Using temporal order to identify spatial reference frames

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A new method for identifying spatial reference frames is described and applied to the study of spatial span. In this method, a spatial sequence is displayed in relation to two reference frames that move relative to each other, so that different temporal orders are described in each reference frame. As applied to spatial span, a sequence of dots was displayed on a rectangular template that moved relative to the computer screen and the observer. Three experiments showed that the choice of reference frame is influenced by prior conditions, the size of the template, and the presence of an alternative stationary reference frame. Recall was impaired (1) when the template moved, suggesting that movement interference occurred, and (2) with increasing template size, but only if the template was used as the reference frame.

This article will describe a new method for identifying the spatial reference frame used to encode a sequence of spatial locations. The method is quite general and can be applied in any situation in which two reference frames can be moved in relation to each other in a controlled manner. Here, the method will be used to address concerns about the nature of the reference frame and the involvement of movement interference in spatial span, a task commonly used to estimate spatial short-term memory (STM). Spatial span provides an ideal vehicle for illustrating the method, so we shall first review recent findings and issues concerning spatial span and then proceed to describe the method.

Spatial Span

In spatial span, a sequence of discrete spatial locations is presented at a fixed rate in full view of an observer. The observer's task is to remember the sequence and reproduce it by pointing to the locations of the sequence in the correct order. The task was initially devised by Corsi (1972) as an analogue of digit span and was presented as an array of nine wooden blocks fixed to a rectangular board. The experimenter indicated a spatial sequence by tapping each block in succession. The Corsi task can readily be adapted to computerized presentation, in a format in which the board is shown in plan view as a rectangular frame enclosing a number of squares and the sequence is indicated by highlighting each square in turn. With computer presentation, the configuration is more flexible; for example, the positions of the squares can be varied across trials, rather than fixed, and the number of squares can vary. In addition, computer presentation allows the visibility of the tokens during presentation to be controlled. In the original Corsi task, all the possible locations, which were fixed objects, were visible throughout presentation

and recall. In the form of the task used here, only one spatial token is displayed at a time during presentation, derived from the *dots* task developed by Jones and his colleagues (Jones, Farrand, Stuart, & Morris, 1995). In all cases, all the potential spatial locations are visible during recall, when the observer reconstructs the sequence. For a review of spatial span and its clinical applications, see Berch, Krikorian, and Huha (1998).

A number of dual-task studies have explored the effect of various kinds of interference presented concurrently with the spatial sequence or during the retention interval. These studies have consistently shown impairment caused by spatial tapping, by spatial attention shifts, and by directing eye movements to irrelevant targets (e.g., Lawrence, Myerson, & Abrams, 2004; Lawrence, Myerson, Oonk, & Abrams, 2001; Pearson & Sahraie, 2003; Smyth, 1996; Smyth & Scholey, 1994; Tremblay, Saint-Aubin, & Jalbert, 2006), but not by repetitive gestural movements that involve touching body parts (Smyth, Pearson, & Pendleton, 1988). One interpretation is that the sequence of locations is remembered in the form of a motor plan, so that any task that engages movement control processes will produce interference. A similar account has been proposed to explain interference with visual imagery tasks (e.g., Baddeley, 1986; Logie, 1995; Postle, Idzikowski, Della Sala, Logie, & Baddeley, 2006). Others have argued that movement and oculomotor distractor tasks interfere by controlling attention and that it is attentional control mechanisms that maintain the sequence (e.g., Smyth, 1996; but see Lawrence et al., 2004). It should be noted that in all such interference studies, attention was directed to task-irrelevant stimuli in the region of space surrounding the spatial span task. Moreover, the nature of the space in which the distracting stimuli were presented and its relation to the encoding of spatial position

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have generally been ignored (see Woodin & Allport, 1998, for one exception).

In recent studies of spatial span, researchers have intensively investigated encoding processes by varying the parameters of spatial sequences and measuring the effects on task difficulty. Considerable evidence now exists to show that simple or redundant sequences are easier to encode and remember than less predictable ones (e.g., Kemps, 1999, 2001; Parmentier & Andrés, 2006; Parmentier, Andrés, Elford, & Jones, 2006; Parmentier, Elford, & Maybery, 2005; Schumann-Hengsteler, Strobl, & Zoelch, 2004). Another approach has been to look for grouping effects in spatial span by clustering the spatial locations and manipulating the convergence of temporal and spatial orders (e.g., De Lillo, 2004; Smyth & Scholey, 1994). Taken together, these studies suggest that spatial locations are encoded as a path or trajectory across a sequence of locations and that organizing principles are applied to the path to form an efficient and succinct internal description.

These studies show how interference and task structure limit performance on spatial span and provide valuable insight into the processes taking place when the task is performed. A fundamental issue that has received less attention is the nature of the reference frame used to encode position in spatial span. A reference frame requires a fixed reference location (or set of locations) linked to a coordinate system capable of specifying direction and distance in relation to these fixed locations. Typically, in spatial span, the displayed locations either are presented as blocks fixed to a horizontal board, in the traditional Corsi version, or are drawn on a vertical computer screen. In either case, the locations that are used to make up the spatial span sequences are stationary with respect to the observer and the local environment throughout the presentation and test phases of each trial. Hence, the sequence of locations could be encoded using any of a number of possible reference frames, either singly (i.e., one reference frame is chosen to represent the sequence) or in combination (the sequence is represented in several reference frames simultaneously). For example, the spatial locations may be encoded using a system of egocentric reference frames, specifying position with respect to the body axis, head, eyes, or body parts of the observer. Egocentric reference frames are useful for coordinating actions, because the movements required to interact with objects can be computed directly from egocentric information (Milner & Goodale, 1995). Alternatively, environmental reference systems specify location with respect to features of the environment, such as the walls or furniture of a room, or, in the case of a computerized display, location in relation to the display screen. For a discussion of environmental reference frames in relation to memory for scenes, see, for example, McNamara (2003) and Sholl and Nolin (1997). A third possibility is that the reference frame is provided by local features of the display, such as the board used in the Corsi task or the analogous rectangular frame used in computerized presentations. We will refer to these permanent local features of the display within which sequences are displayed as the *template*, and descriptions of spatial locations encoded in relation to these local features will

be referred to as *template centered*. Thus, in template-centered representations, spatial locations are described with respect to a coordinate system based on the template and independent of the wider environmental context. The spatial locations may also be specified in relation to the observer or to the local environment (e.g., the display screen or supporting surfaces) beyond the template. Manipulations based on translation movements of the template with a stationary observer cannot distinguish between egocentric and environmental frames of reference, so these will be considered together and will be referred to as the *extrinsic* frame of reference.

Avons (2007) explored the nature of the reference frame used in spatial span, employing a computerized display. The primary manipulation required translating the template around the computer screen during presentation of the sequence and/or during recall, and the rationale was as follows. The whole template moved without any rotation or plastic transformation, so it was argued that descriptions in the template-centered frame of reference would be unchanged by translation and, hence, should show little if any effect of movement. However, moving the template with respect to a stationary observer would change target locations in the extrinsic reference frame. Performance was impaired when the template was moved between the display of each location during presentation, but not when the same translation movements occurred during the recall phase (Avons, 2007, Experiments 1 and 2). Avons and Trew (2006) also found that performance was disrupted when template movements occurred in the retention interval. One account proposes that interference arises from the conflicting demands posed by encoding (or rehearsing) the sequence while monitoring the moving template. This interpretation is consistent with the dual-task interference studies reviewed above: Following the moving template would require eye movements or shifts of attention that are known to interfere with spatial span, at least when directed to task-irrelevant targets.

An alternative account proposes that with a stationary display, information from several distinct spatial reference frames is available for spatial memory. It is easy to see that in a static display with a stationary observer, the sequence of spatial positions will have the same configuration with respect to the observer, the computer screen, or the template itself, because these are in a fixed relationship to each other. However, if the template is subjected to unpredictable translation movements during presentation and is stationary during recall, the target locations will trace disjoint trajectories the template-centered and the extrinsic reference frames, and only the former can be used to support recall. According to this account, performance falls in conditions with a moving template because knowledge of the sequence encoded with respect to the extrinsic reference frame cannot be used to support performance. It is impossible to disentangle these accounts by studying the effects of moving the template. Any decrease in performance that occurs when the template is moved can be explained as (1) removing the contribution from extrinsic reference frames or (2) inducing the attentional or oculomotor demands that impair working memory.

With a moving template, it is possible to set up sequences so that the extrinsic locations are repeated from trial to trial, even though the template-centered locations vary. When this is done, there is no evidence of learning across trials, although robust learning readily occurs when template-based sequences are repeated (Avons, 2007, Experiments 3 and 4). This result shows that by the end of the trial, memory for the sequence is stored in a format consistent with the template-based sequence, with no trace of extrinsic coding. So either the sequence is originally and exclusively coded in a template-centered reference frame (in which case the impairment seen when the template moves during input must be due to movement interference), or the sequence is initially encoded using the extrinsic reference frame but this representation decays before the end of the trial. The notion that spatial memory is supported by transient extrinsic (possibly egocentric) information is consistent with the absence of interference from template movement during recall (Avons, 2007, Experiment 2) and with self-to-object updating (Sholl & Nolin, 1997). Another concern is that the displays used in Avons favored template-centered encoding, because locations on the template were visible throughout each trial, whereas extrinsic locations were unmarked. The technique described below avoids both of these problems by allowing us to determine the frame of reference adopted as the sequence is encoded, rather than inferring this from learning across trials, and by marking template-centered and extrinsic locations identically.

The Temporal Ambiguity Method

In the method used here, spatial sequences are set up so that the spatial reference frame used to encode a sequence of events determines the temporal order of the sequence. This is made possible by displaying the events in two reference frames that change position relative to each other. By carefully coordinating the relative movements of the reference frames, the spatial positions at which different events occur can be made to coincide in the two reference frames, so that different temporal orders are described in each reference frame. The process is illustrated in Figure 1 and will be described in detail below.

Consider first the case in which the reference frames are in a fixed spatial relationship to each other. Suppose that a series of identical discrete events E_1, E_2, E_3 , occur at times t_1, t_2, t_3 , at locations P_a, P_b, P_c in Reference Frame 1 and at corresponding locations P_x, P_y, P_z in Reference Frame 2. If the reference frames remain in the same fixed relationship, the temporospatial order of the events will be the same in either reference frame (i.e., the spatial sequence P_a, P_b, P_c is the same as P_x, P_y, P_z).

Suppose now that we move the reference frames relative to each other before the display of each event. This can be done so that event E_1 occurs at location P_a in Reference Frame 1 but at location P_y in Reference Frame 2. This is easily accomplished by moving Reference Frame 2 through a distance of $P_y - P_x$ before event E_1 occurs. Then, after a second relative movement of the reference frames, event E_2 occurs at t_2 , in location P_b in Reference Frame 1, but in location P_z in Reference Frame 2. The movement needed

to achieve this is the sum of $P_x - P_y$ (needed to bring the frames back into alignment) and $P_z - P_y$ (required to ensure that P_b in Reference Frame 1 matches P_z in Reference Frame 2). Finally, after moving a distance of $(P_y - P_z) + (P_x - P_z)$, E_3 is displayed at time t_3 in locations P_c, P_x . The two reference frames are then brought back into alignment for recall, and all locations P_a, P_b, P_c in Reference Frame 1 (corresponding to locations P_x, P_y, P_z in Reference Frame 2) are displayed. Note that with these relative movements of the reference frames, the locations of the events in Reference Frame 1 (P_a, P_b, P_c) also occur at corresponding locations in Reference Frame 2 (P_x, P_y, P_z). However, the apparent temporal order of events will now depend on the Reference Frame in which the events were encoded: The order will be P_a, P_b, P_c for Reference Frame 1, but P_y, P_z, P_x for Reference Frame 2. This process is illustrated in Figure 1, where each event consists of a single dot, and the reference frames are (1) a rectangular template that moves relative to (2) a second, larger reference frame (e.g., the screen boundaries). In the experiments reported here, all temporally ambiguous sequences were mutually exclusive; that is, no displayed dot occupied the same temporal position in the two sequences defined by the two reference frames.¹

Experiment 1 investigated the use of this technique for short sequences of spatial positions, comparing recall with a moving template with that in the standard condition, using a stationary template and a condition in which no template was provided, so that only extrinsic coordinates could be used to code position. Experiments 2 and 3 illustrate how the choice of a reference frame was influenced by varying one parameter of the display, the size of the moving template, when the moving template was displayed alone (Experiment 2) and when it was displayed in conjunction with a stationary rectangle that provided a competing reference frame (Experiment 3).

EXPERIMENT 1

The aim of Experiment 1 was to measure spatial span performance using the temporal ambiguity method to identify the reference frame used with a moving template. In this experiment, three conditions were compared. One was the temporal ambiguity condition, in which there were two possible temporal orders determined by template-based or extrinsic encoding. Memory in this condition was contrasted with that for sequences described on a stationary template positioned in the middle of the screen and with that for sequences in which the dots appeared on an otherwise blank screen without a template. With a stationary template, the temporal orders of template-based and extrinsic coding are the same; without a template, only extrinsic coding is possible. We would expect performance to be higher in the stationary template condition than in the moving template condition, because of a contribution from extrinsic coding in the stationary condition and/or because the movement of the template impairs memory. We would expect poorer performance in the absence of the template, because the reference frame is more distant from the target positions. The advantage of the temporal ambiguity

Figure 1. Illustration of the method. The figure shows seven stages in the presentation of a sequence of three locations, plus the display used at test. The large rectangle represents a stationary extrinsic frame of reference (e.g., the borders of the computer screen); the inner smaller rectangle represents the template. The sequence shows the movements of the template and the display of the target dots. Note that the apparent temporal order of the dots depends on the choice of reference frame. In the extrinsic reference frame, the dots appear in the order top, left, lowest. With respect to the template, the dots appear in the order lowest, top, left. A sequence length of three is used here for illustrative purposes. In all experiments, the sequence length was five locations.

method is that we can now identify the reference frame used to encode the sequence in the moving template condition. This allows us to determine whether spatial position is always encoded in the same way or whether different strategies are adopted across trials or across participants. In addition, it permits precise measurement of span when the encoding strategies are homogeneous.

Method

Participants. The participants were 7 male and 17 female students drawn from the undergraduate and postgraduate population at the University of Essex. The mean age of the participants was 20.2 years ($SD = 2.47$ years).

Design. There were three blocked conditions, which varied in terms of the display of a template that surrounded the dots during the presentation of each sequence. In the *stationary template* condition, the template remained in the center of the screen. In the *moving template* condition, the template moved to a new position during the interval between the displays of successive dots. The position of the dots and the movement of the template were carefully coordinated so that the temporal order of the sequence of dots defined with respect to the template was different from the order defined with respect to screen locations, as explained above. In the *absent template* condition, there was no template displayed, and the dots were drawn on an otherwise blank screen.

Apparatus. In all the experiments reported here, the stimuli were displayed using a Mitsubishi Diamond 19-in. color monitor driven by a Macintosh G3 computer at a refresh rate of 75 Hz, with a screen resolution of $1,024 \times 768$ pixels. The stimuli were drawn in black on a white ground. Software was written in C, incorporating the VideoToolbox subroutines (Pelli, 1997). Responses were made using a computer mouse.

Materials. The spatial sequences to be remembered consisted of the display of five dots, where each dot was displayed for 1 sec, with an interdot interval of 1 sec. Each dot measured 9 mm (27 pixels) in diameter. The positions of the dot centers were chosen at random within an area measuring 105 mm wide $\times$ 73 mm high, in the center of the screen, with the constraint that no two dots could have centers within three diameters of each other. Depending on the condition, each dot was displayed either inside an unfilled rectangle (the template) measuring 114×84 mm (334×248 pixels) or alone, in the case of the absent template condition.

Procedure. The participant started each trial by clicking the mouse on a small target at the bottom right of the screen. The sequence of five dots was then displayed as follows. In the stationary condition, the template was displayed in the center of the screen for 2 sec, after which each dot was shown for a 1-sec display time, with a 1-sec off time. After the last dot had been displayed, there was a 1-sec interval before the recall display. In the moving condition, the template initially was displayed in the center of the screen for 1 sec and then was translated across the screen to a new position. The movement of the template was continuous, occurred at a constant velocity, and lasted for 1 sec, after which the first dot was displayed for 1 sec. This cycle of template movement, followed by the dot display, continued until the last dot had been shown, after which the template moved back to the center of the screen. In this and the following experiments, if a template was provided, it was always visible during the trial. In the absent template condition, the screen was initially blank for 2 sec, after which each dot was displayed alone for 1 sec, followed by a 1-sec blank screen.

In all conditions, the recall phase was identical. The template was displayed in the center of the screen enclosing the five dots drawn in outline. The dots were shown at screen positions that were the same as those at which the dots had been displayed during the presentation phase. In the case of the conditions in which the template was present during the display, the dots were also shown in the same positions, relative to the template. As each dot was selected, it was filled and then became unavailable for selection. After the last dot had

been chosen, the screen was cleared and prepared for the participant to initiate the next trial.

The participants were given a block of five trials in each of the three conditions. Across participants, each of the six possible orders of blocked conditions was used four times. The participants were told that a sequence of dots at different positions would be shown and that they were to recall the order in which they had seen them. No mention was made of reference frames or how position should or could be encoded in this experiment, nor in any of the following experiments.

Results and Discussion

On each trial, the order in which the dots were selected was recorded, and responses were scored as the proportion of dots recalled in the correct serial position. In the case of the stationary template and absent template conditions, responses were scored according to the unambiguous order in which the dots appeared. In the moving template condition, responses were scored in two ways according to the two possible temporal orders: the order in which dots appeared in spatial positions relative to the template, and the order in which they appeared in extrinsic coordinates—that is, relative to the screen or to the observer. If, on any trial in the moving condition, the score was higher for template order scoring than for extrinsic order scoring, it was assumed that the participant used template-centered coding on that trial. Conversely, if the extrinsic order score was higher than the template order score, it was assumed that the extrinsic reference frame was used to determine temporal order.

An important issue is whether, in the moving template condition, the participants used one reference frame consistently or varied their choice of reference frame across trials. Inspection of the scores showed that 14 participants used the same reference frame on all five trials, and 7 participants used the same reference frame on four out of five trials, where usually scores were low on the exceptional trial. The remaining 3 participants were more inconsistent, but their scores were generally low, as if they were guessing. Although we cannot rule out the possibility that a few participants may have encoded the sequence using both reference frames, for the vast majority of participants only one reference frame was used. The participants were grouped according to whether their average score across all five trials was higher using template scoring or extrinsic scoring. By this criterion, 21 participants recalled using template-centered coding, and 3 participants (all of whom were consistent across trials) recalled using extrinsic coding. Thus, for this version of the dots task, template-centered encoding was not mandatory, although the template provided the nearest available landmark for the dot positions.

The mean accuracy for the four informative conditions (stationary template, moving template with template scoring, moving template with extrinsic scoring, and the no-template condition) are summarized in Figure 2A for the participants using template-centered coding and in Figure 2B for the minority using extrinsic coding.

Consider first the participants who used template-centered coding in the moving template condition. For these participants, performance was highest in the stationary template condition, where scores were significantly

higher than the template-based scores of the moving template condition by a paired sample t test [$t(20) = 2.88$, $p < .01$] and also were significantly higher than those in the no-template condition [$t(20) = 2.41$, $p < .05$]. When scored by extrinsic temporal order, performance in the moving template condition was significantly below the expected chance level of .2 by a one-sample t test [$t(20) = 17.8$, $p < .001$].

For the 3 participants who showed extrinsic coding, scores were again higher in the stationary template condition than in the extrinsic or moving template condition. Because of the small sample, these differences in performance could not be statistically confirmed. However, the template-based scores in the moving template condition were significantly lower than the expected chance level of .2, using a one-sample t test [$M = .013$; $t(2) = 11.0$, $p < .01$].

Thus, for the majority of the participants, we have clear evidence (1) that the moving template was used as the reference frame and (2) that performance was impaired in the moving template condition, relative to the stationary condition. This is consistent with an account in which these participants encoded the sequence initially in a template-centered frame, but at a cost imposed by attending to the moving template.

We now will consider whether the results can be explained in terms of the availability of reference frames without invoking movement interference. Consider first the case in which on any one trial, in any condition, only one reference frame is used to encode the sequence. For the participants using template-centered coding with a moving template, performance was lower than with a stationary template. We can explain this by proposing that extrinsic coding is used in the stationary condition and that this is more efficient and leads to better memory than does template-centered coding. But memory based on extrinsic coding was measured independently in the absent template condition and was found to be significantly *lower* than scores in the stationary template condition. Likewise, we can rule out the complementary explanation that pure template-based encoding is used in the stationary condition, because we would expect similar levels of performance in the moving template condition. Hence, we can dismiss accounts proposing that the sequence is encoded with respect to a single reference frame, either extrinsic or template centered, and movement interference does not occur.

However, explanations that propose that, in the stationary condition, both template-based and extrinsic coding occur and that both codes support performance can still account for the data. This predicts correctly that lower scores will occur in all the other conditions: in the moving template condition (for participants using template-based and extrinsic encoding) and also in the absent template condition, because all these conditions rely on just one code.

It is worth considering why 3 participants adopted the minority position of using extrinsic coding in the moving template conditions. One clue comes from the order in which these participants completed the three conditions. Two participants completed the absent template condition first, followed by the moving template condition. For these

Figure 2. Serial recall accuracy in the three template conditions in Experiment 1. The moving template condition is temporally ambiguous, and both template-centered and extrinsic scores are shown for this condition. (A) Scores for the participants showing template-centered encoding in the moving template condition. (B) Scores for the participants showing extrinsic encoding. The stationary template condition and the absent template condition had only one possible temporal order. Error bars indicate standard errors.

participants, the experience of extrinsic coding in the absent template condition carried over into the following moving template condition, and 1 of these participants reported trying to ignore the moving rectangle. The 3rd anomalous participant completed the moving template condition first. For all the other participants, the template was used to encode temporal order, including all those for whom the stationary template condition preceded the moving template condition. The choice of reference frame observed in the

moving template condition, together with the influence of prior conditions, suggests that the choice of spatial reference frame is strategic, rather than automatic.

In the next two experiments, we used the temporal ambiguity method to investigate how the choice of reference frame is influenced by changes in the geometry of the display. In Experiment 2, we varied the size of the template while the field within which dot sequences occurred was kept constant. In Experiment 3, we provided both a mov-

ing template and a stationary rectangle as a competing reference frame and varied these in terms of relative size.

EXPERIMENT 2

Experiment 1 has shown that when a template is provided that closely surrounds the locations of the dot sequence, the majority of participants recall the sequence using a template-centered reference frame. In this experiment, we considered what would happen when the template varied in size while the spatial distribution of dot positions was kept constant. With template-centered encoding, a large template should make it more difficult to encode location, because the target locations of the sequence are more distant from the only visible feature of the template, its rectangular border, which provides the reference frame (Nelson & Chaiklin, 1980). By the same token, extrinsic encoding, whether with respect to the observer or to features of the environment such as the screen boundary, should remain roughly constant in difficulty, because the spatial scales of the reference frames are constant. Thus, we should expect that, as the template size increases, performance based on template-centered encoding should decrease, whereas that based on extrinsic coding should remain constant. In the experiment, participants completed series of temporally ambiguous trials on which the size of the template increased or decreased gradually.

A further consideration was the extent to which the changes in frame size would influence participants' choices of strategy. For example, as template size increases and the utility of template-based encoding decreases, there may be a tendency to switch to extrinsic encoding, which can be readily detected. On the other hand, participants may adhere to their initial strategy and consistently reject information from an alternative reference frame, even if it is more efficient. The latter case would be more consistent with the view that participants perceive the sequence in relation to only one reference frame.

Method

Participants. Eighteen participants, 11 of them female, were drawn from students and staff at the University of Essex. Their mean age was 22.7 years ($SD = 8.4$ years). Five participants were paid £4 for participating; the remainder were volunteers.

Design. Three independent variables were manipulated. The size of template, with six levels, and the direction of template size change (template size increasing or descending) were manipulated as repeated measures. The third independent variable was the order in which the series were encountered: Half the participants completed the ascending series first, and half the descending series first.

Materials. The spatial sequences to be remembered consisted of the display of five dots, where each dot was displayed for 1 sec, with an interdot interval of 1 sec. Because there was a requirement to vary the size of the template, the dimensions of the components were changed from Experiment 1, so that the linear dimensions of the smallest template and the dots were reduced by half. The size of the dots was reduced to 4.5 mm in diameter (14 pixels), and the smallest template was 56 mm wide $\times$ 41 mm high (170 $\times$ 124 pixels). The six graded sizes of template were formed by increasing the linear dimensions by an amount corresponding to 0.7 $\times$ the minimum template size to form each successor, giving six template widths of 170, 288, 408, 526, 646, and 764 pixels, with height changing in proportion. The largest template measured 260 $\times$ 190 mm. Because of the

limitations of the display hardware, displays in which the template moved were updated on alternate frames.

Procedure. Each trial was initiated by the participant, and the events closely followed the sequence of the template moving condition in Experiment 1. The template was shown for 1 sec, followed by a movement lasting 1 sec, after which the first dot was displayed. Each dot was displayed for 1 sec, followed by a 1-sec movement; after the fifth dot, the template returned to the center of the screen. In the ascending series, the first 10 trials were at the smallest template size; thereafter, 5 trials were provided at each template size up to the largest. In the descending series, 10 trials were provided with the largest template, decreasing in size after every 5th trial. Thus there were 70 trials in all. The first 5 trials of each sequence were discarded as practice.

The participants were instructed to remember the sequence of dots and to recall the order in which they appeared by clicking on the dots in turn. They were informed that the template would change size during the course of the experiment but were given no instructions regarding the possible methods of encoding dot positions or temporal order.

Results and Discussion

As in Experiment 1, the first step in the analysis was to segregate the participants according to the strategies used. To determine the strategy the participants had adopted at the start of the experiment, the first five trials of the ascending and descending series were discarded as practice. Scores averaged over the first five experimental trials of the session were used to classify the participants according to their initial encoding strategy: If the template-based score was higher than the extrinsic score, the participant was classified as using an initial template-based strategy, and vice versa. When classified in this way, 7 participants out of 9 who started with the ascending sequence initially used template-based encoding, whereas only 3 of those starting with a descending sequence did so. The association between order and initial coding type just failed to reach significance [$\chi^2(1) = 3.6, p = .058$]. This suggests that the geometry of the initial configuration influences the choice of reference frame, so that a small template encourages template-centered encoding. For all the participants, the template-based and extrinsic scores were then compared at each template size. Of the 18 participants, only 1 appeared to have switched reference frames, using template-based encoding when the template width was 288 pixels and below and extrinsic encoding when the template width was 408 pixels and above. This participant initially adopted an extrinsic-coding strategy. After excluding this participant, we have two groups who showed consistent template-centered encoding ($n = 10$) and extrinsic encoding ($n = 7$).

The mean scores for those participants who used template-based encoding throughout are shown in Figure 3A. The results for this group show a linear decrease in their template-based scores as the size of the template increased. At the same time, the extrinsic scores increased slightly but remained below chance level. The decrease in template-based scores reflects the difficulty of encoding spatial position against a progressively more distant reference frame. A 2 $\times$ 6 repeated measures ANOVA was performed on these template-centered scores, with direction (ascending, descending) and template size as factors. The results, after applying Greenhouse-Geisser correc-

Figure 3. Serial recall accuracy in Experiment 2 as a function of template size, scored with respect to template-centered and extrinsic order. The template sizes varied from 1 (smallest) to 6 (largest). The data are grouped according to the encoding strategy used. (A) Data for the participants using a consistent template-centered encoding strategy. (B) Data for the participants using an extrinsic reference frame. Error bars indicate standard errors.

tion, showed a significant effect of template size [$F(3.16, 28.4) = 5.6$, $MS_e = .0307$, $p < .001$] but no effect of direction [$F(1,9) < 1$]. Polynomial contrasts showed that only the linear trend was significant [$F(1,9) = 13.8$, $p < .01$]. Considering the extrinsic scores for this group, a separate ANOVA revealed that these scores increased with template size [$F(2.94, 26.5) = 3.45$, $MS_e = .0076$, $p < .05$], again with a significant linear trend [$F(1,9) = 9.0$, $p <$

.05], even though the scores remained at below-chance levels. This is a reflection of the mutually exclusive nature of the scores: As template-based performance decreases, extrinsic scores will drift upward toward chance levels.

Turning to the group of 7 participants who showed consistent extrinsic coding, Figure 3B shows that accuracy in this group was unrelated to template size. A 2×6 ANOVA of the extrinsic scores, with direction and template size

as independent variables, showed no significant effect of template size [$F(2.35, 14.12) = 1.62, MS_e = .0477, p > .05$]. No other effects approached significance.

This experiment has shown that accuracy at encoding spatial sequences depends on the nature of the reference frame. For participants known to be encoding position with respect to the template, performance decreased as template size increased. This was expected because coding of position is more precise in relation to proximal reference frames. This was not the case for the participants using extrinsic encoding, where the reference frames remained constant in size.

An unexpected result was that most of the participants persisted with their initial coding strategy and did not change this, even though template-centered encoding varied in difficulty across conditions. Three participants in the extrinsic-coding group reported that they had tried to ignore the template during presentation. This suggests that selective attention was tuned to encode spatial positions extrinsically and that information that would support template-based coding was filtered out. Thus, under conditions in which the template moves, the encoding strategy appears to select one of the two reference frames.

One limitation of this experiment is that, although varying in size, the template was always smaller than the nearest available allocentric reference frame, the screen borders. In all the conditions, these reference frames were always in the same size relation, so that a smaller template moved around inside the fixed edges of the screen. If, however, the two potential reference frames changed with respect to their relative sizes, so that the frame that was initially smaller becomes larger than its competitor and vice versa, there may have been a greater tendency to switch between reference frames. In the following experiment, we examined this possibility by introducing two competing reference frames drawn on the screen—one moving, one stationary—that changed in relative size.

EXPERIMENT 3

In this experiment, we introduced a new stimulus that provided a potential competing reference frame with the moving template. This was a stationary rectangle, intermediate in size between the smallest and the largest moving templates, that was always present on the screen during presentation. (This stationary rectangle, of course, fulfilled all the requirements of a template for the dot display, since all the dot locations fell inside the stationary rectangle. For the sake of consistency with Experiment 2, we will use the term *template* to refer to the moving rectangle that varied in size.) The template size varied as in Experiment 2, but now, on half the trials, there was a competing reference frame (the stationary rectangle) closer than the moving template. We anticipated that this would exert a strong influence on the initial strategy adopted, with participants in the descending series adopting the smaller stationary rectangle as the reference frame, and those in the ascending series adopting template-based coding. Because the stationary rectangle was fixed with respect to the observer, its use as a reference frame would

be reflected in extrinsic scores using the temporal ambiguity method. If the participants encoded spatial positions relative to the nearest reference frame, we should observe a switch in strategy when the template and stationary rectangle changed in their relative sizes.

Method

Participants. Twenty-four participants, 20 of whom were female, were drawn from the undergraduate and postgraduate students at the University of Essex. Their mean age was 22.8 years ($SD = 4.5$ years). Fifteen were paid £4 for participating; the remainder took part to fulfill a course requirement.

Materials. The templates and dots were displayed in the same way as those in Experiment 2. In addition, on each trial, a stationary rectangle was displayed in the center of the screen. This rectangle was midway in size between the smallest and the largest templates (157×113 mm [468×342 pixels]). Thus, the three smaller templates were smaller than the stationary rectangle, and the three largest templates were larger. Moreover, the smallest template was always wholly within the stationary rectangle, whatever its movements, and likewise the stationary rectangle was always entirely contained within the largest template. Again, each spatial sequence consisted of the display of five dots, where each dot was displayed for 1 sec, with an interdot interval of 1 sec.

Procedure. The procedure was exactly the same as that in Experiment 2. The participants again were instructed to remember the locations of the five dots and to recall them in order but were not given instructions concerning how to do this. They were informed at the outset that the template would increase/decrease in size during the current series but were given no instructions regarding the possible methods of encoding dot positions or temporal order.

Results and Discussion

The initial coding strategy was determined for all the participants as described for Experiment 2. Of the 12 participants who started with the small template (ascending series), only 4 used the moving template as a reference frame. All 12 participants who started with the descending series adopted extrinsic coding. The association between the order of conditions and the initial strategy was significant by a χ^2 test [$\chi^2(1) = 4.8, p < .05$]. Thus, the presence of the stationary rectangle strongly encouraged extrinsic coding, and this was the favored initial strategy for all the participants who first experienced the descending series.

Close inspection of the individual scores was used to detect switching between reference frames as the moving template changed size. Two of the original 4 participants initially adopting template-centered encoding switched strategy when the stationary rectangle was surpassed by the template. Two of the 20 participants initially adopting extrinsic coding also switched strategy. This left two very unequal groups of 18 participants who adopted an extrinsic-coding strategy and 2 participants who used a template-centered strategy. The results of the group consistently using extrinsic coding are presented in Figure 4A, and those of the 4 participants who switched strategy are represented in Figure 4B. Figure 4A shows that extrinsic scores show no marked tendency to vary with template size. This was confirmed by a 2×6 repeated measures ANOVA with direction and template size as the two measures, which failed to show a significant effect of template size [$F(3.78, 64.3) = 3.05, MS_e = .012, p > .05$], although there was a trend toward more accurate perfor-

Figure 4. Serial recall accuracy in Experiment 3 as a function of template size, scored with respect to template-centered and extrinsic order. The template sizes varied from 1 (smallest) to 6 (largest). The data are grouped according to the encoding strategy used. (A) Data for the majority of participants using a consistent extrinsic-encoding strategy. (B) Data for those participants identified as switching strategy, using template-centered encoding at small template sizes and extrinsic coding at large template sizes. Error bars indicate standard errors.

mance with larger template sizes. No other significant effects were found. There was likewise no significant effect of template size on the template-centered scores, which remained below chance throughout [$F(3.6, 61.2) = 1.73$, $MS_e = .0193$, $p > .05$]. Figure 4B shows mean scores for the participants who switched strategy, showing high template-centered scores and chance-level extrinsic scores at small template sizes and the reverse at intermediate and large template sizes.

Thus, Experiment 3 shows that the presence of a stationary rectangle of intermediate size heavily influences the choice of reference frame. The majority of the participants preferred the stationary rectangle as the reference frame, using this even when there was a smaller moving template that was closer to the target positions. Of the 18 participants adopting extrinsic coding, 6 reported that they had tried to ignore the moving template.

GENERAL DISCUSSION

The purpose of this article was to describe the temporal ambiguity technique for determining reference frames. In this version of the technique, spatial sequences were presented by displaying target locations on a moving template, so that, at recall, (1) the set of template-centered and extrinsic positions were identical in the two reference frames and (2) the targets were apparently presented in different temporal orders, depending on which reference frame was used to encode position. Thus, from the temporal order at recall, it is possible to determine the reference frame used. The method is tolerant of changes in level of performance, because the temporal orders are incongruent in their respective reference frames. Provided there is some memory for the sequence, the scores in the reference frame adopted will be at above-chance levels, and those in the alternative reference frame will be below chance level. Thus, we can clearly distinguish manipulations that impair performance in spatial span with a constant reference frame from those that lead to changes in the reference frame used to encode positions.

In this article, we have illustrated the method in three experiments, using the dots task version of spatial span (Jones et al., 1995), in which a series of dots are shown singly inside a moving rectangular template. In Experiment 1, performance was measured with a stationary template and with no template, as well as in the temporally ambiguous condition with a moving template where the reference frame could be identified. This showed clearly that the majority of the participants adopted the moving template as a reference frame in the temporal ambiguity condition. The minority who adopted an extrinsic reference frame were probably influenced by prior conditions. The results also demonstrated that performance in the stationary condition was superior to that in both the extrinsic and the moving template conditions. As has been noted above, it is difficult to explain this result if performance in each condition was supported by just one reference frame and movement interference did not contribute.

Experiments 2 and 3 varied the size of the template, with the intention of reducing the efficiency of template-centered encoding at large template sizes, relative to ex-

trinsic encoding. The majority of the participants (17 out of 18 in Experiment 2, 20 out of 24 in Experiment 3) continued to use the strategy adopted at task onset and did not switch reference frames as the layout varied. The initial strategy was influenced by the size of the template first encountered; if the template was large, it was more likely that the participants would adopt extrinsic encoding.

For those participants who consistently used a template-centered strategy in Experiment 2, performance varied inversely with template size. This cannot be explained by movement interference, because template movement was constant as template size varied. The decrease in performance arises from the difficulty of coding spatial position with respect to a more distant reference frame. As was expected, there was little or no effect of template size on accuracy for the participants using extrinsic encoding in Experiments 2 and 3.

The present experiments examined preferences and strategies in the selection of a reference frame when a small number of potential reference frames were available, but orientation was constant (up, down, left, or right). In Experiment 1, most of the participants used the template to encode the sequence, possibly because this was the nearest reference frame, although there were exceptions influenced by prior conditions. The preference for template-centered encoding in Experiment 1 suggests either a bias toward the nearest available reference frame or a bias toward a moving reference frame. In Experiment 2, the choice of reference frame was again influenced by the first displays encountered, so that there was a marked preference for template-centered encoding if a small template was first encountered. This result suggests that the choice of reference frame was based on proximity. However, in Experiment 3, an intermediate stationary rectangle was used as the reference frame by most of the observers, even when the moving template was closer to the encoded positions. This preference for the intermediate rectangle may reflect the fact that it was stationary or may have occurred because it was centrally placed and symmetrically aligned with respect to the screen and the observer. Thus, in these experiments, the initial choice of reference frame appears to have been partially, but not wholly, determined by proximity. However, the choice of reference frame appears to be strategic: It is determined by prior conditions and adhered to even when conditions change to favor the alternative reference frame. A possible reason for this is that in the present paradigm, adoption of one reference frame involves selective attention that highlights certain features of the display, whereas other features that are critical for localization in other reference frames are relegated to the background. In all three experiments, a proportion of the participants using extrinsic coding of position, as determined by temporal order, reported that they had tried to ignore the moving template. Thus, under these conditions in which explicit memory for temporal sequences is required and the temporal sequences are incongruent across reference frames, the choice of one spatial reference frame may preclude the use of other reference frames.

Similar concerns have been reported in studies investigating the selection of spatial coordinates in arrays of ob-

jects in enclosed three-dimensional spaces (McNamara, 2003; Mou & McNamara, 2002; Mou, McNamara, Valiquette, & Rump, 2004; Mou, Zhao, & McNamara, 2007). The results have shown that the reference frame adopted was somewhat variable; for example, it was not mandatorily aligned with viewing position but could depend on local environmental features (Mou & McNamara, 2002; Shelton & McNamara, 2001) or layout geometry (Mou et al., 2007). Position information seemed to be encoded in just one reference frame, although alternatives were available. Across individuals, there was some variation in the choice of coordinates, but these tended to remain stable within individuals (Mou et al., 2007). In a similar way, our experiments showed that the choice of reference frame is influenced, but not wholly determined, by prior conditions and layout geometry and that strategies, once acquired, tend to remain stable when conditions vary.

The real-environment studies required intensive learning of spatial relationships in relatively complex environments. Much of our knowledge of spatial reference frames has come from studies of immediate memory for a single spatial location, assessed by the accuracy of pointing under various controlled conditions. Spatial reference frames were inferred from the pattern of pointing errors, which depended on the arrangement of stimuli at presentation and conditions at the time of response. For example, Diedrichsen, Werner, Schmidt, and Trommershäuser (2004) reported that the pattern of pointing errors made to briefly presented and masked dots was influenced by the presence of landmark stimuli in the otherwise blank field. Similar error patterns were found when observers were required to encode position with respect to landmarks that moved between presentation and recall, consistent with (but not necessarily implying) allocentric coding. With visually guided reaching, Lemay, Bertram, and Stelmach (2004) reported that the error patterns and kinematics of pointing responses depended on whether targets were presented alone or accompanied by a surrounding square. They argued that the response characteristics depended on the use of egocentric or allocentric encoding of target position and that, where both representations were possible, an allocentric representation was used. If their conclusion is true, this suggests that our extrinsic frame of reference was allocentric (e.g., the boundary of the computer screen), rather than egocentric, and that our experiments showed competition between allocentric reference frames, consistent with Experiment 3. In contrast, Chieffi, Allport, and Woodin (1999) reported evidence for hand-centered coding of spatial position in a pointing task in which responses were made without visual guidance. They argued that the presented targets were immediately encoded in a hand-centered reference frame, rather than being encoded in a visual frame of reference and translated to a hand-centered code at recall. The conclusions of these three studies differed, although the methods were similar, involving pointing to single target positions in the presence or absence of landmarks. Thus, the reference frame used to encode or report stimulus position in these studies was again sensitive to task demands.

Relatively few studies have made explicit reference to working memory, the notable exception being Woodin and Allport's (1998) interference study of memory for a single location. The target location was specified by a brief sound, and the blindfolded participant pointed to the sound, then was moved in a rotating chair, and was asked to recall the location in an egocentric or an allocentric framework. Between presentation and recall, the participant pointed to previously learned visual targets, also specified in egocentric or allocentric coordinates. Interference from the irrelevant targets was selective, so that the allocentric interference task affected only allocentric target memory and vice versa. Taken at face value, the results are striking, since they suggest that separate spatial memories exist for different reference frames and that spatial interference may be minimized by allocating memory loads to different reference frames. However, other interpretations are possible. For example, the egocentric memory may be gestural (memory for how the body folds), rather than spatial, and we know that there is little interference between systems that encode such information (Smyth et al., 1988).

The temporal ambiguity method outlined here provides a novel and efficient method for determining reference frames but also has limitations. First, it can be used only when the stimuli and responses occur as sequences. In the present study, we used sequences of five locations to ensure that the task demands were similar to those of conventional spatial span. Of course, the sequence need not be this long, but a minimum sequence length of two is required. The serial requirement is not necessarily a strong limitation, since serial order tasks are commonly used in adults and children and in animal studies (e.g., Kawai & Matsuzawa, 2000). However, one constraint is that the temporal ambiguity method is adjusted to the capacity of the observer to reproduce a sequence accurately. A second limitation is that the requirement to encode and retain a sequence of positions may influence the reference frame used for encoding. Recent studies of spatial span suggest that the spatial sequence is encoded as a series of transitions or movements between one spatial location and the next. Our assumption is that each position is coded in an appropriate reference frame depending on local conditions and that an independent process subsequently links these to form the transitions. However, we cannot rule out the possibility that later stages influence earlier encoding. Another limitation is that the method can decide only between two (possibly three) groups of reference frames that are moved relative to each other. This does not of itself guarantee that any specific reference frame is used. For example, in the present experiments, we crudely characterized the reference frames as extrinsic or template centered, because determination depended on movement of the template. Our extrinsic reference frame can be partitioned further into the egocentric reference frame (trunk or head centered) or an environmental reference frame that is stationary with respect to the observer. Similarly, if the observer always fixated the center of the template, a template-centered sequence could be encoded in retinocentric coordinates.

Although the method provides a convenient way of deciding between candidate reference frames (or disjoint sets of reference frames) when these are known, it is not powerful enough to determine reference frames absolutely.

AUTHOR NOTE

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NOTE

1. One reviewer raised a question about sequences in which the events were not homogeneous—for example, ones in which different spatial tokens were displayed at each position in two relative-moving reference frames. The temporal ambiguity method described here would need to be modified by substituting homogeneous tokens at recall and asking participants to recall the spatial order. Alternatively, the reference frame could be identified by choosing between the spatial arrangements of items in each of the two reference frames—that is, using spatial, rather than temporal, ambiguity.

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