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Temporal and Spatial Reference Frames in Visual Working Memory Are Defined by Ordinal and Relational Properties

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Natural environments provide a rich spatiotemporal context that allows for visual objects to be differentiated based on different types of information: their absolute or relative spatial or temporal coordinates, or their ordinal positions in a spatial or temporal sequence. Here, we investigated which spatial and temporal properties are incidentally encoded along with to-be-remembered features to provide reference frames in visual working memory (VWM). We tested the different possibilities in a spatiotemporal color change-detection task by transforming spatial and/or temporal structures of item presentation at retrieval relative to encoding. More precisely, spatial and/or temporal coordinates were (a) switched, changing the order of items in a spatial or temporal sequence (ordinal transformation); (b) multiplied by different factors, changing interitem distances (relational transformation); or (c) multiplied by a constant factor, expanding or shrinking the entire configuration (global transformation). Such transformations of the external reference frame at retrieval should only interfere with VWM if the internal reference frame relies on the spatial or temporal properties affected by the respective transformation. We found that ordinal and relational transformations of either the spatial or temporal structure impaired performance, whereas global transformations did not. Thus, reference frames appear to be primarily defined by interitem relations—including relative distances between items as well as their order—rather than absolute positions in space or time. These results corroborate and extend previous findings for the spatial domain, and highlight functional similarities of the spatial and temporal dimensions in VWM by revealing the same metrical properties for temporal reference frames.

Keywords: visual working memory, spatial cognition, temporal cognition, context, change detection

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Natural environments typically provide a rich spatiotemporal context for visual events. When you are watching a car in traffic, you can refer to this car not only by its model or color, but also by a variety of spatial or temporal properties; for example, you can say that it is the one that passed the traffic lights two seconds ago, the one behind the blue car, the fastest one in view, the one at a 10 o'clock direction, or the last one that entered the lane. Space and time are ubiquitous dimensions that shape how we perceive and describe the world. Here, we were interested in how spatiotemporal context shapes how we remember visual information over short periods of time.

It has long been known that space is a particularly important feature dimension in visual working memory, and that this includes not only the spatial location of a specific object, but also its spatial context. For example, spatial representations are spontaneously created and maintained, even when task-irrelevant (e.g., Cai et al., 2019; Chen & Wyble, 2015; Foster et al., 2017; Heuer & Rolfs, 2021; van Ede et al., 2019), memory is impaired when the spatial context that was present at encoding is absent or different at retrieval (e.g., Hollingworth, 2006, 2007; Jiang et al., 2000; Olson & Marshuetz, 2005; Timm & Papenmeier, 2019b), and spatial attention is an especially powerful means to select and prioritize visual working memory contents (e.g., Griffin & Nobre, 2003; Heuer et al., 2017, 2020; Heuer & Schubö, 2018; Heuer et al., 2016; Ohl & Rolfs, 2017, 2018, 2020; Souza & Oberauer, 2016). This vast range of findings has led to the proposal that the organization of visual working memory is essentially location-based (Pertzov & Husain, 2014; Schneegans & Bays, 2017; Treisman & Zhang, 2006). The fact that much of our visual experience is not static but evolves over time has been largely neglected.

We have recently shown that both spatial and temporal properties are incidentally encoded and functionally relevant, providing

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reference frames for storage and retrieval (Heuer & Rolfs, 2021): When to-be-remembered items were presented sequentially, at different locations and at different interstimulus intervals, taking away the distinctive spatial or temporal information at retrieval—by presenting items simultaneously or sequentially at the same location—impaired memory, although spatiotemporal properties were entirely task-irrelevant. For certain arrangements of items in space and time, temporal context was even more important than spatial context. Crucially, no comparable memory costs were observed when distinctive variations in other, equally task-irrelevant, feature dimensions (color or shape) were removed, indicating that these costs were not just the result of any change occurring at retrieval (e.g., Tulving, 1974; Tulving & Thomson, 1973).

The task that we used in our previous work (Heuer & Rolfs, 2021) was designed to provide a spatiotemporally rich context at encoding that—similar to spatiotemporal contexts in natural settings—allowed for memory contents to be differentiated based on (a) their absolute spatial or temporal coordinates ("item A was located at point s in space and point t in time"), (b) their relative spatial or temporal coordinates ("item A had, in a certain direction, twice the spatial distance from item B than from item C and half the temporal distance"), or (c) their position in a categorical spatial or temporal order ("item A appeared before and above item B"). But which of these properties are the critical ones that define spatiotemporal reference frames in visual working memory?

While, overall, we know surprisingly little about contextual reference frames in visual working memory, studies addressing this issue have almost exclusively focused on spatial configurations. The typical approach to study if the spatial configuration present at encoding is used to support memory has been to remove (parts of) that configuration at retrieval, or to change some or all of the item positions and thereby the overall configuration (e.g., Hollingworth, 2006, 2007; Jiang et al., 2000; Papenmeier et al., 2012; Timm & Papenmeier, 2019a, 2019b). The latter approach is ideally suited to clarify which spatial properties are critical, as different transformations of spatial coordinates preserve or disrupt different properties of the spatial reference frame. Decrements in memory performance not only for location but also nonspatial features such as color or shape—relative to a baseline condition with intact spatial configurations—can then be taken to indicate that the configurational representation in visual working memory relied on the spatial properties affected by the transformation.

To determine if memory is supported by bindings between items and their absolute spatial positions, previous studies used global transformations of the spatial configuration. Global changes affect absolute item positions by expanding, shrinking, or shifting the entire configuration, but not interitem relations. As such changes essentially emulate the consequences of a change in viewer distance or of an eye movement, it would be highly detrimental if visual working memory was not invariant to this type of transformation. In fact, spatial transformations of this kind do not seem to interfere with memory performance (Boduroglu & Shah, 2009; Hollingworth, 2007; Jiang et al., 2000; Woodman et al., 2012), indicating that spatial reference frames do not rely on absolute item positions.

Spatial relations between items, by contrast, appear to be encoded along with each item to support their maintenance and retrieval. In a number of studies, relative transformations of spatial configurations, which affect both the absolute and relative locations of the individual items (e.g., random scrambling of all item positions), have been shown to impair memory, even when the spatial configuration was task-irrelevant or when there were explicit instructions to ignore any configurational properties (e.g., Hollingworth, 2007; Jiang et al., 2000; Olson & Marshuetz, 2005; Sun & Gordon, 2009, 2010; Timm & Papenmeier, 2020; Udale et al., 2017). Spatial relations are also bound across time when items are presented sequentially, but this has only been studied in tasks that tested memory for spatial relations or locations, which naturally encourages their encoding (Boduroglu & Shah, 2014; Rondina et al., 2017; Ryan & Villate, 2009).

Overall, however, the evidence regarding the importance of relational spatial coding for visual working memory is mixed. There are also a few studies that failed to observe consistent and significant impairments as a result of relational changes of the spatial configuration (Boduroglu & Shah, 2009; Woodman et al., 2012), indicating, instead, that objects were stored in a largely independent manner—at least when spatial relations are task-irrelevant. The encoding of spatial relations might thus be subject to certain boundary conditions that have yet to be identified. A number of different factors have been suggested so far, for instance differences in individual strategies (Boduroglu & Shah, 2009), retention duration (Logie et al., 2011), stimulus type, or specific task demands like implicit encouragements to encode spatial relations (Woodman et al., 2012).

How transformations of the spatial order of items (e.g., clockwise, when items are arranged on a circle) affect memory performance has not been directly tested. It has been shown, though, that configurational representations do not just comprise the spatial layout but also the bindings of individual items (e.g., object identities or surface features like color or shape) to each location: Memory for a given item suffers when its context is made up of the same locations but the identities of the items at those locations have been removed or switched (Hollingworth, 2007; Sun & Gordon, 2009), the latter of which is essentially an ordinal change in the spatial configuration.

For the temporal domain, the critical properties for reference frames in visual working memory are unknown. The temporal structure of visual events is often mainly thought of as temporal order, especially with respect to feature binding—here, serial position might take over the role of spatial location in indexing bound objects (Manohar et al., 2017; Schneegans & Bays, 2019; Schneegans et al., 2021). A first piece of evidence indicates that ordinal transformations of temporal configurations indeed affect memory for a nontemporal feature (i.e., spatial relations, Rondina et al., 2017). It remains unclear, though, if temporal reference frames in visual working memory rely on temporal properties beyond ordinal information, for instance relative temporal distances between items (e.g., "item B was closer in time to item C than to item A").

In sum, previous work indicates that interitem relations, rather than absolute item locations, define spatial reference frames in visual working memory. The goal of this study was to corroborate and extend these findings for the spatial domain, and, most importantly, to determine if the same holds true for the temporal domain.

In a spatiotemporal variant of a color-change detection task, we had participants memorize four colors that were presented at different locations, sequentially and at different interstimulus-intervals (ISIs). As task-relevant color changes always involved a new color that had not been present in the respective trial, the task did not require item colors to be bound to spatial or temporal properties (nor was that, in principle, advantageous for solving the task, because spatial and/or temporal positions were likely to change). As a consequence, participants were instructed to just focus on the colors. Nonetheless, items could be differentiated based on (a) their position in a categorical spatial or temporal order, (b) their spatial or temporal coordinates relative to the other items or (c) absolute spatial or temporal coordinates. To determine specifically which of these properties are critical for reference frames in visual working memory, we applied different types of transformations to either the spatial structure, the temporal structure or to both spatial and temporal structures of item presentation at retrieval: (a) ordinal transformations (Experiments 1 and 4), (b) relational transformations (Experiments 2 and 5), and (c) global transformations (Experiment 3). Such transformations of the external frame of reference at retrieval should only affect memory performance if the metric of the internal reference frame in visual working memory is not invariant to the specific type of transformation. In all experiments, a "no transformation" condition with intact spatial and temporal structures at retrieval was included to provide a baseline.

Experiment 1: Ordinal Transformations

In a first experiment, we applied ordinal transformations to the spatial and/or temporal structure: All four items switched spatial locations and/or temporal positions in the sequence at retrieval, so that each item had a different location and/or serial position than it had at encoding. This type of transformation affected the spatial and temporal structures drastically—it changed absolute and relative item positions as well as the order of items in a spatial (e.g., clockwise) or temporal sequence (i.e., order of appearance/serial position).

Method

Participants

Twenty volunteers participated in the experiment for course credit or monetary compensation (8.50€/hour). We determined sample size based on the effect sizes observed in our prior study using a similar paradigm (Heuer & Rolfs, 2021; Experiments 1 and 2), an alpha level of .05 and a power of .80 (Faul et al., 2007). The data from one participant had to be excluded, because performance did not exceed chance level. The analyses were based on the remaining 19 participants (14 women, 5 men; *M* age: 25 years; age range: 20–34 years). All participants were naive to the purpose of the experiment, had normal color vision and normal or corrected-to-normal visual acuity, and provided written informed consent before the experiment. The experimental protocol was approved by the ethics committee of the Department of Psychology at Humboldt-Universität zu Berlin and in accordance with the ethical standards laid down in the Declaration of Helsinki (2008).

Apparatus and Stimuli

The experiment was conducted in a dark, sound-attenuated room. Participants placed their head on a chin and forehead rest to face the monitor (ViewPixx/3D monitor, 24", 1,920 × 1,080 pixels) at a viewing distance of 53 cm. Stimulus presentation and response collection were controlled using Matlab (Mathworks, Natick, MA) and the Psychophysics Toolbox 3 (Brainard, 1997; Kleiner et al., 2007). To respond, participants pressed one of two buttons on a keyboard in front of them with their left or right index finger. The assignment of buttons to responses (color change or no change) was counterbalanced across participants.

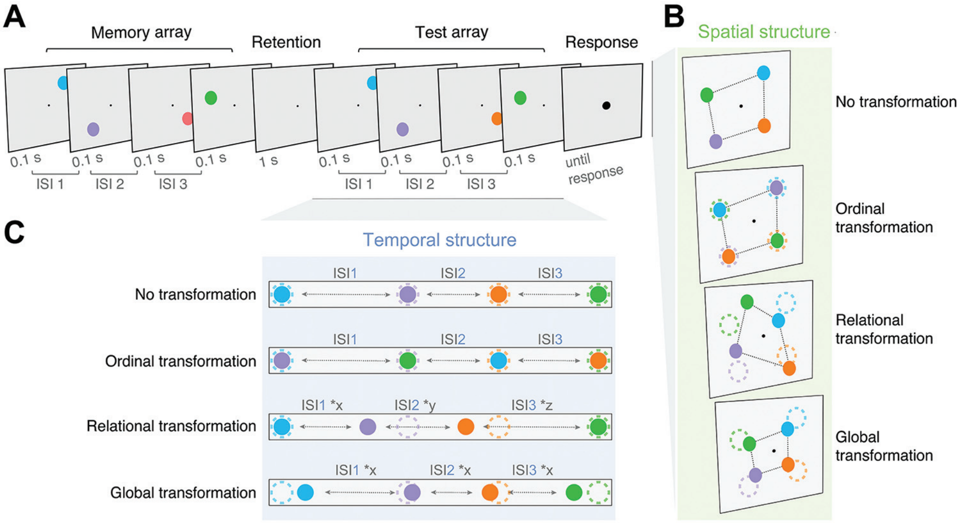
On each trial, four different colors were randomly chosen from a set of seven approximately equiluminant colors (CIE coordinates x/y; luminance): blue (.093/.347; 48.95 cd/m^2), green (.051/.720; 47.84 cd/m^2), orange (.478/.441; 51.85 cd/m^2), pink (.314/.287; 51.73 cd/m^2), red (.400/.361; 49.88 cd/m^2), violet (.232/.285; 52.94 cd/m^2), and yellow (.338/.502; 49.86 cd/m^2). In trials with a color change, the color of one of the items changed to a new color not shared by any of the other items on that trial (randomly chosen from one of the three remaining colors). Each item, a disk of 1.16 degrees of visual angle (dva) in diameter, was presented in one of the four quadrants of the display. There were four predefined locations within each quadrant, one of which was randomly selected for each trial. These locations were arranged on two imaginary circles around fixation (dot of .17 dva in diameter), at eccentricities of 4.68 and 5.23 dva and at 30° and 60°. Interstimulus intervals (ISIs) were permutations of two sets consisting of a short, a medium, and a long interval (100, 300, and 600 ms; 200, 400, and 800 ms). In trials with an ordinal transformation of either the spatial and/or temporal structure, a permutation of the spatial locations and/or serial positions in the memory array was selected for the test array, so that all items were presented in a different quadrant of the display (spatial transformation; Figure 1B) and/or at a different serial position (temporal transformation; Figure 1C) at retrieval relative to their positions at encoding. Permutations were randomly selected from digram-balanced Latin squares (Wagenaar, 1969) of the spatial locations/serial positions at encoding. The enlarged fixation dot signaling response onset subtended .23 dva. All stimuli were presented on a gray background.

Procedure and Design

The trial procedure is illustrated in Figure 1A. At the beginning of each trial, four colored disks were presented (each for 100 ms) in a spatiotemporal memory array—that is, sequentially, at different locations and at different ISIs. Participants had to memorize item colors. They were informed that the spatial and temporal item positions could be the same or different at retrieval, but also that these positions were irrelevant for their task, as color changes would always involve a new color and never swaps between items. After a retention interval of 1 second, the test array was presented. When the spatial and temporal structures were intact (i.e., not transformed), the spatiotemporal structure of the test array was identical to that of the memory array (i.e., same order, locations, and ISIs). In trials with an ordinal transformation of the temporal structure, each item in the test array appeared at a different serial position than it had in the memory array. For ordinal transformations of the spatial structure, items switched locations, so that each item appeared at a different location than the respective item in the memory array. Examples of ordinal transformations of the spatial or temporal structure are shown in Figure 1A. ISIs remained the same between memory and test array (i.e., encoding and retrieval, respectively). The colors of the test items were either the same as the colors in the memory array (no-change trials), or one had

Figure 1

Task and Different Types of Transformations Applied to the Spatial and/or Temporal Structures



Note. (A) Trial procedure of all experiments. Participants had to memorize four colors in order to indicate, after a retention interval, if there was a change in one of the colors. In this example, the red item changed to orange. Items were presented spatiotemporally—sequentially, at different locations and different ISIs—at both encoding (memory array) and retrieval (test array). The spatial and/or temporal structures of item presentation at retrieval were either identical to the spatiotemporal structure at encoding, or they were transformed. (B) Examples of the different types of transformations applied to the spatial structures: no transformation, ordinal transformation (Experiment 1), relational transformation (Experiment 2), and global transformation (Experiment 3). Item outlines mark the positions at encoding. (C) Examples of the different types of transformations applied to the temporal structures, analogous to the spatial transformations shown in panel B. See the online article for the color version of this figure.

changed to a new color (change trials). After the test array, the fixation dot was enlarged to indicate that participants now had to report if there was a change in color. This display was present until response, but participants were encouraged to respond both as accurately and as quickly as possible. The next trial started after an intertrial interval of 2 seconds (1s blank display followed by 1s with the fixation dot to signal the upcoming onset of the memory array). Participants had to maintain fixation throughout each experimental trial.

Transformation conditions of the spatial and temporal structures (intact vs. transformed) were fully crossed, yielding four different conditions: (a) intact spatial and temporal structures, (b) transformed spatial structure and intact temporal structure, (c), intact spatial structure and transformed temporal structure, and (d) transformed spatial and temporal structures. Each participant performed 96 trials for each transformation condition (50% color-change trials, color changes equally likely to occur for each of the four items), yielding 384 trials in total. Transformation conditions varied randomly from trial to trial. Between blocks of 48 trials each as well as in the middle of each block, participants had the opportunity to take a short break. After each block, they received feedback about their performance (percentage of correct responses).

Data Analysis

Our primary measure of interest was the sensitivity to detect a change [$d' = \text{z(hit rate)} - \text{z(false alarm rate)}$], but we additionally analyzed mean reaction time (RT). We corrected hit or false alarm rates of 0 by replacing them with $.5/n$, and rates of 1 by replacing them with $(n - .5)/n$ (Stanislaw & Todorov, 1999). In the correction of hit rates, n is the number of trials with a color change; in the correction of false alarm rates, n is the number of trials without a color change. RT outliers (± 2.5 *SD* from individual mean RT; 2.89% of all trials) were removed from the data; only correct responses were included in the analysis of reaction times.

Individual measures were submitted to repeated measures analyses of variance (ANOVA) with the factors spatial structure (intact vs. transformed) and temporal structure (intact vs. transformed). To specifically test which transformation type(s; spatial, temporal, spatial + temporal) memory performance was sensitive to, we then tested performance in each transformation condition against performance in the baseline condition (intact spatial and temporal structures) with planned one-tailed *t*-tests (not corrected for multiple comparisons). For nonsignificant effects of interest (i.e., when spatial or temporal transformations were found not to significantly affect memory performance), we additionally computed Bayes Factors indicating the evidence in support of the null hypothesis over the alternative hypothesis (BF_{01}) using the default settings of JASP (Version .9.1; JASP Team, 2020).

Transparency and Openness

We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study. All data are available via the Open Science Framework (https://osf.io/bfdm4/). Scripts are available from the authors upon request. Data were analyzed using Matlab, Version 2018b (Mathworks, Natick, MA) and JASP, Version .9.1 (JASP Team, 2020). The experiments were not preregistered.

Results and Discussion

Ordinal transformations of either the spatial or temporal structure impaired participants' sensitivity to detect a change (spatial: $F(1, 18) = 13.23$, $p = .002$, $\eta_p^2 = .424$; temporal: $F(1, 18) = 14.00$, $p = .001$, $\eta_p^2 = .438$; Figure 2A, left panels) and slowed down responses (spatial: $F(1, 18) = 10.97$, $p = .004$, $\eta_p^2 = .379$; temporal: $F(1, 18) = 5.17$, $p = .036$, $\eta_p^2 = .223$; Figure 2A, right panels). Performance in the baseline condition with intact temporal and spatial structures at retrieval was significantly better than with a transformed spatial but intact temporal structure (d': $t(18) = 2.66$, $p = .008$, $d = .61$, 95% CI [.11, 1.10]; RT: $t(18) = -3.67$, $p < .001$, $d = -.84$, 95% CI [−1.36, −.31]), a transformed temporal but intact spatial structure (d': $t(18) = 2.82$, $p = .006$, $d = .65$, 95% CI [.14, 1.14]; RT: $t(18) = -2.50$, $p = .011$, $d = -.57$, 95% CI [−1.05, −.08]), or transformed spatial and temporal structures (d': $t(18) = 5.74$, $p < .001$, $d = 1.32$, 95% CI [.69, 1.93]; RT: $t(18) = -3.61$, $p < .001$, $d = -.83$, 95% CI [−1.34, −.30]). The effects of spatial and temporal transformations were roughly additive and did not interact (d': $F(1, 18) < .01$, $p = .983$; RT: $F(1, 18) = 4.20$, $p = .055$).

These results show that visual working memory is sensitive to ordinal transformations of both spatial as well as temporal configurations, indicating that the ordinal position of an item in a spatial or temporal sequence is encoded to support memory—even when item order is not task-relevant.

Experiment 2: Relational Transformations

In a second step, we manipulated spatial and/or temporal relations at retrieval by multiplying the spatial distances and/or ISIs between all items at encoding by different factors. These relational transformations affected absolute positions and relative interitem distances. The order of items in a spatial or temporal sequence, however, remained the same.

Method

Unless stated otherwise, the methods of Experiment 2 were identical to those of Experiment 1.

Participants

Twenty volunteers (18 women, 2 men; *M* age: 26 years; age range: 20–34 years) participated in the experiment. Four of them had already participated in Experiment 1.

Apparatus and Stimuli

We predefined six spatial configurations based on 24 locations that were arranged at 23°, 45°, and 67° in each quadrant on two imaginary circles at eccentricities of 4.68 and 5.23 dva. Every configuration consisted of four items, one in each quadrant and at different interitem distances. We then assigned configurations to one of two sets of three configurations each, which all had different relative interitem distances (Euclidean distances; for example, in one configuration, the relative distances between items A to D, designated as A-B, B-C, etc., were as follows: D–A < A–B < B–C < C–D; in another configuration of the same set, the relative distances were: C–D < B–C < D–A < A–B). In trials with a relational transformation of the spatial structure, one of the other two configurations in the same set as the configuration used for the memory array was randomly selected for the test array (see Figure 1B for an example of a relational transformation of the spatial structure). We employed a similar approach for the selection and transformation of temporal structures, assigning the same ISIs as used in Experiment 1 (permutations of 100, 300, and 600 ms, and of 200, 400, and 800 ms) to two sets of three configurations (separately for the short and long ISIs) with different relative intervals between items. For example, one set consisted of the following ISIs (listed in the temporal order in which they were used in a given trial): 100, 300, and 600 ms; 300, 600, and 100 ms; 600, 100, and 300 ms. In trials with a relational transformation of the temporal structure, one of the two remaining configurations in the same set as the configuration at encoding was randomly chosen for retrieval (see Figure 1C for an example of a relational transformation of the temporal structure).

Procedure and Design

The trial procedure and design of Experiment 2 was identical to Experiment 1, except that relational instead of ordinal transformations were applied to the temporal and/or spatial structure of item presentation at retrieval (see Apparatus and Stimuli and Figure 1).

Data Analysis

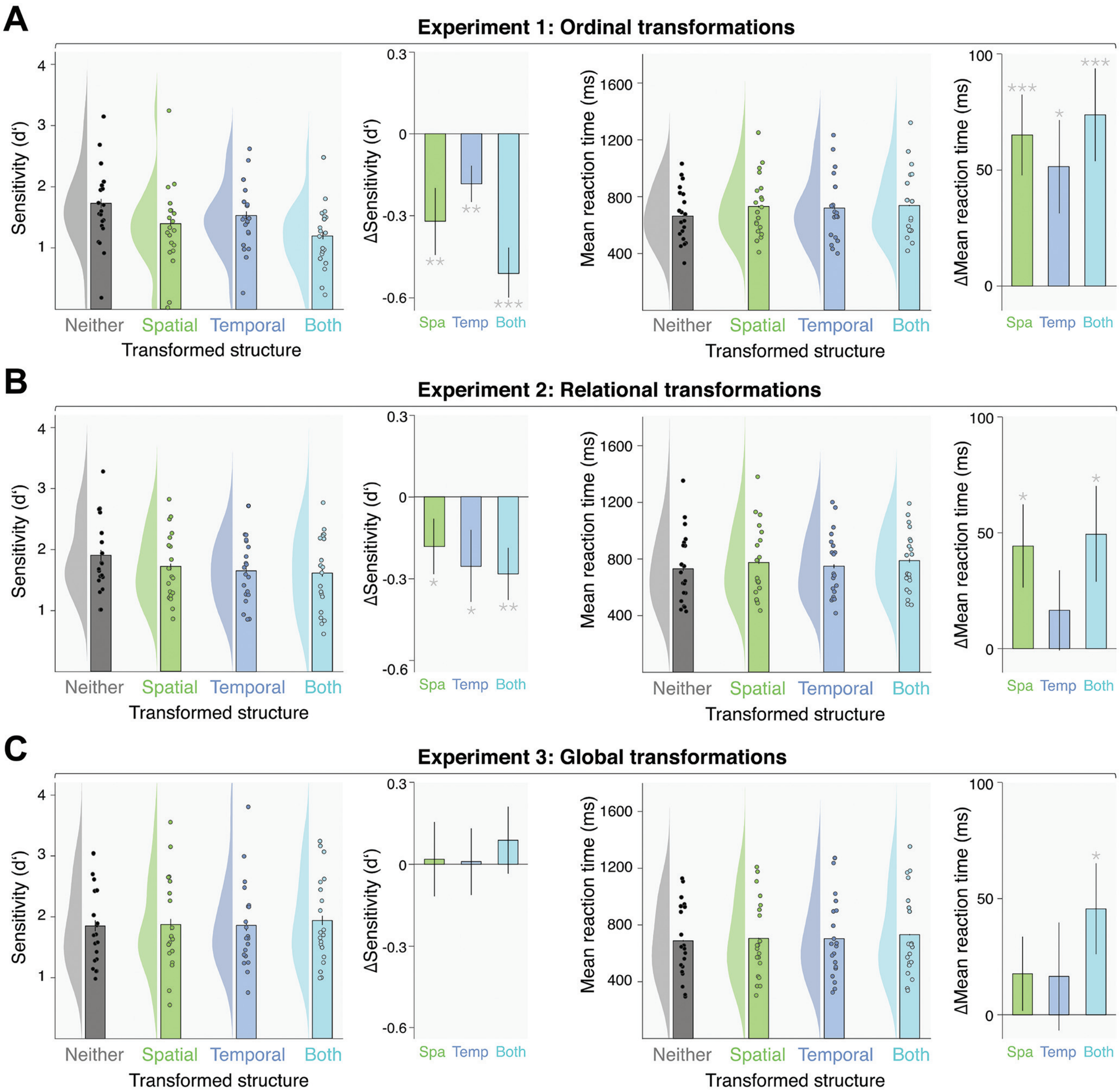
Using the same criteria as in Experiment 1, RT outliers (2.70% of all trials) were removed from the data.

Results and Discussion

The pattern observed for relational transformations of either the spatial and/or temporal structure mirrored the pattern observed for ordinal transformations in Experiment 1, albeit memory decrements were generally less pronounced. Relational transformations of the temporal structure of item presentation at retrieval relative to its structure at encoding reduced the sensitivity to detect a change ($F(1, 19) = 5.80$, $p = .026$, $\eta_p^2 = .234$; Figure 2B, left panels) but did not increase reaction times significantly ($F(1, 19) = .72$, $p = .408$; Figure 2B, right panels). While relational transformations of the spatial structure slowed down responses ($F(1, 19) = 6.42$, $p = .02$, $\eta_p^2 = .253$), the main effect of spatial transformations on sensitivity failed to reach significance ($F(1, 19) = 3.18$, $p = .09$, $BF_{01} = 1.88$). However, relative to the baseline condition (intact spatial and temporal structures), a transformed spatial but intact temporal structure did not only increase reaction times ($t(19) = -2.46$, $p = .012$, $d = -.55$, 95% CI [−1.02, −.07]) but also reduced sensitivity ($t(19) = 1.77$, $p = .046$, d = .40), 95% CI [−.06, .85]. Transforming the temporal structure while leaving the spatial structure intact resulted in a decrement in sensitivity (d': $t(19) = 1.92$, $p = .035$, $d = .43$, 95% CI [−.03, .88]) but did not affect reaction times ($t(19) = -.97$, $p = .172$, $BF_{0-} = 1.74$). As in Experiment 1, the effects of spatial and temporal transformations did not interact (d': $F(1, 19) = .92$, $p = .350$; RT: $F(1, 19) = .32$, $p = .578$) but

Figure 2

Results of Experiments 1–3



Note. Sensitivity (left) and mean reaction times (right) for (A) ordinal transformations (Experiment 1), (B) relational transformations (Experiment 2), and (C) global transformations (Experiment 3) of neither ("no transformation" baseline condition), either or both the spatial and/or temporal structure at retrieval. Raincloud plots (modified from Allen et al., 2019) show the individual means, their distribution (probability density function) and the group mean for each transformation condition; error bars represent within-subject standard errors of the means (Cousineau, 2005; Morey, 2008). The panels to the right show mean performance in the transformation conditions relative to the "no transformation" condition (asterisks indicate statistical significance at * $p < .05$; ** $p < .01$; or *** $p < .001$). See the online article for the color version of this figure.

were approximately additive. When the relations of both spatial and temporal structures were changed, sensitivity was reduced ($t(19) = 2.88$, $p = .005$, $d = .64$, 95% CI [.15, 1.12]), and reactions times increased ($t(19) = -2.39$, $p = .014$. $d = -.54$, 95% CI [−1.00, −.06]) relative to when both were intact.

Overall, the memory costs associated with relational transformations were rather small. Unlike ordinal transformations, however, relational transformations can be more or less pronounced, which likely affects how much they interfere with memory. As the relational transformations that we applied were relatively mild—for instance, spatial positions only changed within their quadrants, and ISIs were switched instead of radically different, which only subtly changed the “rhythm” of item presentation—the observed effects may represent a lower bound on the range of possible effects.

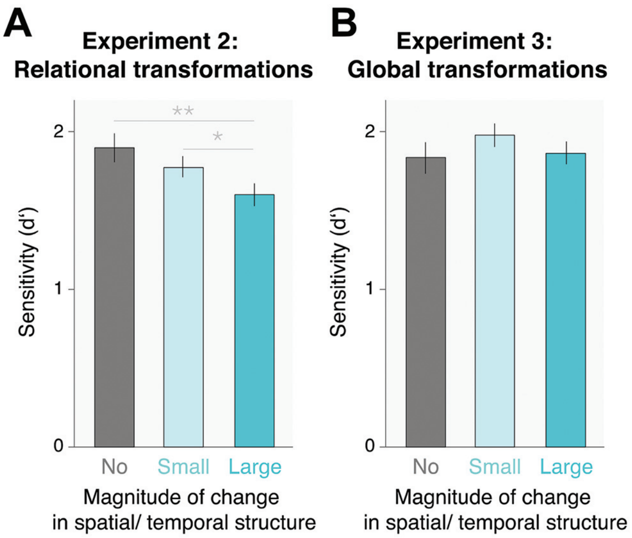
To substantiate this idea that memory costs increase with the magnitude of relational changes in spatial or temporal structures, we additionally analyzed performance separately for trials with small and large relational changes. We quantified the relational change by representing the distances between items (the four spatial distances between items A-B, B-C, C-D, and D-A or the three temporal distances, ISIs, between items 1–2, 2–3, and 3–4, respectively) as vectors in four- or three-dimensional space (for spatial or temporal distances, respectively). Specifically, we calculated the angle between these vectors at encoding and at retrieval. Larger angular differences indicate larger relational changes in the spatial or temporal structure. For example, in a trial with a relational transformation of the temporal structure, the vectors representing ISIs at encoding (600, 300, 100 ms) and at retrieval (300, 100, 600 ms) are of the same length (i.e., $[100^2 + 300^2 + 600^2]^{½} = 678.23$ ms) but differ in their direction: The angle between these vectors is 54.06° (i.e., $\arccos[(600*300 + 300*100 + 100*600)/(100^2 + 300^2 + 600^2)]$). For each participant and each transformation condition, we then sorted trials by the magnitude of the relational change, separated small (angular differences for spatial transformations: 18.80° ± .12°, mean location change of 2.36 dva; temporal transformations: 48.23° ± .01°, mean ISI change of 333.66 ms) from large (spatial transformation: 23.38° ± .04°, mean location change of 2.72 dva; temporal transformation: 54.03° ± .01°, mean ISI change of 400 ms) relational-change trials using a median split, and calculated d' separately for each half. As the main analyses revealed that spatial and temporal transformations exerted equivalent effects, we averaged performance with small and large changes across transformation conditions in order to obtain more reliable estimates with this additional split of the data.

A repeated measures ANOVA (no change vs. small change vs. large change) revealed that performance scaled with the magnitude of the relational change (Figure 3A; $F(2, 38) = 4.86$, $p = .013$, $\eta_p^2 = .204$): the sensitivity to detect a color change was lower when there was a large relational change in the spatiotemporal structure than when there was a small change ($t(19) = 2.75$, $p = .006$, $d = .62$, 95% CI [.13, 1.09]) or no change ($t(19) = 2.33$, $p = .016$, $d = .52$, 95% CI [.05, .98]). Sensitivity with a small relational change was also numerically worse than in the baseline condition without relational transformations, but this difference did not reach statistical significance ($t(19) = 1.26$, $p = .111$).

These findings provide a first piece of evidence that memory impairments due to relational transformations of spatiotemporal context increase with the magnitude of the change that these transformations induce. Here, this pattern was observed even though the relational changes and their variation were relatively small (i.e., small and large relational changes did not differ that much). In any case, it is evident that memory performance was sensitive to these subtle relational transformations of spatial or temporal configurations, revealing that relative spatial or temporal distances (i.e., intervals) between items are included in reference frames as well.

Figure 3

Sensitivity as a Function of the Magnitude of Change in the Spatial or Temporal Structures That Resulted From (A) Relational Transformations (Experiment 2) and (B) Global Transformations (Experiment 3)



Note. Small and large changes are averaged across transformation conditions. Error bars represent within-subject standard errors of the means (Cousineau, 2005; Morey, 2008). Asterisks indicate statistical significance at * $p < .05$; ** $p < .01$. See the online article for the color version of this figure.

Experiment 3: Global Transformations

In the third experiment, we changed spatial and/or temporal structures at retrieval globally: spatial and/or temporal coordinates at encoding were multiplied by the same factor, expanding or shrinking the entire configuration. While this type of transformation affected absolute item positions in space or time, relational spatial or temporal properties—that is, positions relative to other items and item order—remained intact.

Method

Unless stated otherwise, the methods of Experiment 3 were identical to those of Experiment 1.

Participants

Twenty volunteers (15 women, 5 men; *M* age: 26 years; age range: 18–31 years) participated in the experiment. Four of them had already participated in Experiments 1 and 2, two only in Experiment 1, and one only in Experiment 2.

Apparatus and Stimuli

For item presentation at encoding (i.e., in the memory array), we used the same six spatial configurations as in Experiment 2 and six temporal configurations, which were permutations of ISIs of 200, 400, and 800 ms. On each trial, one spatial and one temporal configuration was chosen randomly and independently. For item presentation at retrieval (i.e., in the test array), the eccentricities of spatial locations and ISIs between items were either all identical to those at encoding (no transformation) or they were all equally decreased or increased by one quarter or one half of their magnitude (global spatial or temporal transformation). That is, the entire configuration was either shrunk or expanded (equally likely, randomly chosen on each trial). For example, a temporal ISI configuration of 400–800-200 ms was either shrunk to 300–600-150 ms or to 200–400-100 ms, or it was expanded to 500–1,000-250 ms or to 600–1,200-300 ms. Examples of global transformations of the spatial or temporal structure are shown in Figure 1B and 1C, respectively.

Procedure and Design

The trial procedure and design of Experiment 3 was identical to Experiment 1, except that global instead of ordinal transformations were applied to the temporal and/or spatial structure of item presentation at retrieval (see Apparatus and Stimuli and Figure 1).

Data Analysis

Using the same criteria as in Experiment 1, RT outliers (2.77% of all trials) were removed from the data.

Results and Discussion

Global transformations of the entire configuration, which left relative interitem relations intact, did not affect the sensitivity to detect a change (Figure 2C, left panels)—neither when these transformations were applied to the spatial structure ($F(1, 19) = .28$, $p = .606$, $\mathrm{BF}_{01} = 3.89$) nor when they were applied to the temporal structure ($F(1, 19) = .28$, $p = .606$, $\mathrm{BF}_{01} = 4.08$). We did not observe sensitivity decrements relative to the baseline condition in any of the transformation conditions (spatial: $t(19) = .15$, $p = .560$, $\mathrm{BF}_{0+} = 4.80$; temporal: $t(19) = .10$, $p = .537$, $\mathrm{BF}_{0+} = 4.61$; spatial and temporal: $t(19) = .71$, $p = .758$, BF_{0+} 6.77). There was even a trend in the opposite direction: Sensitivity in the transformation conditions was numerically higher than in the baseline condition. Reaction times (Figure 2C, right panels) were delayed when the spatial structure was transformed ($F(1, 19) = 5.69$, $p = .028$); there was no such delay with transformations of the temporal structure ($F(1, 19) = 2.79$, $p = .111$, $\mathrm{BF}_{01} = 1.14$). Directly comparing reaction times in the transformation conditions against the baseline condition revealed that responses were only significantly delayed when both spatial and temporal structures were transformed ($t(19) = -2.36$, $p = .015$, d $= -.53$, 95% CI $[-.99, -.05]$), but not when only the spatial ($t(19) = -1.09$, $p = 1.45$, $\mathrm{BF}_{0-} = 1.52$) or only the temporal structure ($t(19) = -.73$, $p = .238$, $\mathrm{BF}_{0-} = 2.27$) was transformed. The effects of spatial and temporal transformations did not interact (d': $F(1, 19) = .07$, $p = .797$; RT: $F(1, 19) = 5.69$, $p = .028$).

To ensure that no effect of global transformations in a certain subset of trials (e.g., trials with a shrinkage of the configuration or trials with a larger global change) would go undetected, we performed two additional analyses. First, we compared sensitivity in trials with a shrinkage of the spatial or temporal configuration with trials with an expansion of either configuration (Figure S1 in the online supplemental materials). An ANOVA with the factors dimension (spatial vs. temporal) and transformation type (shrinkage vs. expansion) revealed that sensitivity did not depend on whether the configuration was shrunk or expanded ($F(1, 19) = 1.58$, $p = .225$, $\mathrm{BF}_{01} = 2.32$). There was no interaction between transformation type and dimension ($F(1, 19) = 2.22$, $p = .153$). Sensitivity did not differ from the baseline condition with intact spatial and temporal structures in any of these transformation conditions (two-tailed t-tests; spatial shrinkage: $t(19) = -.34$, $p = .741$, $\mathrm{BF}_{01} = 4.09$; spatial expansion: $t(19) = -.37$, $p = .716$, $\mathrm{BF}_{01} = 4.05$; temporal shrinkage: $t(19) = -.80$, $p = .431$, $\mathrm{BF}_{01} = 3.23$; temporal expansion: $t(19) = .98$, $p = .339$, $\mathrm{BF}_{01} = 2.81$).

Second, as global transformations, just like relational transformations, can be more or less pronounced, we additionally analyzed sensitivity as a function of change magnitude. We used the same approach as in Experiment 2, except that we focused on a different vector property: Global changes in spatiotemporal structures affect the lengths of the vectors representing spatial or temporal distances between items, with larger absolute length differences reflecting larger changes in either direction (expansion or shrinkage). For example, in a trial with a global transformation of the temporal structure, the vectors representing ISIs at encoding (200, 400, 800 ms) and at retrieval (100, 200, 400 ms) do not differ in direction (the angle between vectors is 0°), but the length of the vector at encoding is 916.52 ms, and the length of the vector at retrieval is 458.26 ms. We calculated the magnitude of the global change as percent change = 100*(vector length at encoding − vector length at retrieval)/vector length at encoding, and split data accordingly into trials with a small global change (spatial transformation: 25.41% ± .28%, corresponding to a mean location change of 1.28 dva); temporal transformation: 26.08% ± .21%, mean ISI change of 121.68 ms) and trials with a large global change (spatial transformation: 48.66% ± .26%, mean location change of 2.43 dva; temporal transformation: 49.60% ± .13%, mean ISI change of 231.47 ms). Note that this is essentially the same as dividing trials based on the predefined magnitude of configuration shrinkage or expansion by a factor of .25 versus .5 (see Stimuli and Apparatus).

The magnitude of global contextual changes, however, did not affect sensitivity ($F(2, 38) = 1.06$, $p = .357$, $\mathrm{BF}_{01} = 3.49$), which was at the same level with small and large global changes ($t(19) = 1.49$, $p = .077$, $\mathrm{BF}_{01} = 1.67$) and was not reduced with either small ($t(19) = -1.23$, $p = .883$, $\mathrm{BF}_{01} = 2.23$) or large global changes: $t(19) = -.20$, $p = .576$, $\mathrm{BF}_{01} = 4.23$) relative to the baseline condition without a change. In fact, even with large global changes, performance was numerically still slightly better than in the baseline condition.

Position changes that leave interitem relations and thus the relative context configuration intact do not seem to impair memory, indicating that absolute positions in space or time are not critical for spatial or temporal reference frames in visual working memory.

Experiment 4: Partial Ordinal Transformations

In Experiment 4, we applied partial ordinal transformations to the spatial or temporal structure: Unlike in Experiment 1, only two of the four items switched their spatial locations or temporal positions at retrieval. The probed item—that is, the item that changed its color in color-change trials—was either involved in this transformation (i.e., one of the two items that had switched positions) or not (i.e., one of the two items at the same locations or serial positions as at encoding). This experiment served two purposes.

First, by comparing the transformation conditions against the baseline condition with intact spatial and temporal structure we were able to clarify if spatial and temporal reference frames are also sensitive to ordinal changes that are less pronounced and only affect a part of the context configuration. Second, comparing transformation conditions in which the probe item was involved versus not involved in the transformation allowed us to determine if memory for a specific item is only impaired when its own (ordinal) position is changed, or if it is generally sensitive to any change in its spatial or temporal reference frame—even if the item itself is not directly affected and a part of the context remains intact as well.

Method

Unless stated otherwise, the methods of Experiment 4 were identical to those of Experiment 1.

Participants

Twenty volunteers (15 women, 5 men; mean age: 26 years; age range: 18–33 years) participated in the experiment. Two of them had already participated in Experiments 1 to 3, one only in Experiment 1, one only in Experiment 2, and two only in Experiment 3.

Apparatus and Stimuli

For item presentation at encoding, we used the same spatial and temporal structures as in Experiment 2. At retrieval, spatial and temporal structures were either the same as those at encoding (intact spatial and temporal structures), or we applied partial ordinal transformations to the spatial or temporal structures by switching the locations or serial positions of two of the four items relative to their positions in the memory array. All six pairwise item combination (A-B, B-C, C-D, A-C, A-D, B-D) were equally likely to be switched and randomly chosen on each trial. The probe item, for which a color change occurred in color-change trials, was chosen from either the item pair that was switched (probe item involved in transformation) or from the pair of items that remained at their original locations or serial positions, respectively (probe item not involved in transformation).

Procedure and Design

The experiment consisted of 864 trials, which were completed in two identical sessions on separate days. Trials were equally distributed among the transformation conditions (intact vs. spatial transformation vs. temporal transformation) and probe item conditions (involved vs. not involved in transformation). Transformation and probe item conditions were fully crossed. The condition with transformations of both spatial and temporal structures was dropped in favor of larger trial numbers in the remaining conditions.

Data Analysis

Using the same criteria as in Experiment 1, RT outliers (2.32% of all trials) were removed from the data. For the calculation of sensitivity, an equal number of trials without a color change was randomly assigned to the two probe-item conditions (which only affected color-change trials). Individual measures of sensitivity and mean reaction times were first submitted to repeated measures ANOVAs with the factor transformation condition (intact vs. spatial transformation vs. temporal transformation) to establish if partial ordinal transformations of the spatial or temporal structures generally affected memory performance. To determine if memory for a specific item was impaired by a transformation of any two items in the configuration or only when that item itself was transformed relative to its context, we first tested each of the four conditions with a transformed spatial or temporal structure (probe item involved and not involved) against the baseline condition (intact spatial and temporal structures) with one-tailed *t*-tests. We then compared the probe item conditions (involved vs. not involved) within transformation conditions (spatial vs. temporal) with two-tailed *t*-tests.

As the manipulation of whether or not the probe item was involved in the transformation only concerned color-change trials, we additionally analyzed accuracy in percent for these trials and again compared probe item conditions within each transformation condition.

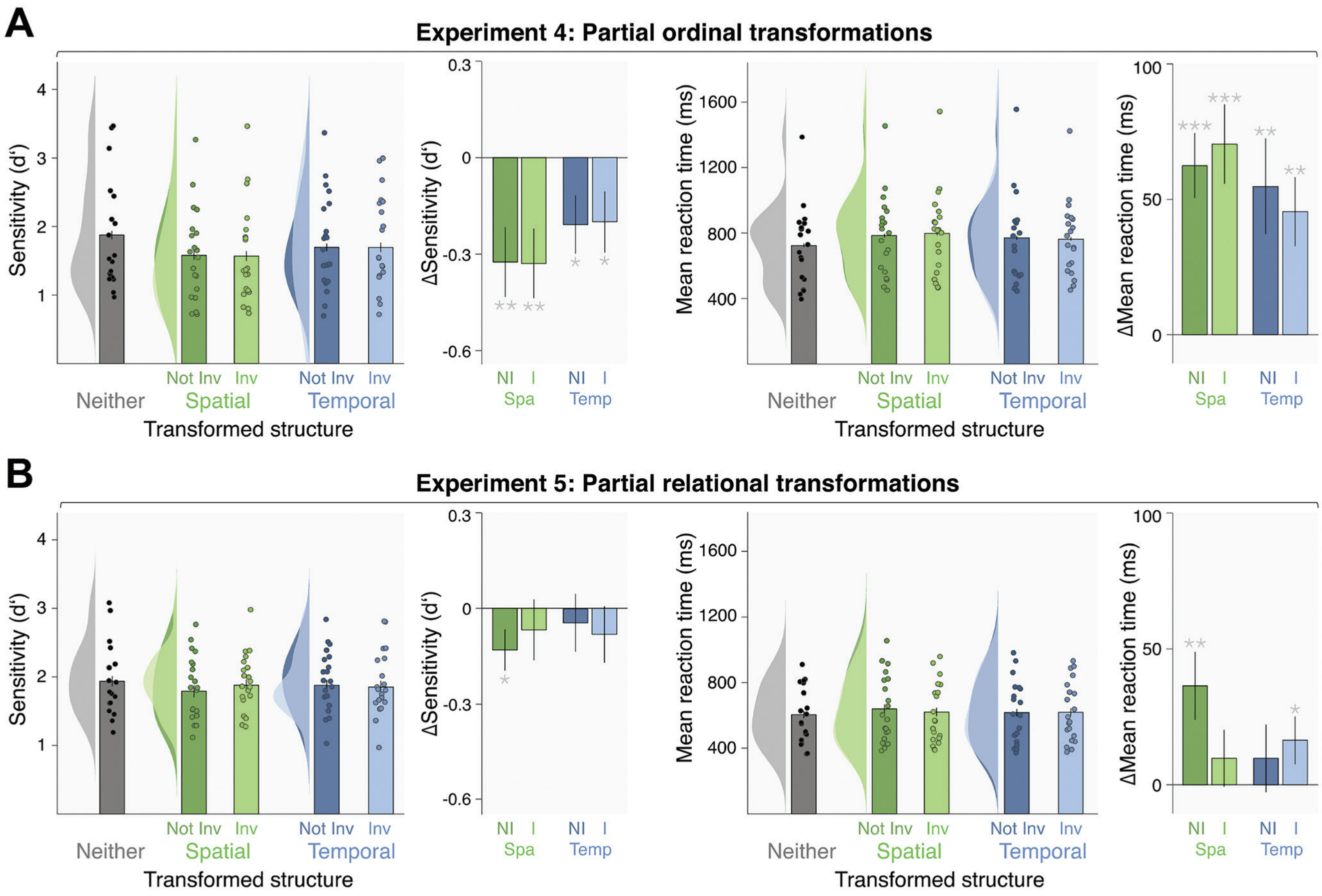
Results and Discussion

Overall, even partial ordinal transformations affected the sensitivity to detect a color change ($F(2, 38) = 6.93$, $p = .003$, $\eta_p^2 = .267$; Figure 4A, left) and mean reaction times ($F(2, 38) = 16.22$, $p < .001$, $\eta_p^2 = .461$; Figure 4A, right). Performance relative to the baseline condition was impaired irrespective of whether the probe item was involved in the transformation or not: When any two items switched their spatial location, sensitivity was reduced (probe item not involved: $t(19) = 2.91$, $p = .004$, $d = .65$, 95% CI [.16, 1.13]; probe item involved: $t(19) = 3.12$, $p = .003$, d = .70, 95% CI [.20, 1.18]) and reaction times increased (probe item not involved: $t(19) = -5.60$, $p < .001$, $d = -1.25$, 95% CI [−1.83, −.65]; probe item involved: $t(19) = -5.32$, $p < .001$, $d = -1.19$, 95% CI [−1.76, −.60]). The same pattern of reduced sensitivity (probe item not involved: $t(19) = 2.16$, $p = .022$, $d = .48$, 95% CI [.01, .94]; probe item involved: $t(19) = 2.01$, $p = .029$, d = .45, 95% CI [−.02, .91]) and delayed responses (probe item not involved: $t(19) = -2.96$, $p = .004$, $d = -.66$, 95% CI [−1.14, −.17]; probe item involved: $t(19) = -3.22$, $p = .002$, $d = -.72$, 95% CI [−1.21, −.22]) was observed when two items switched their temporal positions in the sequence. Memory performance for probe items that were involved in the partial ordinal transformation did not differ from memory performance for probe items that were not involved—both when the transformation was applied to the spatial structure (d': $t(19) = .10$, $p = .925$, $BF_{01} = 4.29$; RT: $t(19) = 1.11$, $p = .279$, $BF_{01} = 2.50$) as well as when it was applied to the temporal structure (d': $t(19) = .05$, $p = .958$, $BF_{01} = 4.30$; RT: $t(19) = .72$, $p = .478$, $BF_{01} = 3.41$).

Given that there was no designated probe item in trials without a color change, a potentially stronger effect on memory when the tested item was involved in a spatial or temporal ordinal transformation might have been obscured by performance in the no-color-change trials, which were included in the main analyses. Therefore, we additionally computed accuracy for color-change trials only. As in the main analyses, however, there was no difference in performance for probe items that were not involved and performance for probe items that were involved in the ordinal transformation of either the spatial (not

Figure 4

Results of Experiments 4 and 5



Note. Sensitivity (left) and mean reaction times (right) for (A) partial ordinal transformations (Experiment 4) and (B) partial relational transformations (Experiment 5) of neither or either the spatial or temporal structure at retrieval. Partial transformations were applied to only two out of the four items and the probe item was either involved in this transformation or not (abbreviated as “inv” or “not inv”, respectively). Raincloud plots (modified from Allen et al., 2019) show the individual means, their distribution (probability density function) and the group mean for each transformation condition; error bars represent within-subject standard errors of the means (Cousineau, 2005; Morey, 2008). The panels to the right show mean performance in the transformation conditions relative to the “no transformation” condition (asterisks indicate statistical significance at * $p < .05$; ** $p < .01$; or *** $p < .001$). See the online article for the color version of this figure.

involved: 72.24% ±2.64%; involved: 71.97% ±2.70%; $t(19) = .14$, $p = .891$, $BF_{01} = 4.27$) or the temporal structure (not involved: 70.22% ±2.75%; involved: 70.68% ±2.70%; $t(19) = .25$, $p = .806$, $BF_{01} = 4.19$). It should be noted, however, that the detrimental effects of spatial or temporal transformations turned out to be primarily driven by an increase in false alarms in trials without a color change rather than by an increase in misses in trials with a color change (Figure S2 in the online supplemental materials). Thus, it comes as no surprise that performance did not depend on whether the probe item in color-change trials was or was not involved in the transformation, as performance in these trials was hardly affected by the transformations to begin with.

Based on these findings, we can conclude that ordinal transformations substantially interfere with memory even when they involve only a part of the context configuration and irrespective of whether the probed item is affected by this transformation or not. Remarkably, memory for a surface feature of a given item depends, to a certain degree, on the integrity of the item’s task-irrelevant spatiotemporal context and thus on other items’ spatial or temporal positions.

Experiment 5: Partial Relational Transformations

In Experiment 5, we applied partial relational transformations to the spatial or temporal structure at retrieval, following the same logic as in Experiment 4. For transformations of the spatial configuration, one item changed its position, which affected two of the four relative interitem distances between neighboring items (e.g., the relative spatial distances between items A to D were C–D < D–A < B–C < A–B at encoding; at retrieval, item B was presented in a new position, changing the relative interitem relations to C–D < A–B < B–C < D–A); for transformations of the temporal configuration, ISIs were changed, likewise affecting the relative temporal distances between items (e.g., relative temporal distances between items changed from ISI1 < ISI3 < ISI2 at encoding to ISI3 < ISI1 < ISI2 at retrieval). The probed item, whose color changed in color-change trials, was either involved in this transformation or not directly affected.

Method

Unless stated otherwise, the methods of Experiment 5 were identical to those of Experiment 1.

Participants

Twenty volunteers (12 women, 8 men; mean age: 26 years; age range: 20–34 years) participated in the experiment. One of them had already participated in Experiments 1 to 4, one in Experiments 1 and 4, one in Experiments 2 and 4, one in Experiments 3 and 4, three only in Experiment 1, one only in Experiment 3, and two only in Experiment 4.

Apparatus and Stimuli

The same six spatial and temporal structures as in Experiments 2 and 4 were used for item presentation at encoding. For partial relational transformations of the spatial structure, one of the items was presented at a different location (but still in the same quadrant) at retrieval, changing the relative interitem distances to its two neighboring items in clockwise and counterclockwise direction. For each spatial configuration, each item was equally likely to change position. The probe item was either the item that changed position (probe item involved in transformation) or the item in the opposite quadrant, whose relative distances to its neighboring items were not affected by the transformation (probe item not involved in transformation). Temporal structures were partially transformed in an analogous manner: One item shifted its temporal position relative to the other items. If this was the first or last item in the sequence, one ISI was changed (e.g., the ISI between the first and second items); if this was the second or third item in the sequence, the two surrounding ISIs were changed. The remaining ISI(s) was/were the same as at encoding. Each item was equally likely to change its relative temporal position. ISIs changed to one of the ISIs not part of the temporal structure in that trial—i.e., when a permutation of 100, 300, and 600 ms was used at encoding, ISIs changed to 200, 400, or 800 ms and vice versa. The probe item was either one of the items whose relative temporal distances (i.e., ISIs) to the preceding and/or succeeding items was changed (probe item involved in transformation) or one of the items whose relative temporal distances to its temporal neighbors were the same (probe item not involved in transformation).

Procedure and Design

The experimental design was analogous to that of Experiment 4: A total of 864 trials were equally divided among transformation conditions (intact vs. spatial transformation vs. temporal transformation) and probe item conditions (probe item involved vs. not involved in transformation), and completed in two sessions on separate days.

Data Analysis

Using the same criteria as in Experiment 1, RT outliers (2.49% of all trials) were removed from the data. As in Experiment 4, we first conducted repeated measures ANOVAs with the factor transformation condition (intact vs. spatial transformation vs. temporal transformation) to determine if partial relational transformations of either the spatial or temporal structure interfered with memory. We then tested each of the four transformation conditions (Spatial vs. Temporal × Probe Item Involved vs. Not Involved) against the baseline condition with intact spatial and temporal structures (one-tailed *t*-tests) to clarify if memory was reduced in each of these cases. Finally, we compared probe item conditions within transformation conditions (two-tailed *t*-tests).

Results and Discussion

Overall, partial relational transformations did not significantly reduce sensitivity ($F(2, 38) = 1.13$, $p = .332$, BF_{01}: 3.29; Figure 4B, left) and their effect on reactions times fell just short of statistical significance ($F(2, 38) = 3.24$, $p = .05$, partial eta: .145, $BF_{01} = .77$; Figure 4B, right). At the descriptive level, performance was reduced in all conditions with partially transformed spatial or temporal structures. But significant performance decrements in terms of both sensitivity and reaction times were only observed with a spatial transformation, in which the probe item was not involved (d': $t(19) = 2.00$, $p = .03$, $d = .45$, 95% CI [−.02, .90]; RT: ($t(19) = -2.93$, $p = .004$, $d = -.66$, 95% CI [−1.13, −.16]). Sensitivity did not differ significantly from the baseline condition in any of the other three transformation conditions (spatial, probe item involved: $t(19) = .70$, $p = .247$, $BF_{01} = 2.33$; temporal, probe item not involved: $t(19) = .50$, $p = .313$, $BF_{01} = 2.84$; temporal, probe item involved: $t(19) = .93$, $p = .182$, $BF_{01} = 1.82$). Responses were also significantly delayed when the probe item was involved in a relational transformation of the temporal structure ($t(19) = -1.86$, $p = .039$, d = −.42, 95% CI [−.87, .05]), but not in the remaining two transformation conditions (spatial, probe item involved: $t(19) = -.88$, $p = .193$, $BF_{01} = 1.91$; temporal, probe item not involved: $t(19) = -.79$, $p = .220$, $BF_{01} = 2.12$). Sensitivity was not affected by whether the tested item was involved in the partial relational transformation or not (spatial: $t(19) = .63$, $p = .533$, $BF_{01} = 3.60$; temporal: $t(19) = .42$, $p = .677$, $BF_{01} = 3.97$), and neither were reaction times for temporal transformations ($t(19) = .69$, $p = .498$, $BF_{01} = 3.48$). Due to the delay in reaction times when the probe item was not involved in a spatial transformation, there was, however, a difference between probe item conditions with spatial transformations ($t(19) = 2.27$, $p = .035$, $d = .51$, 95% CI [.04, .97]).

The effects of relational transformations were already rather small when they affected the entire spatial or temporal configuration (see also Experiment 2 and General Discussion). However, the costs associated with relational changes appear to scale with the magnitude of these changes (Figure 3A). Here, we not only used rather subtle relational transformations to begin with, but now also applied these to only a small part of the context configuration—meaning that only one item slightly changed its spatial position within its quadrant, or one to two ISIs their duration. This seems to have reduced the effects to a degree that most of them no longer reached statistical significance. At the descriptive level, however, the pattern of results was consistent with the results obtained for partial ordinal transformations: Memory did not differ as a function of whether or not the probed item was involved in the partial transformation, with only one curious exception for spatial transformations in terms of RT; here, however, reaction times were actually longer when the probed item was not involved.

General Discussion

The visual objects or events we encounter in natural and thus often dynamic settings can be differentiated based on their spatial or temporal properties. With this study, we sought to clarify specifically which spatiotemporal properties are incidentally encoded along with nonspatiotemporal features to form reference frames in visual working memory. To this end, we applied different types of transformations—ordinal, relational, and global—to the task-irrelevant spatial and/or temporal structures of item presentation at retrieval, reasoning that memory performance should only be impaired if the internal reference frame in visual working memory relies on the spatial or temporal properties that are affected by the respective transformation (ordinal, relative or absolute position in space or time). Relative to a no-transformation condition, memory decrements were observed when spatial or temporal item positions changed in a manner that affected either their ordinal position in a sequence (ordinal transformation) or their relative distances to the other items (relational transformation). By contrast, global transformations of spatial or temporal structures, which involved changes in the absolute item positions but left interitem relations intact by shrinking or expanding the entire configuration, did not interfere with memory.

For the spatial domain, these results corroborate previous reports that memory for object identity depends on the object's location relative to other items (e.g., Hollingworth, 2007; Jiang et al., 2000; Olson & Marshuetz, 2005; Timm & Papenmeier, 2020) and confirm that memory does not only suffer when the locations are shifted, but also when the locations are the same but the bindings between objects and locations are swapped—that is, when the spatial order of items (e.g., clockwise) changes (Hollingworth, 2007; Sun & Gordon, 2009). More importantly, we have shown that the same holds true for the temporal domain: Temporal reference frames in visual working memory are defined by temporal relations between items, which include not only their order of appearance but also the relative temporal distances (i.e., ISIs) between them. Applying partial transformations, which affected only half of the item relations at retrieval, further revealed that memory for a given item was impaired irrespective of whether its own position or relations to immediate spatial or temporal neighbors changed, or whether there was any change in its spatial or temporal reference frame (though our findings only allow for definitive conclusions in this regard for ordinal transformation). Taken together, these findings provide evidence that both spatial and temporal reference frames are primarily established by interitem relations.

Overall, the costs associated with relational changes of spatial or temporal structures were rather small and less consistent than the costs associated with ordinal changes, for both full as well as partial transformations, so it is tempting to conclude that ordinal position is more important than the relative distances (in certain directions) between items. One must keep in mind, however, that relational transformations naturally involve more degrees of freedom than ordinal transformations: They can be more or less pronounced, which appears to affect the extent to which these changes interfere with memory (see Figure 3). As the relational transformations that we used in the present experiments were subtle, the observed effects are likely close to the lower bound of effects that can be achieved by relational transformations of spatial or temporal reference frames in visual working memory. Moreover, as an ordinal position switch necessarily also includes a change in relative interitem distances (i.e., what is here referred to as a "relational change"), it is essentially impossible to disentangle their relative contributions.

As global transformations can also be more or less pronounced, one might argue that we failed to observe any effects of global transformations not because absolute position information is generally not critical for spatial or temporal reference frames, but because the global changes were not extensive enough. According to this line of reasoning, the overall pattern of results across experiments could be taken to reflect a gradient of change magnitudes induced by the transformations and thus of associated memory impairments rather than qualitative differences in the type of transformations that spatial and temporal reference frames are sensitive to. However, we consider this to be an unlikely scenario for a couple of reasons. First, there was no indication that memory performance depends on the magnitude of global changes in spatiotemporal context (unlike what we observed for relational changes, Figure 3). Even large global changes—which involved an expansion or shrinkage of the entire spatial or temporal configuration by 50%—did not reduce the sensitivity to detect color changes relative to when there was no change in spatiotemporal structures. By comparison, even with small and subtle relational changes, performance dropped below baseline. Second, our findings are in line with previous studies that also demonstrated an insensitivity to global transformations of spatial configurations (e.g., Jiang et al., 2000; Woodman et al., 2012). Given that the consequences of these transformations resemble the consequences of changes in viewer distance (shrinkage or expansion) or eye movements (shifts of the entire configuration), such an insensitivity would also make perfect sense and render visual working memory better suited to meet the demands of everyday life. Note that we are only considering global transformations within a reasonable range of manipulation—extreme global changes of configurations can certainly be expected to impair performance due to other factors such as crowding (shrinkage) or the absence of relational coding (expansion).

While our primary goal was to establish the metrical properties of spatial and temporal reference frames, the present experiments also lend support to two related ideas that we and others have recently put forward. First, they confirm that not only spatial (e.g., Cai et al., 2019; Foster et al., 2017) but also temporal configurations are incidentally encoded, even when they are not required for the task at hand (Heuer & Rolfs, 2021). In fact, in the present series of experiments, spatial and temporal properties were not only task-irrelevant but also highly unreliable—there was a change in the spatial or temporal structure of item presentation in 75% of all trials. In spite of this high likelihood of configuration changes, items were represented and maintained within their spatiotemporal context, suggesting that this is a largely automatic process. Second, our findings provide additional support for the idea that space and time may play analogous roles in visual working memory (Heuer & Rolfs, 2021; Manohar et al., 2017; Schneegans & Bays, 2019; Schneegans et al., 2021). Across all experiments, spatial and temporal reference frames were found to be sensitive to the same types of transformations (ordinal and relational). This even resulted in memory decrements of approximately equivalent magnitudes, which we did not necessarily expect, as it is virtually impossible to perfectly match configurations—and, in these experiments, transformations—across dimensions. We do not know which temporal distance "corresponds" to which spatial distance, for example, with respect to how useful they are for differentiating between items, and there are likely pronounced individual differences (Heuer & Rolfs, 2021). Therefore, it seems reasonable to assume that different combinations of spatial and temporal parameters for the configurations and their transformations would result in different performance levels and costs. Regardless of the relative extent of memory impairments associated with spatial or temporal transformations, our results show that spatial and temporal reference frames share the same metrical properties, which dovetails nicely with other findings indicating a functional equivalence of space and time in visual working memory. For instance, both spatial location and temporal (ordinal) position mediate the binding of surface features like color or shape (Schneegans et al., 2022), memory items that are spatially or temporally close are more easily confused (e.g., Rerko et al., 2014; Sapkota et al., 2016; Schneegans et al., 2021), prioritization of visual working memory contents based on temporal position is as direct, fast and effective as prioritization based on spatial location (Heuer & Rolfs, 2022) and the removal of distinctive but task-irrelevant spatial or temporal properties at retrieval interferes with memory, whereas no similar costs were observed when distinctive variations in other task-irrelevant feature dimensions were taken away (Heuer & Rolfs, 2021). Moreover, memory appears to rely more on either space or time, depending on the distribution of items in either domain and hence its usefulness for item individuation: When items are spatially close, temporal separation can be leveraged to differentiate between items, and vice versa (Heuer & Rolfs, 2021; see also Schneegans et al., 2021). The notion of functional equivalence is also consistent with the observation of independent effects of spatial and temporal transformations in the present study.

Thus, the incidental scaffolding of objects by their spatial and temporal contexts seems to provide reference frames that mediate feature binding and facilitate retrieval; in their function, space and time can "stand in" for each other.

An issue that remains somewhat unresolved at this point is for which function(s) specifically space and time are equivalent. That is, which processes or mechanisms of visual working memory are supported by spatial and temporal reference frames (and thus disrupted by transformations of either the spatial or temporal structure). As manipulating the availability or integrity of spatial or temporal structures at test has repeatedly been shown to impair memory (e.g., Heuer & Rolfs, 2021; Hollingworth, 2006, 2007; Jiang et al., 2000; Olson & Marshuetz, 2005), it seems likely that spatiotemporal reference frames support the *retrieval* stage. For one, they might reduce uncertainty and thus contribute to ensuring reliable access to memoranda. If visual working memory contents are (automatically) bound to their relative spatial and temporal positions (Heuer & Rolfs, 2021; Schneegans et al., 2022), their retrieval may involve the activation of their position along either context dimension. As content and context dimensions, as well as their bindings, are represented with limited precision, retrieval is subject to uncertainty (Oberauer & Lin, 2017). Having both spatial and temporal context information available (and intact) might reduce that uncertainty, improving memory (Heuer & Rolfs, 2021). A closer proximity of items in either space or time, by contrast, increases uncertainty and the likelihood of errors —in particular swap errors in (continuous) report tasks—presumably due to overlapping activations (e.g., Heuer & Rolfs, 2021; Rerko et al., 2014; Sapkota et al., 2016; Schneegans et al., 2022).

In change-detection tasks, spatiotemporal context might be also utilized to establish correspondence between the sample and test displays. Transformations of spatial or temporal relations would accordingly disrupt this matching process and impair performance. More specifically, one might predict that the mismatch between spatiotemporal context at retrieval versus in memory (i.e., the reference frame as defined by ordinal and relational properties) would primarily increase the proportion of false alarms (rather than misses), because the mismatch signal in same-color trials leads participants to mistake the irrelevant change for a relevant one. An increase in false alarms is indeed what we observed in the experiments with ordinal and relational transformations (Figure S2 in the online supplemental materials).

It is entirely conceivable that spatiotemporal context does not only support retrieval but also earlier stages of visual working memory processing, for example the *maintenance* stage by facilitating processes such as individuation or attentional refreshing. The specific function fulfilled by the representation of memory contents within their spatiotemporal context might even take slightly different forms, depending on the respective task demands (e.g., establishing correspondence for change detection or ensuring reliable access for report), and become manifest in different behavioral signatures (e.g., an increase in false alarm rate as in the present study, or specific patterns of error correlations as in Schneegans et al., 2022).

Another important avenue for future research will be to identify principles that govern the formation of spatiotemporal reference frames under more natural conditions. Everyday visual scenes are markedly different from the simple visual arrays that have previously been used to study spatial or temporal reference frames in visual working memory. For example, they typically contain a variety of objects that are entirely irrelevant for our current goals; in the present and in previous studies, by contrast, space and time constituted task-irrelevant feature dimensions of task-relevant objects. While we know that task-irrelevant objects can be filtered out (more or less successfully; e.g., Gazzaley & Nobre, 2012; Jost et al., 2011; Vogel et al., 2005), there may be conditions, under which their spatial or temporal positions are encoded to complement reference frames. For the spatial domain, one study found that changed distractor locations impaired memory (Olson & Marshuetz, 2005), whereas others did not find any indication that distractors were bound to spatial configurations (Jiang et al., 2000; Udale et al., 2018). As memory and distractor items were easily distinguishable in these studies, the inconsistencies cannot be attributed solely to differences in filtering difficulty. Other factors appear to be at play—possibilities include grouping principles such as proximity or overlap (see also Olson & Marshuetz, 2005) or semantic relations between to-be-memorized information and distractors. The inclusion of distractors in spatial or temporal reference frames might also be more dependent on strategic factors than that of task-relevant objects (see also Timm & Papenmeier, 2019a, 2019b, 2020). For instance, a high likelihood of distractor changes might discourage their encoding into spatiotemporal reference frames (Udale et al., 2018). Finding out if and how such factors contribute to the formation of spatiotemporal reference frames in richer visual environments will be facilitated by a new perspective on memory function that embraces more complex designs and ecologically valid scenarios (cf. Snow & Culham, 2021).

To conclude, we have shown that spatial and temporal reference frames in visual working memory are defined by interitem relations—as defined by both the ordinal position of items in a spatial or temporal sequence as well as the relative distances between items in space or time—rather than by bindings between items and their absolute positions. The encoding of objects within their spatiotemporal context appears to be a largely automatic process, which occurs even when spatiotemporal configurations are irrelevant and unreliable. By revealing that spatial and temporal reference frames share the same metrical properties, our results further complement recent findings indicating that time serves a similar function as space for visual working memory.

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