Distance- rather than location-based temporal judgments are more accurate during episodic recall in a real-world task

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Definitions of episodic memory typically emphasize the importance of spatiotemporal frameworks in the contextual reconstruction of episodic retrieval. However, our ability to retrieve specific temporal contexts of experienced episodes is poor. This has bearing on the prominence of temporal context in the definition and evaluation of episodic memory, particularly among non-human animals. Studies demonstrating that rats rely on elapsed time (distance) rather than specific timestamps (location) to disambiguate events have been used to suggest that human episodic memory is qualitatively different to other species. We examined whether humans were more accurate using a distance- or location-based method for judging when an event happened. Participants (n = 57) were exposed to a series of events and then asked either when (e.g. 1:03 p.m.) or how long ago (HLA; e.g. 33 minutes) a specific event took place. HLA judgements were significantly more accurate, particularly for the most recently experienced episode. Additionally, a significantly higher proportion of participants making HLA judgements accurately recalled non-temporal episodic features across all episodes. Finally, for participants given the choice of methods for making temporal judgements, a significantly higher proportion chose to use HLA judgements. These findings suggest that human and non-human temporal judgements are not qualitatively different.

Keywords: human episodic memory; episodic-like memory; passive encoding; temporal estimation; mental time travel

Introduction

Episodic memory is a fundamental memory process that allows the apparently automatic encoding of attended experience (Morris & Frey, 1997). It is often defined as memory for events and the temporal-spatial properties that allow us to distinguish memory for one event from other similar events (Tulving, 1983). In principle, any piece of information that is specific to an event can be used to disambiguate that memory from other memories including spatial location, contextual features of the event (e.g. weather, mood, specific stimuli) and time (Persson, Ainge, & O'Connor, 2016). Time is a particularly interesting and attractive candidate for disambiguating specific events in memory as each event will have a unique timestamp. In contrast, it is relatively rare for other features of an event to be completely unique. Consequently, many theories and definitions of episodic memory stress the importance of a temporal component (Clayton, Bussey, & Dickinson, 2003; de Kort, Dickinson, & Clayton, 2005; Roberts, 2002; Tulving, 1983).

Temporal memory can, however, take a number of forms. Friedman (2001) puts forward two main strategies used to recall when a previously experienced episode occurred, referred to as 'distances' and 'locations' (Friedman, 2001). A distance-based approach involves remembering how long ago an event took place relative to the present. In contrast, a location-based strategy employs the use of information stored in memory, such as knowledge of personal, natural or social time patterns, to reconstruct the specific instance of when an event occurred. Location-based strategies would be consistent with the influential Temporal Context Model of episodic memory (Howard and Kahana, 2002). According to this model, information is stored either as context or content representations. As new content is encoded corresponding new context is associated with it. The contextual representation is an aggregation of previous experiences and serves as source of location information to help disambiguate memories from other memories.

Both distance- and location-based strategies have plausible neurobiological mechanisms. Mechanisms that support distance-based strategies would need to show gradual change in representations that can be correlated with time passed. The hippocampus and surrounding parahippocampal cortices have been shown to have gradually changing representations that could represent changes in time elapsed at short (seconds-minutes; Eichenbaum, 2014; Kraus, Robinson, White, Eichenbaum, & Hasselmo, 2013; MacDonald, Lepage, Eden, & Eichenbaum, 2011; Pastalkova, Itskov, Amarasingham, & Buzsaki, 2008; Tsao et al., 2018) and medium (hours-days; Mankin, Diehl, Sparks, Leutgeb, & Leutgeb, 2015; Mankin et al., 2012; Mau et al., 2018) timescales. Recordings of hippocampal long-term potentiation (LTP) suggest a slow decrement over weeks-months providing a potential mechanism for distance-based strategies at even longer timescales (Abraham, Logan, Greenwood, & Dragunow, 2002). The hippocampus also displays robust responses to stimuli that could be used to support location-based strategies including, most obviously, spatial location (Colgin, Moser, & Moser, 2008; O'Keefe & Dostrovsky, 1971), but also contextual features of the environment (Anderson & Jeffery, 2003; Leutgeb et al., 2005; Muller & Kubie, 1987), motivation (Kennedy & Shapiro, 2009), social environment (Danjo, Toyoizumi, & Fujisawa, 2018; Omer, Maimon, Las, & Ulanovsky, 2018) and on-going behavioural tasks (Ainge, Tamosiunaite, Woergoetter, & Dudchenko, 2007; Ainge, van der Meer, Langston, & Wood, 2007; Ferbinteanu & Shapiro, 2003; Lee, Griffin, Zilli, Eichenbaum, & Hasselmo, 2006; Smith & Mizumori, 2006; Wood, Dudchenko, Robitsek, & Eichenbaum, 2000).

A key difference between location- and distance-based strategies is that location-based memory involves the recall of specific source information from the encoding event to place the event in a temporal context (Diana, Van den Boom, Yonelinas, & Ranganath, 2011; Yonelinas, 1999). Distance-based strategies, however, rely on a familiarity-based retrieval mechanism that allows the age of a memory to be inferred from the relative strength of the memory trace. This lack of specific source information in distance-based temporal memories has been used to suggest that distance-based strategies are not episodic (Clayton et al., 2003; Roberts, 2002; Roberts & Feeney, 2009; Suddendorf & Busby, 2003). This distinction between episodic and potentially non-episodic strategies for remembering when something happened has become relevant when examining non-human animals' memory for time. It has been suggested that reliance on distance-based strategies in some animals is evidence that human and non-human animal (hereafter animal) episodic memory are qualitatively different (Roberts et al., 2008).

Over the past two decades, episodic memory research in animals has considerably expanded, not least with the aim of finding an animal model of the first major symptom of Alzheimer's disease that can be used to test potential therapeutic targets. These studies have focused on demonstrating that animals can remember trial-unique combinations of specific stimuli within spatial locations at specific times. This integrated memory of what, where and when has been termed episodic-like memory in non-human animals and has been demonstrated in many species of birds (Clayton & Dickinson, 1998, 1999; Clayton, Yu, & Dickinson, 2001; de Kort et al., 2005; Feeney, Roberts, & Sherry, 2009, 2011; Zinkivskay, Nazir, & Smulders, 2009), primates (Martin-Ordas, Haun, Colmenares, & Call, 2010), cuttlefish (Jozet-Alves, Bertin, & Clayton, 2013), and rodents (Babb & Crystal, 2005, 2006a, 2006b; Davis, Easton, Eacott, & Gigg, 2013; Eacott & Norman, 2004; Kart-Teke, De Souza Silva, Huston, & Dere, 2006). However, the degree to which episodic-like memory for what, where and when is equivalent to episodic memory in humans is still greatly debated (Suddendorf, 2013; Suddendorf, Addis, & Corballis, 2009; Suddendorf & Busby, 2003; Tulving, 1983). One of the defining characteristics of human episodic memory is the ability to mentally travel in time and relive an experience, autonoetic consciousness, but in the absence of a test for mental time travel in animals it has not been possible to definitively say whether or not animals have human-like episodic memory. One route of enquiry would be to ask whether animals remember time using the apparently more episodic location-based strategies or whether they rely on distance-based time estimation.

Roberts et al. (2008) asked whether rats were capable of using a location-based strategy to remember time or whether, instead, they rely on a distance-based strategy. Rats were split into three groups and trained on an episodic-like memory task using a radial arm maze. The rats had to learn when cheese would be replenished or pilfered on a specific arm during the test trial using either a location-based strategy that they called 'when' (time of day that they received their sample trial) or a distance-based strategy that they called 'how long ago' (the elapsed time between test and sample trial). Rats using a how long ago (*HLA*) strategy were more accurate at learning a temporal rule to guide behavior than those using a *when* strategy. When specific location-based cues were minimized by testing in the middle of the light-dark cycle, rats could no longer accurately use *when* strategies. These findings were used to suggest that animals use a different temporal strategy to humans when performing a what-where-when memory task, raising questions about the similarity between episodic-like memory in animals and episodic memory in humans.

However, the Roberts study sought to specifically minimize location-based cues and, as such, it is not clear that humans would use location-based strategies in the same situation. In order to conclude that rats and humans have fundamentally different mechanisms for remembering when things happened, we must first ask how humans would perform when asked to solve a temporal memory problem using either distance- or location-based strategies. While it would not be logistically possible to train human subjects on the same type of paradigm that Roberts et al. (2008) used for their rat studies, we have sought to test the same cognitive mechanisms supporting temporal memory. In the current study, we examined what type of temporal information humans use to remember episodes and whether temporal accuracy is affected by asking participants to use different temporal strategies. Participants were signed up to take part in a study of ‘Technology and Social Interaction’ to ensure that they were unaware that this was a memory experiment and prevent them actively trying to remember the details of the episodes. During a one-hour testing session each participant experienced 3 events that happened in different spatial locations at specific times (after 3, 23 and 33 minutes). At the end of testing participants were asked to provide details of the events they had experienced including when it happened and critically were assigned to one of three groups depending on the temporal strategy they were required to employ (location, distance, and location or distance). The design of the experiment captured many of the key aspects of the animal studies whilst also aiming to provide an ecologically valid way of testing how we integrate the temporal features of an event into an episodic memory. Participants were required to make temporal judgements of real-world trial unique experiences that were passively encoded offering a realistic assessment of episodic memory compared with most lab studies. We also investigated which temporal strategy participants chose to use when given an option between location- and distance-based approaches.

Considering work by Friedman (1993) and Roberts et al. (2008), we predicted that participants using a location-based temporal strategy would be more accurate at recalling when episodes occurred as well as specific non-temporal aspects of those episodes. We also expected that participants would actively choose to use a location-based temporal approach when given a choice.

Materials and methods

Participants

Fifty-seven University of St Andrews students (36 female) took part in a study approved by the University Teaching and Research Ethics Committee. All participants were paid £8 for their participation.

Apparatus and materials

The experiment took place in a 17x9 foot room with no potential time cues. Windows were blocked, and the room was well isolated from ambient sound. Participants sat around a long table. One end of the table faced a purple wall and the other end had a white backdrop. Metal cabinets were located in a corner of the room opposite the door. Participants were provided with magazines, a board game and a pack of playing cards. At the end of the experiment, participants were asked to fill out a questionnaire pertaining to the three *episodes* that took place during the study (see *Procedure*).

Design

The experiment was advertised as a study examining the role of technology on human social interaction. This was done to prevent participants from trying to keep track of time as well as to provide a logical reason for requiring participants to surrender electronic devices that could display time. In the first two experimental conditions, participants had to recall the time of episodes either using a location- (*when)* or distance-based (*HLA*) strategy. A third condition was included to allow participants to freely choose either temporal strategy. A total of 12 experimental sessions were conducted, each running for 45 minutes with a group of 5 participants. Participants were assigned to a specific experimental condition depending on the session number they signed up for (Sessions 1, 4, 7 and 10 – *when* condition; Sessions 2, 5, 8 and 11 – *HLA* condition; Sessions 3, 6, 9 and 12 – *free choice* condition). Four sessions were run every day (10:00, 12:00, 14:00 and 16:00) over three days. Although 20 participants were recruited in total for each condition, one participant in each condition did not attend. Therefore, sessions 3, 4, and 5 only had four participants.

Participants had to make temporal judgements on three distinct episodes that took place. The episodes occurred 3 minutes, 23 minutes and 33 minutes from the start of the session. The time points at which the episodes took place were chosen to have one episode at the midpoint of the session and two episodes on either side of the halfway mark but not at symmetrical points from the start and end of the session respectively to avoid participants using that as a strategy for estimating time.

Procedure

All participants were required to email their completed consent forms ahead of time to ensure that they were compliant with surrendering their electronic devices as well as to avoid any feelings of succumbing to peer pressure, should they want to withdraw at the start of the experiment, given the group nature of the study. Participants were also made aware that their consent had not been sought regarding the video or audio recording of the session and, therefore, no such footage would be captured. This was clarified so that participants would be incentivised to interact with each other naturally. The two temporal landmarks available to all participants beforehand were the start time and duration of the experiment as featured in the study advertisement and information sheet. Precautions were taken to limit participants using these cues as reference points. The study duration was advertised as being 90 minutes long while the actual session lasted 45 minutes. When participants arrived for the study, they were met at an adjoining building and then walked over to the testing room. Upon arriving in the room, participants were asked to surrender all electronic devices. There was an approximate 15-minute delay between when the participants arrived for the study and the start of the experimental session. Before the start of the experiment participants were asked to read a New York Times article about technology and social interaction entitled ‘Step away from the phone!’ (Tell, 2013). This reinforced the false nature of the experiment and created a gap in time between when participants surrendered their devices and the start of the test session.

Participants were instructed to interact with each other freely by talking or making use of materials provided in the room. The researcher then left the room and discreetly started a timer. Three minutes into the experiment, the researcher re-entered the room claiming to collect a diary on top of one of the cabinets. At the 23-minute stage, the researcher returned to the room with bottles of water and plastic cups for the participants and placed them at the near end of the table close to the purple wall. At 33 minutes, the researcher brought in a pack of playing cards for the participants to use and placed it at the opposite end of the table next to the white wall. During each of these three episodes the researcher made sure to knock clearly and loudly before entering the room and to speak to and make eye contact with all participants so that they were all aware of the event taking place. At the end of the 45 minutes, the researcher entered the room for the final time and informed the participants that the study had finished. Participants were then handed questionnaires. Participants were asked to complete the three questions below for each of the three episodes during which the experimenter entered the room. Questions 1 and 2 were common for participants across all time strategy groups. Question 3 was modified depending on the experimental condition. Participants in the *when* group received question 3a, those in the *HLA* group answered 3b and ones in the free choice group responded to 3c. Below are the task instructions with episodic memory questions for the first out of three episodes, which were referred to as *situations* to the participants:

Please answer the following questions in as much detail as possible regarding the 3 situations, in order of sequence (from first to last), when the experimenter entered the room between the start and end of the experiment.

Situation 1

(1) What happened, i.e., what did the experimenter do/want?

(2) Where did it happen, i.e., which part of the room specifically?

(3a) When did it happen, i.e, at what specific time? Please be as specific as possible (e.g. 3.13pm)

(3b) How long ago did it happen? Please be as specific as possible (e.g. 53 minutes ago)

(3c) When or how long ago did it happen? Please be as specific as possible and choose to respond in only one format (e.g. either 3.13pm or 53 minutes ago).

Statistical analyses

Of the 57 participants who completed the final questionnaire, responses from ten participants were excluded because participants either did not consistently use a when/HLA strategy for all three episodes (n=2) or did not complete one or more of the temporal judgements (n=8). Therefore, the final dataset included responses from 47 participants. Data from the *free choice* condition were assigned to the *when* or *HLA* conditions depending on participants' chosen time strategy for initial analysis. For the majority of the variables (7/12), homogeneity of variance assumption was not violated (see Supplementary Material). To assess the accuracy of time judgements of episodic memories, we calculated mean temporal estimation errors, for each episode. This was calculated as the difference between the reported and actual time of an episode. This can be calculated in two ways using either signed or unsigned values. The unsigned, absolute value of mean temporal estimation errors provides an absolute measure of temporal accuracy, while the signed value allows the examination of systematic bias for either under- or over-estimation of time elapsed. Both are presented here.

For sessions that involved participants using a *HLA* strategy, a composite end time was generated and used as a baseline time from which to calculate when all the participants in a particular session predicted how long ago each episode took place. The baseline time, calculated separately for each session, was the midpoint between when the questionnaires were administered and when the last questionnaire was completed. A baseline time was required as a consequence of administering paper rather than digital questionnaires. Paper questionnaires were used to ensure quick and efficient distribution of survey materials and recording of responses in a group setting devoid of electronic devices.

To examine whether participants were aware of the three times the experimenter entered the room, participants were scored on whether or not they could correctly recall the non-temporal features of each of the three episodes: *what, where* and combined *what and where*. For example, if a participant correctly recalled that the experimenter entered the room to collect a diary at episode one, then the participant would receive a score of 1 under the *what* category for episode one. Conversely, an incorrect answer would result in a score of 0. A summary table with descriptive statistics of temporal error and accuracy of non-temporal episodic aspects across both time strategies can be found in the Supplementary Material. Shapiro-Wilk tests of normality were conducted to establish the normality of the current dataset (see Supplementary Material). Although some data were not normally distributed, parametric tests (mixed ANOVAs) were performed for temporal estimation errors. This is because *F*-tests produced by ANOVAs have been shown to be robust to Type 1 error, with data transformations or non-parametric analyses not providing any additional benefit for non-normally distributed data (Blanca, Alarcon, Arnau, Bono, & Bendayan, 2017). This is true even for groups with unequal sample sizes, as is the case with the present study. In instances where the sphericity assumption was violated for the repeated measures factor, a Greenhouse-Geisser correction was applied.

A 3 X 2 mixed ANOVA, with the three episodic events as the repeated measures factor and temporal strategy (*when* vs *HLA*) as the independent factor, was performed for temporal estimation errors. The same analysis was repeated using only temporal estimation errors from memories where the non-temporal components were correctly recalled. *Post-hoc* comparisons using Bonferroni corrections were conducted on significant main and interaction effects. Bonferroni corrections were carried out in the usual way by dividing the p-value by the number of comparisons. Mann-Whitney *U* tests were conducted on the accurate recall for each of the three non-temporal *what, where* and *what and where* episodic features across the three episodes. Chi-square tests of association were conducted between the two temporal groups to assess whether there was a significant difference in the proportion of participants who correctly recalled non-temporal episodic aspects across all three episodes. A binomial test from chance was used to assess whether there was a preferred temporal strategy in the *free choice* condition. All analyses were performed using IBM SPSS Statistics 26.0®.

Results

Temporal estimation errors

We first examined temporal estimation errors to see how accurate participants were at recalling the time at which an episode had taken place depending on the strategy employed. If human episodic memory relies primarily on location-based strategies, then we would expect memories based on this *when* strategy to be more accurate. Figure 1a. shows that this was not the case with no systematic difference between the groups as evidenced by no significant main effect of strategy ($F_{(1, 45)} = 3.79$, $p = .058$, $\eta_p^2 = .078$). Accuracy of temporal judgements for the three episodes did not change significantly across the testing session demonstrated by a non-significant main effect of episode ($F_{(1.66, 74.50)} = 1.11$, $p = .325$, $\eta_p^2 = .024$). Interestingly though, there was a significant episode x strategy ($F_{(1.66, 74.50)} = 10.60$, $p < .001$, $\eta_p^2 = .191$) interaction. *Post hoc* tests revealed that this interaction effect was primarily driven by a difference in performance between the two strategies at episode three. Independent sample *t*-tests revealed that using a *when* relative to a *HLA* strategy at episode three resulted in significantly greater temporal error judgements ($t_{(45)} = 3.79$, $p < .001$). Differences in temporal errors between the two strategies were non-significant at episodes one ($t_{(45)} = -0.59$, $p = .556$) and two ($t_{(45)} = 0.48$, $p = .632$). This clearly demonstrates that the predicted increased accuracy by those using a *when* strategy was not found. Indeed, the only significant difference between the groups was an interaction driven by increased accuracy of the HLA group at timepoint three.

Additionally, one-way ANOVAs revealed a significant difference in temporal error judgements across episodes for participants using both *when* ($F_{(2, 30)} = 6.84$, $p = .004$, $\eta_p^2 = .313$) and *HLA* ($F_{(1.60, 47.92)} = 4.49$, $p = .023$, $\eta_p^2 = .130$) strategies. Bonferroni-corrected pairwise comparisons showed that significantly greater temporal errors were made for those employing a *when* strategy at episode three relative to episodes one ($M = -6.82$, $SE = 2.43$, $p = .040$) and two ($M = -6.63$, $SE = 2.09$, $p = .019$). There was a similar but opposing pattern of results for those adopting a HLA strategy, with participants making significantly greater temporal errors at episode one relative to episode three ($M = 4.68$, $SE = 1.77$, $p = .039$). Overall, participants adopting a *when* strategy made significantly greater temporal estimation errors by specifically overestimating the time at which episode three took place.

We next went on to examine signed temporal estimation errors to see whether there was systematic under or over-estimation of when events took place. Figure 1b shows that temporal judgements were more accurate using a *HLA* than a *when* strategy, again contrary to our initial prediction. This higher accuracy was seen for every episode and was confirmed by a significant main effect of strategy ($F_{(1, 45)} = 6.98$, $p = .011$, $\eta_p^2 = .134$). Accuracy of temporal judgements for the three episodes did not change significantly across the testing session demonstrated by a non-significant main effect of episode ($F_{(1.47, 66)} = 2.86$, $p = .080$, $\eta_p^2 = .060$). Consistent with the unsigned analysis there was, however, a significant episode x strategy ($F_{(1.47, 66)} = 3.69$, $p = .043$, $\eta_p^2 = .076$) interaction on temporal estimation errors. *Post hoc* tests again confirmed that this interaction effect was primarily driven by a decrease in the performance of participants employing a *when* strategy at episode three. Independent sample *t*-tests revealed that using a *when* relative to a *HLA* strategy at episode three resulted in significantly greater temporal error judgements ($t_{(45)} = -3.60$, $p < .001$). Differences in temporal errors between the two strategies were non-significant at episodes one ($t_{(45)} = 0.92$, $p = .365$) and two ($t_{(45)} = 1.43$, $p = .160$). Additionally, one-way ANOVAs revealed a significant difference in temporal error judgements across episodes for participants using a *when* ($F_{(2, 30)} = 4.51$, $p = .019$, $\eta_p^2 = .231$) but not a *HLA* ($F_{(1.30, 38.96)} = 0.83$, $p = .398$, $\eta_p^2 = .027$) strategy. Bonferroni-corrected pairwise comparisons showed that significantly greater temporal errors were made for those employing a *when* strategy at episode three relative to episode one ($t_{(15)} = -2.74$, $p = .015$). There was no significant difference in temporal errors made between episodes one and two ($t_{(15)} = -1.35$, $p = .198$) or episodes two and three ($t_{(15)} = -1.72$, $p = .106$). Overall, participants adopting a *when* strategy made significantly greater temporal estimation errors by overestimating the time at which an episode took place (Figure 1b), although it is clear from the interaction that this effect is primarily driven by a difference in accuracy between groups at timepoint three. These analyses were conducted on data collapsed across free and forced choice but the difference in temporal accuracy was maintained when we examined forced choice only ($t_{(31)} = -2.48$, $p = .019$).

Temporal strategy choice

While it is clear that participants' accuracy in making temporal judgements was better when forced to use a *HLA* strategy, it could be the case that this strategy is not routinely employed by humans remembering episodes from their lives. To test this, we examined which strategy participants voluntarily chose to adopt in the *free choice* condition. A binomial test indicated that the proportion of participants who chose a *HLA* strategy *(.860)* was significantly above chance [.500; p = .013; Figure 2a]. Within this group the temporal estimation errors between the *when* and *HLA* participants showed the same pattern as in the forced choice condition [Figure 2b-e]. Additionally, and in line with the data shown in Figure 1, participants tended to overestimate *when* but not *how long ago* an episode took place. Again, this effect is driven by an interaction whereby the *when* group overestimated the time at which event three took place.

One issue related to the strategy choice of those in the free choice condition is that it created unequal group sizes in the main analysis of temporal estimation error. To determine the likelihood of the reported effects persisting in groups of equal size, we ran bootstrapped Monte Carlo simulations using random selections without replacement of 16 out of the 31 participants in the *HLA* group, comparing them to the 16 participants in the *when* group. For each simulation we ran the same ANOVA as we had previously used on the unsigned data, but this time with equal group sizes and without Greenhouse-Geisser adjustments to the degrees of freedom. This was repeated 100,000 times. The proportion of matches between these simulations with equal group sizes and the original analyses were: Between subjects effect matches: 76.6%, Within subjects effect matches: 99.7%, Interaction matches: 99.7%.

Accuracy of non-temporal episodic features

One potential explanation for the difference in temporal accuracy is that *HLA* judgements are used to support simpler non-episodic memories whereas memories supported by *when* judgements come with the rich contextual detail associated with episodic memory. If this is the case, we would expect memories driven by *when* judgements to be associated with greater accuracy for the non-temporal features of episodic memory. To test this, we examined whether memories supported by *HLA* and *when* strategies were similarly accurate for the non-temporal contents of the memory. Figure 3 depicts the proportion of participants in both groups who correctly recalled non-temporal episodic features across the three episodes. Mann-Whitney U tests were conducted on the accurate recall for each of the three non-temporal *what, where* and *what and where* episodic features. For the *what* episodic features, there was a significant difference in recall accuracy between the two groups at episode one ($U = 323.50$, $z = 2.04$, $p = .042$) but not at episodes two ($U = 247.50$, $z = -0.03$, $p = .979$) and three ($U = 255.00$, $z = 0.29$, $p = .769$). At episode one, *what* recall accuracy was significantly higher for participants in the *HLA* group (mean rank = 26.44) compared to those in the *when* group (mean rank = 19.28). For the *where* episodic features, there was no significant difference in recall accuracy between the two groups at episodes one ($U = 253.00$, $z = 0.14$, $p = .893$), two ($U = 269.00$, $z = 0.58$, $p = .559$) and three ($U = 246.00$, $z = -0.06$, $p = .953$). Similarly, for the *what and where* episodic features there was no significant difference in recall accuracy between the two groups at episodes one ($U = 299.50$, $z = 1.35$, $p = .177$), two ($U = 269.00$, $z = 0.58$, $p = .559$) and three ($U = 261.50$, $z = 0.39$, $p = .696$). Overall, participants in the *when* group showed poorer recall, relative to their *HLA* counterparts, specifically for *what* happened towards the start rather than the middle or end of the experiment. This indicates that aspects of episodes that happened further back in time were recalled with reduced accuracy while using a *when* strategy. There was no difference between groups on recall accuracy for *where* and *what and where* aspects across all three episodes. Taken together, these results are not consistent with the suggestion that memories supported by *HLA* judgements, are simpler and lacking in contextual details.

Another potential issue is that the previous findings of increased temporal accuracy in *HLA* may be driven by memories that do not contain fully accurate recall of integrated episodes. To test this, we assessed whether there was a difference in temporal accuracy when using different temporal recall strategies specifically on trials where non-temporal episodic aspects were correctly recalled. Consistent with our previous analysis, there was main effect of strategy ($F_{(1, 39)} = 5.00$, $p = .031$, $\eta_p^2 = .114$) with participants using a HLA strategy making more accurate temporal judgements relative to their *when* counterparts. Therefore, even in specific cases where participants accurately recalled all features of an integrated episode, adopting a *HLA* strategy resulted in significantly more accurate temporal judgements [Figure 4]. There was no main effect of episodic feature ($F_{(1.69, 65.87)} = 1.64$, $p = .204$, $\eta_p^2 = .040$) or episodic feature x strategy ($F_{(1.69, 65.87)} = 1.14$, $p = .319$, $\eta_p^2 = .028$) interaction effect. These results were obtained using unsigned temporal error data. The same pattern of results was observed when signed temporal error data were analysed [strategy: ($F_{(1, 39)} = 9.53$, $p = .004$, $\eta_p^2 = .196$); episodic feature: ($F_{(2, 78)} = 0.24$, $p = .787$, $\eta_p^2 = .006$); episodic feature x strategy: ($F_{(2, 78)} = 0.20$, $p = .818$, $\eta_p^2 = .005$)].

One of the key characteristics of episodic memory is integration of features to form a coherent representation of a specific event. Another useful line of enquiry, therefore, is to ask whether the two strategies produce fully integrated *what, where,* and *when* memories. To test this, we compared the proportion of participants who correctly recalled all the episodic aspects for all three episodes and whether this differed depending on the type of temporal strategy adopted. Chi-square tests revealed there was a significant association between strategy and the proportion of participants who correctly recalled all three pairs of *what and where* episodic features ($\chi^2(1) = 3.92$, $p = .048$), with .484 of participants in the HLA group correctly recalling all *what and where* episodic features from the experiment compared with .188 of participants in the *when* group. In contrast there was no significant association between strategy and the proportion of participants who correctly recalled either all *what* ($\chi^2(1) = 2.52$, $p = .112$) or all *where* ($\chi^2(1) = 1.27$, $p = .260$) episodic features. These results point specifically to a *HLA* strategy in facilitating the integration and accurate recall of multiple episodic features.

Discussion

Temporal judgements of when an event occurred have been suggested to be a critical feature of episodic memory (Clayton et al., 2003; de Kort et al., 2005; Roberts, 2002; Roberts et al., 2008; Tulving, 1983). These temporal judgements can either be supported by distance-based strategies, where the time of an event is inferred from the relative memory strength, or by location-based strategies where source information from the encoding event is retrieved to provide a temporal context (Friedman, 2001). Here we tested the suggestion that episodic memory is supported by location-based temporal judgments in humans (Roberts et al., 2008). We report three key findings. Firstly, there was an interaction between temporal strategy and time of episode such that participants using distance-based strategies were significantly more accurate than those making location-based temporal judgments for recently experienced events. There was no difference in accuracy between those using different temporal strategies for events experienced less recently. Secondly, given a choice, most participants used a distance-based strategy to report when an event took place. Thirdly, a greater proportion of participants using a distance-based temporal strategy correctly recalled all *what and where* non-temporal episodic features. These data clearly show that in conditions outlined in the present study, distance-based judgements are more accurate for more recently experienced events and also the preferred method of remembering when an event took place.

The main finding of the study is the significant interaction of strategy and event such that participants asked to remember when something happened using a location-based *when* strategy were less accurate for events that were recently experienced compared to participants using a distance-based *HLA* strategy. There was no difference between the groups for events experienced less recently. One potential reason for the difference between the groups is that the *when* strategy involves the additional cognitive load of calculating the precise clock time relative to the last known time, the start of the experiment. This additional load could introduce error due to increased demands not present for the *HLA* group. It is possible that if we asked participants to use a different location-based strategy based on internal representations of time that this cognitive load would be reduced, and that temporal estimation may improve. Further studies would be needed to examine whether location-based strategies not based on clock time would produce similar results to the current study.

Another interesting issue is that the *HLA* group may use a different reference point from which to estimate elapsed time, the current time. This raises the possibility that both groups may be using the same distance-based temporal strategy for estimating elapsed time but anchored to different reference points. As distance-based strategies will accumulate error with time this would explain the difference in accuracy at time point three as this is close to the reference point for the *HLA* group and far away from the reference point for the *when* group. If this were the case, however, we would expect to see an equivalent difference in temporal accuracy at timepoint one where the *when* group would be expected to more accurate than the *HLA* group as they are making judgments close to their reference point. The fact that there is no difference between the groups at timepoint one argues against this suggestion, however, and suggests that the two groups are not using the same distance-based time estimation strategy.

Another issue that could affect the recall of multiple events in time is salience of these events. More salient events could be remembered more clearly and improve the ability to remember details accurately. Given that the order of the events was kept constant across groups and conditions this would leave open the possibility that differences in salience of the events could affect memory above and beyond temporal recall strategy. However, the key comparisons in the study were across groups and as such any issues caused by differential salience of events would equally affect both groups.

A final methodological consideration is potential bias introduced by providing inaccurate information regarding the duration of the experiment. Information provided to the participants indicated that the experiment would last 90 minutes when in fact the experiment lasted 45 minutes. When making temporal judgements participants might then be biased by their belief that the experiment had indeed lasted 90 minutes. As previously noted participants making *when* judgements might use the start of the experiment as a reference point. This start time could be combined with the advertised experiment duration to give another reference point for when the experiment was supposed to finish. This could manifest as participants in the *when* condition biasing their temporal judgements for the later events towards this reference point which could provide a potential explanation for the decreased performance by the *when* group reported here. However, if participants are biased by the misleading advertised experiment duration, we would also expect those making *HLA* judgements to also be affected. This would manifest in those making *HLA* judgements as increased error at the first time point as they would be biased towards adding more time to their reference point which is the end of the study. The fact that we do not see this argues against the data being explained by bias. It is possible that *when* judgements are affected by bias whereas *HLA* are not but this would be consistent with the main conclusion that *HLA* is a more accurate (less prone to bias) method of making temporal judgements in humans.

While participants in the current study were instructed which temporal strategy to use, there was nothing stopping them from using another strategy to help support memory retrieval. Those instructed to use *when* judgements duly did so despite this resulting in a larger error. These participants could have used a *HLA* strategy and then attempted to convert this into a *when* judgement to improve accuracy. The failure of convergence at the very least suggests that these processes are based on separate mechanisms that do not spontaneously cue each other to produce the most accurate memory. Alternatively, the convergence failure could be a metacognitive failure to evaluate the accuracy of these judgements to identify the strategy that most likely produces the correct response. This possibility could be tested by taking confidence judgements following both *when* and *HLA* judgements to evaluate our knowledge of the accuracy of our temporal judgements. A final possibility is that participants forced to make *when* judgements typically did use a *HLA* strategy and the resulting temporal estimation errors resulted from poor conversion of *HLA* judgements into *when* judgements. However, the pattern of results seen with the free choice group indicates that even participants who actively chose a *when* strategy were poorer at making temporal judgements than those adopting a *HLA* approach.

The present findings show that distance-based temporal judgments can be used to support the retrieval of integrated representations of an event. This is consistent with previous studies that have shown that integrated representations of what-where-when

(Easton, Webster, & Eacott, 2012) and temporal source memory (Persson et al., 2016) can be retrieved using familiarity or distance-based temporal strategies. However, these findings violate the standard assumptions of source memory under the dual process theory, which suggests that source memory can only be retrieved using a recollection strategy (Yonelinas, Kroll, Dobbins, & Soltani, 1999). This either suggests that distance-based temporal strategies for remembering when an event took place do not map exactly onto the familiarity-based retrieval process defined in dual process theory or that in circumstances where recollection is accompanied by high familiarity that familiarity could be used as a temporal source. These memories would clearly be episodic as they describe integrated representations of trial unique experiences. However, these memories would include a distance-based judgement of when something happened. While we are certainly not arguing that the presence of accurate distance-based temporal judgements within a memory defines it as episodic it is clear that reliance on distance-based temporal judgments to support a memory does not necessarily detract from its episodic nature.

While the current study used a significantly different design to the animal studies that addressed the same issue, these findings are at odds with studies suggesting that a reliance on distance-based temporal judgements by animals performing episodic-like memory tasks is evidence that they process time in a qualitatively different way to humans (Roberts et al., 2008). Indeed, the current study suggests that under conditions with similar memory demands both humans and rats are more accurate when using distance-based temporal judgements and will choose to use distance-based temporal judgements over location-based ones to support recall of integrated features of an event. Additional studies could strengthen this argument further using an experimental design that more accurately mimics the animal studies, e.g. memory testing based on observation of memory-guided behaviour rather than the reporting of time to a verbal cue. This would involve long periods of trial and error training, as in the animal studies, but would serve to reinforce the current findings that human memory for temporal judgments is similar to that of animals when tested in a similar way. Despite this proviso, the current data are inconsistent with the suggestion that animals do not possess episodic memory because they rely on distance or familiarity-based temporal judgements (Clayton et al., 2003; Roberts et al., 2008). Further support for the suggestion that humans do not have a qualitatively different mechanism of remembering time comes from studies in rats demonstrating that they can remember the time of day that an event took place (location-based; Zhou & Crystal, 2009) and replay sequences of events in a manner that is independent of familiarity cues (Panoz-Brown et al., 2018).

Further support for the suggestion that distance-based temporal judgements can be used to support episodic memory comes from research examining the neural mechanisms underlying time perception in memory. Time cells in the hippocampus and entorhinal cortex of rats have been shown to encode elapsed time at the level of seconds, hours and days (Kraus et al., 2013; MacDonald et al., 2011; Mankin et al., 2012). However, these representations of time become less accurate as time from the event increases in a manner consistent with them providing distance-based information. These cells have also been shown to integrate information about specific trials and spatial location with time giving a neural mechanism at the level of the single cell for episodic integration. The fact that these cells are found within the hippocampus, a structure critical for episodic memory, suggests that distance-based temporal information can be an integrated feature of memory for an event.

The current study examines relatively short-term memory and while this is consistent with many lab-based studies of episodic memory it is possible that preference for distance-based temporal judgements, and increased accuracy when using them, would diminish at longer time intervals. Indeed studies have shown that distance-based temporal judgements are more prevalent for recently remembered events (Friedman, 1987; Huttenlocher, Hedges, & Bradburn, 1990) and that accuracy of location-based temporal judgments improves over time (Janssen, Chessa, & Murre, 2006). However, this does not detract from the current findings and their relevance to our comparative understanding of temporal judgments in humans and animals. It would be interesting to examine whether reliance on distance-based temporal judgements changes in humans and animals over longer timescales.

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Declaration of interest

The authors declare that they have no conflict of interest.

Data availability

The data that support the findings of this study are available from the corresponding author, JAA, upon reasonable request.

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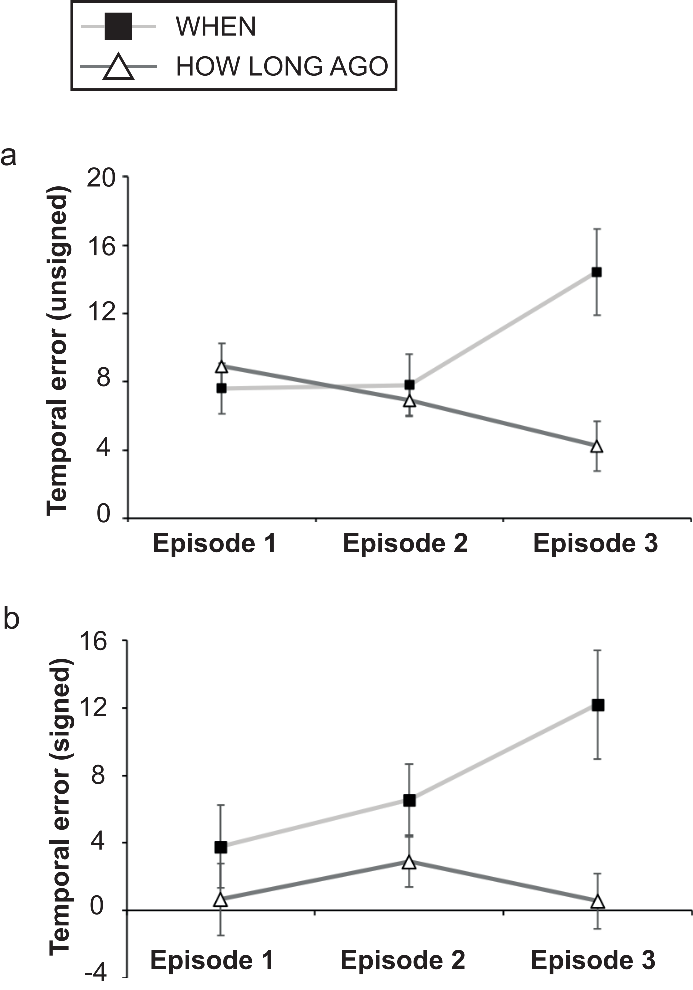
Figure captions

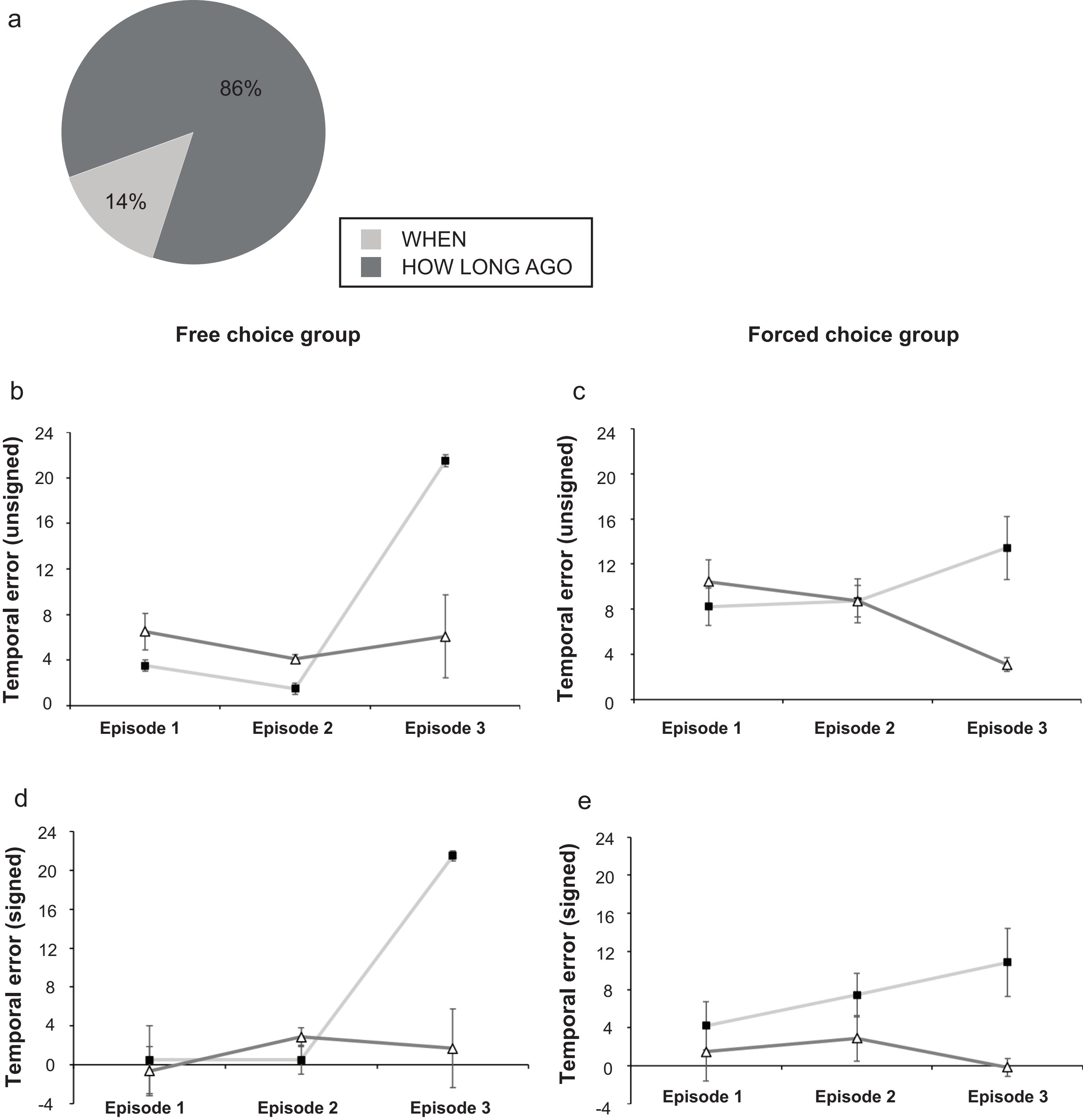
Figure 1. Temporal accuracy in the *when* and *HLA* conditions. (a) Mean unsigned temporal error for each episode using either a *when* or *HLA* strategy. (b) Mean signed temporal error across all three episodes. Negative values imply an underestimation of time. Error bars in all figures represent the standard error of the mean.

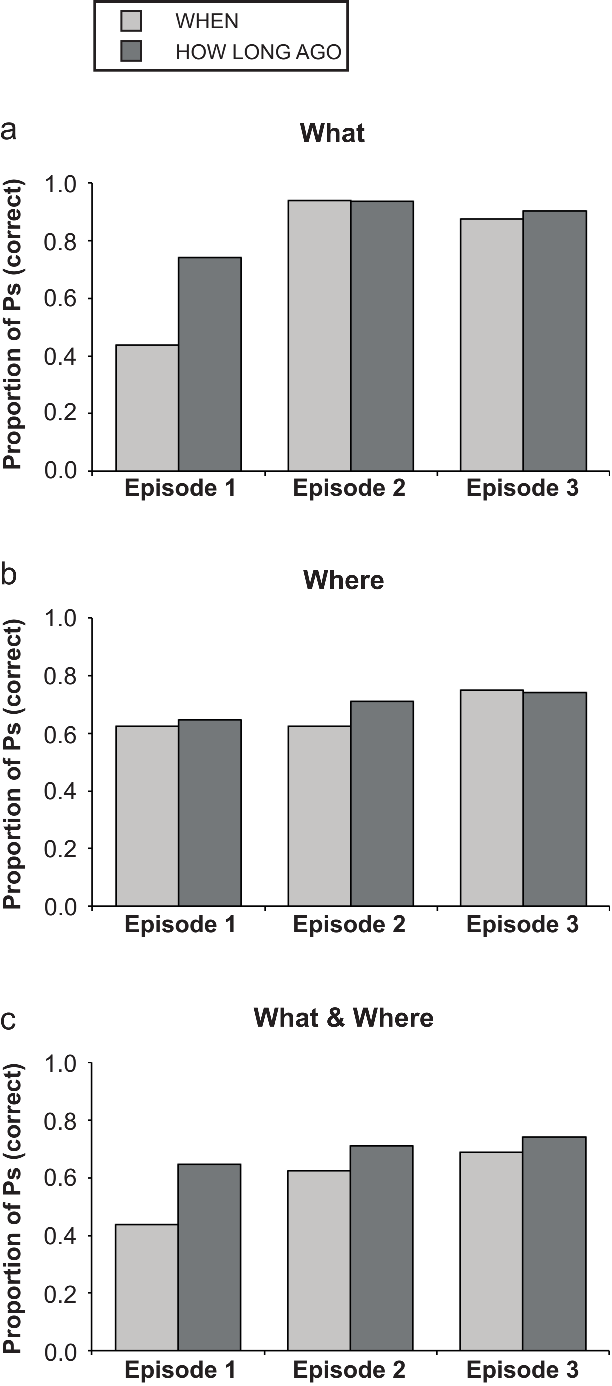
Figure 2. Performance on temporal accuracy by participants in either the free choice (either *when* or *HLA* time strategy) or fixed choice conditions (*when* versus *HLA* time strategy). Error bars in all figures represent the standard error of the mean. (a) Participants preferentially adopted a *HLA* temporal strategy for episodic recall in the free choice group. (b,d) Mean signed and unsigned temporal estimation errors in the free choice group and (c,e) forced choice groups. Mean temporal estimation errors follow a similar trend in both the free and forced choice groups with participants overestimating time of episodic events while using a *when* strategy at episode 3.

Figure 3. (a-c) Proportion of participants across the two temporal strategies who correctly recalled aspects of episodes (*what*, *where* and combined *what* and *where*).

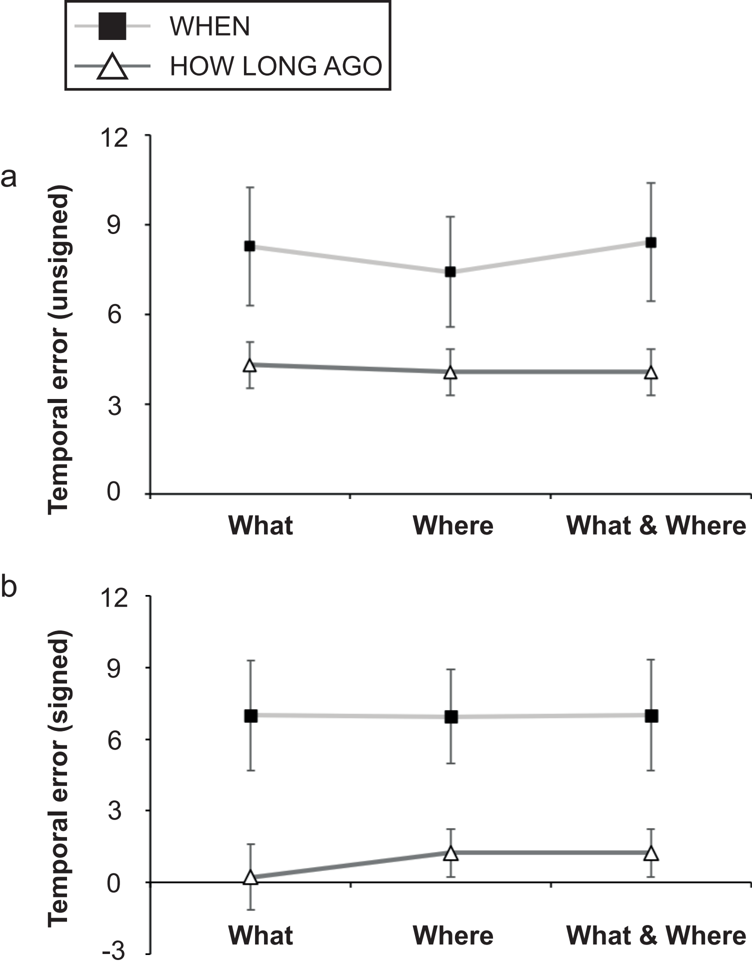
Figure 4: (a) Unsigned and (b) signed performance on temporal accuracy for correctly judged aspects of episodes (what, where and combined what and where) by participants using two different recall strategies.

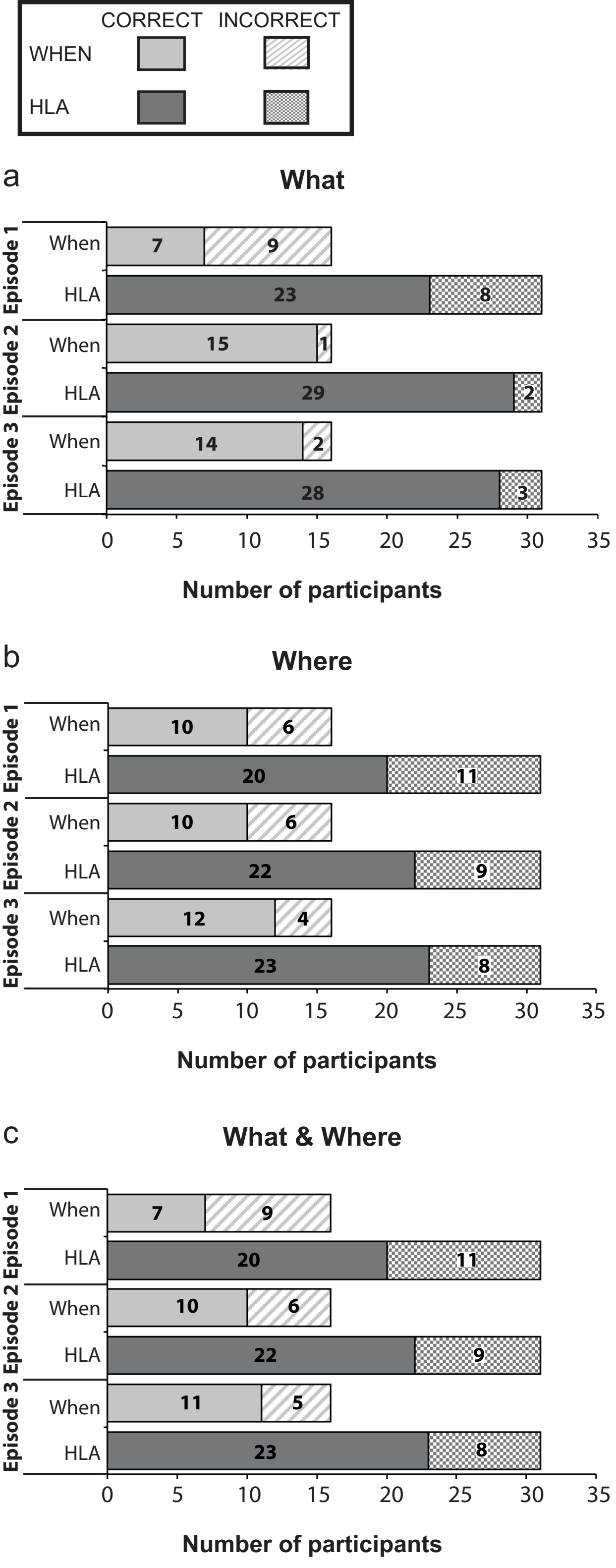

WHEN
HOW LONG AGO
a
Temporal error (unsigned)
20
16
12
8
4
0
Episode 1
Episode 2
Episode 3
b
Temporal error (signed)
16
12
8
4
0
-4
Episode 1
Episode 2
Episode 3


a
86%
14%
WHEN
HOW LONG AGO
Free choice group
Forced choice group
b
c
d
e
Temporal error (unsigned)
Temporal error (signed)
24
20
16
12
8
4
0
-4
Episode 1
Episode 2
Episode 3



WHEN
HOW LONG AGO
a
What
b
Where
c
What & Where
Proportion of Ps (correct)
1.0
0.8
0.6
0.4
0.2
0.0
Episode 1
Episode 2
Episode 3


WHEN
HOW LONG AGO
a
Temporal error (unsigned)
12
9
6
3
0
What
Where
What & Where
b
Temporal error (signed)
12
9
6
3
0
-3
What
Where
What & Where


CORRECT
INCORRECT
WHEN
HLA
a
What
Episode 1
When 7 9
HLA 23 8
Episode 2
When 15 1
HLA 29 2
Episode 3
When 14 2
HLA 28 3
0 5 10 15 20 25 30 35
Number of participants
b
Where
Episode 1
When 10 6
HLA 20 11
Episode 2
When 10 6
HLA 22 9
Episode 3
When 12 4
HLA 23 8
0 5 10 15 20 25 30 35
Number of participants
c
What & Where
Episode 1
When 7 9
HLA 20 11
Episode 2
When 10 6
HLA 22 9
Episode 3
When 11 5
HLA 23 8
0 5 10 15 20 25 30 35
Number of participants