecific) × 2 (type of non-match: position vs. color) repeated measures ANOVA was conducted for mean response times of correct rejections. A significant main effect of the type of non-match emerged, $F(1,15) = 14$, $MSE = 58164$, $p < .005$. Mean response times for color non-matches were significantly longer than those for position non-matches. Moreover, a significant interaction was obtained, $F(1,15) = 11.18$, $MSE = 19085$, $p < .005$. As revealed by planned comparisons, cue specificity had a significant effect in the expected direction upon mean response times for correct rejections in the position working memory task ($F(1,15) = 9.18$, $MSE = 24422$, $p < .01$), but not the color task.

The same method was applied to relative frequencies of correct rejections. Cue specificity yielded a significant main effect, $F(1,15) = 12.09$, $MSE = .008$, $p < .005$. Participants made significantly more correct rejections in trials with specific cues relative to unspecific ones. This effect was independent of the type of non-match.

Discussion

If participants can rehearse movement, end position, position, and color information selectively, they will be faster and more accurate in their judgment with a specific cue as compared to an unspecific one.

For movement information, participants benefited from a specific cue in relative frequencies of correct rejections and the corresponding mean response times. Nevertheless, there were no significant modulations of cue specificity on accuracy or timing of hits. Detection of deviations in the to-be-evaluated feature of S2 seems to work better if participants know which feature will be tested at S2. This effect cannot be due to an attentional modulation at encoding as the cue was presented after S1 offset. A possible interpretation is that selective rehearsal of movement-related parameters helped reduce the number of false alarms but did not augment the number of hits. The latter is probably due to a general liberal response bias of participants in the movement task (Br = .707 in trials with a specific cue, Br = .704 in trials with an unspecific cue). When they were uncertain, participants tended to accept an item as old (see Corwin, 1994; Feenan and Snodgrass, 1990).

The position tasks in the dynamic and the static block yielded a parallel pattern of results. Mean response times for hits and correct rejections were faster in trials with specific cues relative to trials with unspecific cues. For accuracy measures, there was an additional effect of cue specificity on the relative frequencies of correct rejections. Participants made more correct negative responses if they were given a specific cue as compared to an unspecific cue. This speaks to the possibility that participants can selectively rehearse locational information. Only relative frequencies of hits were again unaffected by the specificity modulation.

For color information in working memory, effects on relative frequencies of hits and correct rejections were obtained. As compared to trials involving an unspecific cue, participants made more correct negative and positive evaluations in trials with a specific cue. However, this effect was not coupled with a cue specificity modulation on mean response times for hits and correct rejections.

With mean response times for hits and correct rejections in the dynamic block, an additional significant main effect of the type of working memory task emerged that can be explained on the basis of differential perceptual events at S2 in the movement and end position tasks. The movement S2 was a dynamic stimulus, whereas in the end position task a static S2 was presented. As a consequence, the to be evaluated position was present from S2 onset, movement information, however, was unveiled piece by piece in the 1300/2100 ms after S2 onset. It was in the nature of the different tasks and the corresponding test stimuli that participants needed more time to judge movements relative to end positions. As response times were generally long for dynamic S2, this could be an explanation for the absence of cue specificity modulation on response time for hits in the movement task.

Taken together, when retaining movement, (end) position, and color information in working memory, participants benefit from specific relative to unspecific cues in both response times and accuracy. This can be interpreted as evidence for the ability to selectively retain these types of information.

As revealed by a post-hoc analysis, the number of correct rejections differs significantly between speed and trajectory non-matches in the movement task. This pattern of results fits well with an assumption of a hierarchical organization of different aspects of movement information. We propose that participants are unable to rehearse abstract speed information. Rather, a trajectory is needed to rehearse speed information. On the other hand, trajectory information can be rehearsed selectively without taking speed information into account. Trajectory information is not inherently dynamic, it can be rehearsed as static shape information (Zimmer and Lehnert, 2006). Following this logic, participants should be more prone to false alarms when they are faced with speed non-match and trajectory match items than if they are faced with trajectory non-match and speed match items.

In the fMRI study, we wanted to use a unique operationalization for movement information. Although participants made significantly less correct rejections in speed non-match trials as compared to trajectory non-match trials, we considered speed information to be a more adequate operationalization for movement working memory. Genuinely dynamic aspects are only needed to make speed comparisons, whereas trajectory judgments can be made by static shape information alone. However, the speed task of Experiment 1 has to be modified in several respects to guarantee processing of dynamic information. First, with only two speeds present, verbal recoding of speed information is possible (the same is true for the color task). Second, if we use a constant speed for a dynamic stimulus, two variables will be necessarily confounded. If its end position is kept constant, speed and presentation time will be confounded. However, if presentation time is kept constant, speed and end position will be confounded variables. A dynamic stimulus with variable speed at different segments of its trajectory could avoid this confounding.

With more than one location to be remembered in the position task, and given that position non-match trials were converted by deviation of a single point, participants have at least two possible strategies at hand. They can retain absolute positions or they can retain an object configuration, that is, a shape. As only the former strategy can truly be considered spatial, a modification of the (end) position tasks will be necessary, too.

Our second behavioral experiment focused on the effects of accordingly modified movement, position, and color working memory tasks on accuracy measures.

Experiment 2

Participants

20 participants took part in the study (10 male, 10 female). Their mean age was 25.7 years (range 17-44 years). Most participants were students from Saarland University and they were paid for participation.

Design & Material

Modifications of our first draft stimulus material will be described in the following. We decided to make speed the crucial movement feature for this study. In order not to confound speed, presentation time, and end position, and as there is a risk that participants recode speed information verbally, a dynamic stimulus was made up of a colored point running along a zigzag-trajectory consisting of three segments. These segments were equal in size but not in speed. Even within a segment, speed was not constant but the movement was accelerated and decelerated[3]. A non-matching S2 in the movement task consisted of a colored point running along the same trajectory as S1 but with altered speeds on the three segments. Dynamic stimuli had an overall duration of 3000 ms. Trajectory shapes differed between trials.

As a further manipulation to avoid verbal recoding of dynamic information, a small

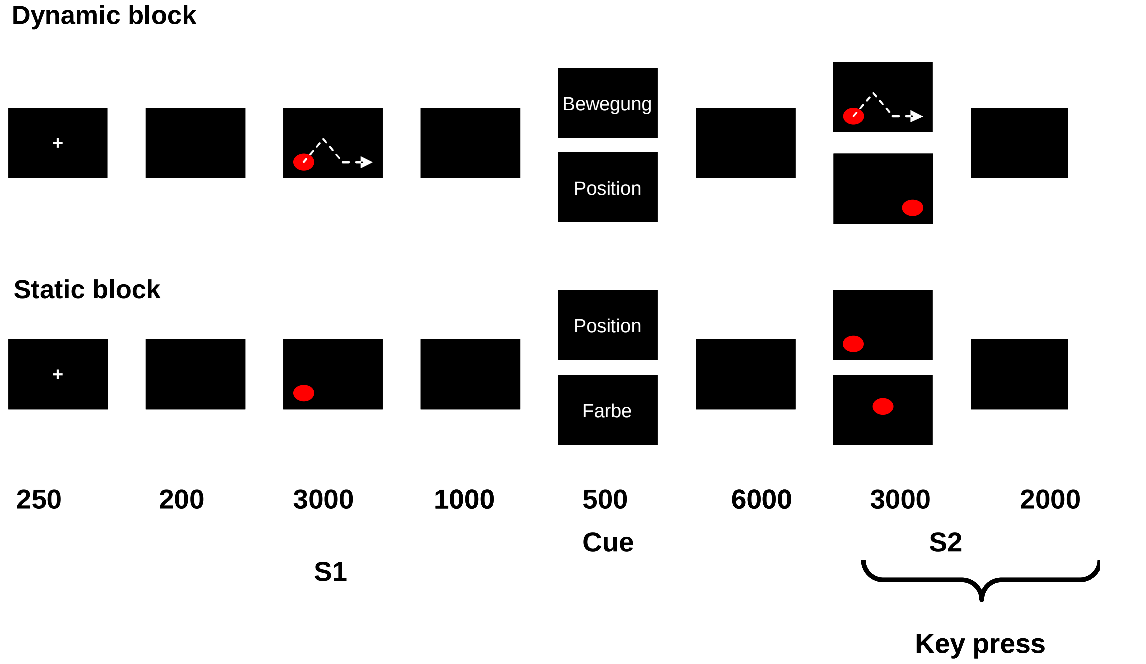

Figure 4. Experimental design and stimulus material of Experiment 2. A dynamic stimulus cosisted of a colored point moving on a three-segment zigzag trajectory. Speed varied between segments. The trajectory is illustrated by a white dashed line which was not visible to the participants. Static stimuli were single colored points presented at a specific position. The feature to be remembered in working memory (movement, end position, position, color) was indicated by a cue after S1 offset. Participants were required to compare an S2 displayed after a retention interval of 6000 ms with S1 in the given feature.

[3] Segments were defined as vectors consisting of a set of locations that were not equally spaced but sine distributed to make verbalization of speed even more difficult (for more details see ERTS Version 3.32, Reference Manual, p. 30, BeriSoft, Frankfurt, Germany).

number of filler trials were included in which S1 and S2 differed in trajectory shape. Accuracy measures in these trials were not analyzed.

We assumed that these modifications would make the movement task more difficult than before, and we therefore required participants to retain specific visual attributes of only one colored point. Thereby, difficulties with the position task were also smoothed out. Participants could use a shape (i.e. visual-object) strategy to detect a deviating absolute position of one point in a configuration, whereas there was a need to rehearse a location (i.e. a spatial feature) in the case of a single point. Position non-match stimuli deviated 2 cm from the S1 (end) position on a 17 inch monitor.

In order to make the color task comparable in difficulty (and again to prevent participants from verbal recoding of visual information), a just slightly different color nuance was used for color non-matches. There were four color groups (red, blue, yellow, green), each consisting of three different nuances. A color S2 was always presented centrally.

Between fixation and S1 presentation, a blank interval of 200 ms was inserted. Except for this modification, as well as S1 and S2 durations which were changed to 3000 ms, timing of trial events was unaltered relative to Experiment 1. Again, a black background was used throughout the experiment.

All participants worked through both a dynamic block with movement and end position tasks and a static block with position and color tasks. Block sequence was counterbalanced between participants. There were only specific cues in Experiment 2 (“Bewegung”, “Position”, “Farbe”, i.e. the German equivalents to movement, position and color). The stimulus material of Experiment 2 is illustrated in Figure 4. Again, ERTS (BeriSoft, Frankfurt, Germany) was used for both the presentation of stimuli and the recording of responses.

Results

As response times were inherently confounded with the type of task (i.e. longer for movement tasks), they were not analyzed. Relative frequencies of hits and correct rejections in the four types of working memory task are summarized in Table 2.

Table 2. Accuracy measures of Experiment 2. The table summarizes mean relative frequencies of hits and correct rejections for each of the four working memory tasks. Corresponding standard deviations are indicated in brackets. SD = Standard deviation.

Task			
		Hits	*Correct rejections*
		Dynamic block	
Movement	*Mean*	.84	.57
	SD	.11	.27
End position	*Mean*	.76	.91
	SD	.11	.06
		Static block	
Position	*Mean*	.84	.96
	SD	.12	.05
Color	*Mean*	.93	.82
	SD	.09	.14

We conducted a 2 (between-subjects factor "block sequence": dynamic-static vs. static-dynamic) × 4 (within-subjects factor "working memory task": movement vs. end position vs. position vs. color) ANOVA on the relative frequencies of hits. The analysis yielded a significant main effect of type of working memory task, $F(3,54) = 10.77$, $MSE = .009$, $p < .005$. Except for the contrast of the movement task and static block position task, a post-hoc Tukey HSD test revealed significant differences between all other pairs of tasks. There was neither a significant main effect of sequence nor a significant interaction of the type of task and block sequence.

An analogous ANOVA was conducted on the relative frequencies of correct rejections. Again a significant main effect of task emerged, $F(3,54) = 42.29$, $MSE = .014$, $p < .001$. As checked with a post-hoc Tukey HSD test, there were significantly less correct rejections in the movement working memory task as compared to each other task. Moreover, the mean relative frequency of correct rejections in the color task differed significantly from that in the position task in the static block. As in the analysis involving hits, a significant main effect of block sequence did not result. However, there was a significant interaction of the factors task and block sequence, $F(3,54) = 8.22$, $MSE = .014$, $p < .005$. Participants made less correct negative answers in the movement task when the dynamic block was performed first as compared to the condition where participants worked on the static block first ($p < .05$) As a consequence, the differences between the relative frequencies of correct rejections in the movement task and each other working memory task were much more pronounced when participants began the experiment with the dynamic block.

Discussion

The purpose of Experiment 2 was to validate the new stimulus material. Hit rates ranged from .76 to .93. Although participants were able to perform the working memory tasks sufficiently well, there were significant differences in task difficulty. Hit rates in the color task were significantly larger than in each other working memory task, but the difference was not that strong.

The only critical result is the relatively low frequency of correct rejections, which is equivalent to a high false alarm rate. There were significantly less correct rejections in movement non-match trials as compared to other non-match types. Reasons for that might be difficulties in rehearsal or in identifying the mismatch of speed. As indicated in the discussion of Experiment 1, we suggest that speed information cannot be rehearsed independently from a trajectory along which a given object moves. Consequently, if participants are faced with a speed mismatch, they nonetheless experience a trajectory match. Hence they might be prone to accept the item as old because of the presence of misleading irrelevant but matching information. Many false alarms might therefore not be due to a loss of S1 information and erroneous guessing but an effect of a too weak mismatch signal caused by differences in speed. On the other hand, making the speed mismatching more salient would enhance the risk of verbal recoding. We therefore decided to modify the speed changes in mismatching trials only slightly, and we made similar changes in the static conditions to make task difficulties more comparable.

Experiment 3

We prepared new non-matching material by revising the size of changes in the mismatching trials. Speed differences were enhanced a bit. Similarly, location deviations in the dynamic condition were enhanced to make their detection easier. In contrast, mismatching colors were made more similar to increase task difficulty. With this new stimulus material we ran the conditions of Experiment 2 again.

Participants

22 participants took part in the study. All participants were undergraduate students from Saarland University. Their participation was part of a course requirement.

Design & Material

The differences in speeds between zigzag-trajectory segments were boosted moderately. Furthermore, as there was a significant difference in hit rates of the two position tasks in Experiment 2, we made non-match deviations in dynamic end position tasks bigger (3 cm) as compared to deviations in static position tasks (2 cm, as before). As the color task was the easiest one in Experiment 2 (significantly higher hit rates than in every other working memory task), we aimed at making it more difficult in Experiment 3. Each color group consisted of three different nuances that were equiluminant across groups. Within a color group, the difference in brightness between a light and a medium as well as a medium and a dark nuance were equal in magnitude.

The first three letters describing the task served as cues ("BEW" for movement, "POS" for end position and position and "FAR" for color tasks respectively). In addition, cue presentation duration was changed to 750 ms to ensure that participants do not miss the information about the type of task to be performed. Cue onset began 1250 ms after S1 offset.

Except for these modifications, the procedure and stimulus material was identical to Experiment 2.

Results

As in Experiment 2, response times were not analyzed. Accuracy measures for the different types of task are summarized in Table 3.

A 2 (between-subjects factor "block sequence": dynamic-static or static-dynamic) × 4 (within-subjects factor "working memory task": movement, end position, position or color) ANOVA was conducted with relative frequencies of hits as the dependent variable. The analysis yielded a significant main effect for the type of working memory task, $F(3,60) = 16.46$, $p < .001$. Post-hoc Tukey HSD tests revealed significant differences in the dependent variable between the movement and end position task as well as the color task and the two position tasks. Participants made significantly more correct positive answers in the movement task as compared to the end position task. In addition, hit rates in the color task were significantly higher relative to the two position tasks in spite of the enhanced color similarity. There was also a marginally significant interaction of block sequence and type of task, $F(3,60) = 2.71$, $p = .05$.

Table 3. Accuracy measures of Experiment 3. The table summarizes mean relative frequencies of hits and correct rejections for each of the four working memory tasks. Corresponding standard deviations are indicated in brackets.

Task			
		Hits	*Correct rejections*
		Dynamic block	
Movement	*mean*	.86	.53
	SD	.11	.24
End position	*mean*	.73	.95
	SD	.14	.06
		Static block	
Position	*mean*	.79	.96
	SD	.14	.06
Color	*mean*	.93	.67
	SD	.08	.15

Compared to the task main effect in hit rates, the difference in relative frequencies of correct rejections between the different types of task as revealed by an analogous ANOVA was again more pronounced, $F(3,60) = 44.45$, $p < .001$. Except for the two position tasks, there were significant differences between all other pairs of tasks as revealed by post-hoc Tukey HSD tests.

A post-hoc t-test for independent samples in order to compare Experiments 2 and 3 in the number of correct rejections in the color task yielded a significant difference, $t(19) = -3.37$, $p < .005$. Participants of Experiment 3 made significantly less correct rejections in the color working memory task than those of Experiment 2.

Discussion

Our modifications in order to reduce differences in task difficulty were, by and large, ineffective.

Boosting speed differences moderately did not have the desired effect of reducing the number of false alarms in the movement working memory task. In contrast, the manipulation of colors affected the number of correct rejections in the color task. As a result, the color task in Experiment 3 can be considered more difficult than the one of Experiment 2, but there were still significant differences in hit rates and the number of correct rejections in comparison to other working memory tasks.

The non-match modification of the end position task was successful in leveling off differences in difficulty for the two position tasks. Unlike in Experiment 2, there were no significant differences between the relative frequencies of hits or false alarms between the end position and the position task.

In total we were therefore only partially successful in equalizing the task performances. Memory performances were sufficiently high, but nevertheless some differences between the tasks remained. However, we were afraid that manipulating sensory mismatches further would cause verbal strategy use. We therefore decided to tolerate the remaining differences between task difficulties especially because they are mainly differences in mismatch trials.

General discussion

It could be demonstrated that selective retention of movement, position, and color information is possible. Participants benefit from receiving a specific cue relative to an unspecific one both in response times and accuracy measures. This suggests that an item in VSSP is not processed as a solid unit in a visuo-spatial or a visual object subsystem. We hypothesize that it should be conceptualized as a vector chunking a multitude of different activated features.

Some of them, for example color or location, can be independently accessed and rehearsed. This rehearsal mechanism is probably provided by focusing attention on the specific subset of features. On the other hand, some information seems to be dependent on other features. An example may be speed information. It may be maintained together with trajectory information because imagining a moving dot always makes necessary that the dot is moving along a path. Further research is necessary to disclose these dependencies.

However, independent of the outcome of these studies, the reported results suggest that we should distinguish at least three types of information in VSSP: information on the appearance of an item (e.g. its color), its location, and in case of dynamic movements, the speed of movement. Because these features are analyzed by different neural structures, it is very likely hat these structures provide the specific information in working memory.

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