When to Use it, When to Lose it: The Effect of Retention Interval Cues on Memory Accessibility over Time

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Abstract

How we retrieve previously learned information is crucial in long-term memory research. One of the remaining questions is how the ‘temporal context’ prompted by the length of a memory retention interval influences this retrieval process. This ‘temporal context’ for memory retrieval has thus far been interpreted to help individuals leverage the knowledge of when information about an item or event was initially encountered during memory retrieval. We aim to investigate the cognitive strategies individuals employ when navigating temporal contexts during both the encoding and retrieval phases of memory and what strategies participants utilise to access temporal contextual information.

Building upon prior work by Otten et al. (2006), which suggests that providing cues about retention intervals during encoding impacts later retrieval, and insights from Bright et al. (2022), indicating that during retrieval, individuals scan their mental timeline for relevant information, this study employs a continuous recognition task with two experimental variants, where cues informed the participant of the likely duration of the retention interval (short or long), either at encoding or at retrieval. Our findings reveal a significant influence of cue type on HR in the encoding variant and an emerging trend for a cue type effect on RT in the retrieval variant. These results support the notion that individuals employ distinct strategies during encoding and retrieval when using temporal contextual cues for memory retrieval. Ultimately, this study provides valuable insights into the potential advantages of utilising retention interval cues to facilitate memory retrieval.

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Long-term memory is the silent keeper of our memories and experiences, a helper in navigating our lives. However, one challenge that arises is anticipating when previously encountered information will become relevant to us again. Whether we have to remember where we parked our car on a busy street before going to work or where we filed our bills to do our taxes annually, we rely on strategies to ensure we can access relevant information when needed. For German law students, the journey toward becoming fully qualified lawyers involves extensive study throughout their time as a university student, culminating in two final state exams. These exams cover various topics studied throughout their degree, with variations in subject matter and exam duration depending on the German county. Notably, students are not informed about which years of their degree the exam topics are drawn from. This raises the question: Would providing cues regarding the duration of material retention or the academic year from which the material is sourced help German law students' ability to access the proper knowledge at the right moment?

The present experiment will investigate this question by building upon previous research by Coppes and Kruijne (2023). The researchers conducted a study focussing on the expectation of when memory would be tested and whether this influences memory retention over time. Their study sheds light on the control over temporal preparation before and during memory retrieval. It highlights potential strategic control over memory encoding based on expectations of when information is needed. The study examined memory retention during a continuous recognition task, focussed explicitly on the encoding stage, using unfamiliar American city names. Words were presented with cues (the colour and positioning of each word) that indicated whether a word would appear early or late in the trial sequence. These cues were provided at the first presentation (study) and the second presentation (test). The results indicated that cues influenced reaction times at study and test, with quicker responses for cued 'long' intervals without affecting accuracy. Moreover, using the EZ-Diffusion Model, which combines reaction time and hit rate results in a single model, the authors concluded that the cues also influenced non-decision time, with ‘short’ retention cues having a longer nondecision time. Non-decision time is the time between stimulus onset and reaction to the stimulus, in this case, through key press. However, the fact that repeated items would always be presented in the same font, colour and position as their previous presentation could have hindered drawing strong conclusions about the nature of the cue type effect, especially whether the cues affected memory processes during encoding or retrieval. Coppes and Kruijne (2023) opened the door for more questions regarding the effect of retention interval cues: What happens when retention interval cues are provided at encoding or retrieval separately? How do retention interval cues affect measures such as hit rate and reaction when provided separately for encoding or retrieval? This study explores how cues related to retention interval duration impact memory accessibility over time.

The present study employs two separate encoding and retrieval variants of a continuous recognition task to investigate the dissociable effects of retention interval cues at encoding and retrieval. We opted for this approach to distinguish differences in strategies employed by participants for temporal memory access during both the encoding and retrieval phases. The method section will elaborate on this in more detail. Coppes and Kruijne (2023) proposed that temporal accessibility at retrieval might occur by scanning our mental timeline for relevant information, suggesting that the existence of the cue might have sped up the mental timeline scanning for items that were cued ‘long’ by looking at reaction time results. Employing two different experimental variants in this study allows us to investigate this claim further. Our objective is to investigate whether the retention interval cues provided at encoding and retrieval help our participants retrieve relevant information by accessing the temporal context of memory. Moreover, we aim to highlight similarities and differences regarding possible strategies employed for encoding and retrieval.

Encoding, Maintenance and Retrieval

Memory consolidation involves three stages: encoding, maintenance, and retrieval. These three stages may have unique attributes but are ultimately connected. For instance, the relationship between encoding and retrieval is tied to the concept of neural reactivation of memory traces. The term 'memory trace' is used in cognitive psychology to describe alterations in the strength of neuronal connections brought about by activity-dependent synaptic plasticity (Takeuchi et al., 2014). The degree of similarity between the neural activation pattern during the encoding and retrieval phases is called pattern similarity. This similarity may determine how easily a stored memory can be retrieved (Ritchey et al., 2012).

Despite distinct cognitive processing, brain regions engaged during encoding and retrieval overlap. Long-term memory formation relies on the activity of several brain areas before, during and after encoding. Research has found that encoding is associated with higher activity in the prefrontal cortex (Rizio & Dennis, 2013), which modulates inhibitory response control and attentional processes (Dalley et al., 2004). Therefore, it encompasses the ability to filter and prioritise relevant information, essential for effective encoding (Blumenfeld & Ranganath, 2007). Concurrently, encoding is also mediated by activity in the medial temporal lobe (Rizio & Dennis, 2013), which, including the hippocampus and adjacent cortices, plays a crucial role in long-term memory, such as enabling encoded information to be maintained

(Squire et al., 2004; Tautvydaitė et al., 2021). Essentially, the frontal cortex, in connection with the medial temporal cortex, is believed to be vital in encoding and creating a lasting memory of the event (Buckner et al., 2000).

Remember the example of the German law students? They arrive on their exam day and can recall all the necessary information during their exam with minimal difficulty. Recalling an event is believed to involve a dynamic interaction between a ‘retrieval cue’ and the memory trace. This interaction subsequently facilitates the reconstruction of either specific aspects or the entirety of the event. A ‘retrieval cue’ can be self-generated or triggered by the environment (Mecklinger, 2010). Whether we then successfully remember something can depend on deciding to recall or dismiss the information, either presently or in the future, including selecting our memories goal-directedly (Tarder-Stoll et al., 2020). As mentioned previously, the degree to which the pattern similarity between encoding and retrieval overlaps influences how easily a stored memory can be retrieved (Ritchey et al., 2012). Therefore, it is unsurprising that some brain areas associated with retrieval are the same as during encoding: the prefrontal cortex and the medial temporal lobe (Nadel & Moscovitch, 2001; Rugg & Vilberg, 2013).

In memory studies, a distinction is sometimes made between retrieval and familiarity. Familiarity has been described as a step that precedes retrieval and reflects the ability to recognise an item or event as something previously seen or experienced. Familiarity can be experienced on a spectrum comprising accuracy and confidence. When retrieval is studied, this is often done by looking at retrieval as a categorical process, meaning it is assumed that memories can either be successfully or unsuccessfully recollected (Mickes et al., 2009). The distinction between retrieval and familiarity is encapsulated in what is known as the ‘dual-process model of recollection memory’, a concept introduced by Yonelinas (1994). It should be mentioned here that some researchers emphasise that the dual-process model is outdated and retrieval should also be regarded as a continuous process rather than a categorical one (Mickes et al., 2009; Slotnick & Dodson, 2005).

Luckily, the law students in our example could recall the contents of their studies on their exam day. However, there are instances when our memory seemingly fails us. Forgetting is a crucial aspect of memory research. Research on this topic has either taken the stance that forgetting is a natural decay process or is enabled by interference processes (Hardt et al., 2013). In fact, the more predominant view is the latter: The ability to recall relevant information is inherently linked to the ability to inhibit irrelevant information (Storm, 2011). The notion that forgetting is an active process has been captured by Anderson (2003) in his inhibition theory. This theory proposes that we make assessments about which information in memory might be relevant to us at the moment of memory retrieval. From this, we can actively inhibit competing or irrelevant information, which facilitates the ability to retrieve relevant information (Anderson, 2003). Inhibition of irrelevant information occurs in two main ways. First, right after we learn something, any new mental activity can weaken our memory, probably because it interrupts the process of strengthening new information (Wixted, 2005). Second, even when memory is fully formed and stored, it can still be hard to recall because of competing stimuli (Skaggs, 1933). Suppressing task- or situation-(in)appropriate memories while trying to retrieve learned information is called retrieval-induced forgetting (Mecklinger, 2010). Often, retrieval failure is not due to the permanent loss of an item but, as in Anderson's inhibition theory (2003), instead the interference caused by other items. Recent studies on retrieval-induced forgetting confirm that we are not just passive recipients of forgetting. Instead, we possess an inhibitory mechanism that aids retrieval by enabling us to navigate retrieval-induced forgetting (Storm, 2011).

In order to investigate control over memory retention and retrieval, a retention cue will be used in our experiment both at encoding and retrieval. How does the presence of such cues, related to the duration of a retention interval, affect retrieval? Electrophysiological studies using EEG have shown that the neural response triggered at frontal electrodes by a cue given immediately before a to-be-memorised word can predict the likelihood of that word being remembered in a subsequent memory test (Otten et al., 2006). Participants' EEG was measured during a task in which cues were presented just before the onset of a word. During analysis, EEG data was turned into event-related potentials (ERPs) by averaging according to whether an item was remembered or forgotten. The researchers found a pre-stimulus effect visible in more negative deflecting ERPs in frontal areas of the brain for cues before words later remembered compared to words later forgotten. Similarly, more positive deflecting ERPs at stimulus presentation for words that were remembered later compared to words that were forgotten. Otten et al. (2006) conclude that whether a lasting memory trace is formed depends on the interaction between neural activity directly elicited when a stimulus is provided and the activity elicited pre-stimulus. The authors call this activity pre-stimulus a ‘neural context’ for an event. Likewise, Schneider and Rose (2016) have compellingly illustrated that the brain activation triggered by a cue presented before a stimulus can be interpreted as a strategic preparation for said stimulus. In their recognition task, participants were split into two groups. Both groups were presented with a series of pictures, which they had to classify as either animate or inanimate. One group was told about the upcoming task and thereby enabled to encode the pictures intentionally, with the knowledge about the task. The other group received no information and only incidentally encoded the information presented to them. The researchers measured pre-stimulus EEG stimulation and found that the intentional encoding group showed a stronger low beta band activity. They concluded that brain activation can be triggered voluntarily if the intention to encode a stimulus is given.

Given our understanding of retention cues, we now look into why the control we can exert over the timing of memories is essential to the present study. In order to remember past events, we need to recall the general time frame in which they took place and the specific time-related connections between items or events (DuBrow & Davachi, 2014). Howard and Kahana (2002) introduced the Temporal Context Model (TCM), which describes explicitly how a context changes over time and how it affects memory. A key role in TCM is that memory is characterised as a process by which newly memorised items are associated with activity shaped by items or events that preceded the context. As such, encoding a new item changes an ongoing context, chaining past events together through associations. TCM helps explain why we remember some items or events better than others and why our memory can be better if we have seen or heard them recently. In other words, it can explain the recency effect. Moreover, TCM helps explain that when trying to remember the order of items, people show signs of mentally revisiting the items in between. This suggests that retaining the order of things involves reactivating memories of what happened in between (Howard & Kahana, 2002; DuBrow & Davachi, 2014). Not only can this be explained in the context of temporal memory, but Folkerts et al. (2018) also researched epilepsy patients who performed an item recognition task. They were asked to rate their confidence in having seen an animal in photographs presented to them. Using implanted electrodes, the researchers measured activity in the medial temporal lobe during encoding and retrieval. Folkerts et al. (2018) found that neural activity in this area during retrieval reinstated the temporal context from the first presentation for well-remembered photographs, suggesting a "jump back in time" during memory reactivation. This relates to a ‘chained’ timeline of events, as Howard and Kahana (2002) suggested: An ongoing creation of a link between the concurrent activity and the new incoming information gives rise to the context necessary for memory recall.

Research has taken this idea one step further: Imagine a library with a single, ever-expanding shelf. Each new piece of information is a book that gets added to the front of the shelf. As more books are added, the older ones get pushed further down the shelf, symbolising their progression into the past. The question arises: Do we intuitively know the importance of certain information and know where to find it in our ‘bag of memories’, or do we scan through our mental timeline to locate the knowledge we desire? Three recent studies have addressed this specific question. For the purpose of this study, we describe one of these in detail and only add what is relevant from the other two papers. Bright et al. (2022) used a continuous recognition paradigm. They asked participants to recognise pictures initially presented and repeated after a certain amount of lag in six experiment variants. The article explores why recollections from the distant past take longer to access than those of the recent past. The authors consider the hypothesis that memory retrieval requires a recovery of temporal context. They hypothesise that the time to recover this context goes up with the logarithm of the time since the context was experienced, which is directly derived from TCM. This increase would be more prominent for more recently repeated items than items repeated much further in the past. They concluded that, indeed, reaction time increases with lag, and the hit rate decreases with lag. More specifically, the reaction time for a repetition of an item consistently depended only on the time the item was shown previously. Based on this evidence, they propose that the increase in reaction time is not only due to a decay of memory trace strength, meaning forgetting. Instead, they propose that individuals scan along a mental timeline to judge the recency of an item or event and use this strategy to find the required item to retrieve. Singh et al. (2017) used a repeat detection task in which participants were asked to indicate whenever a photo of an item was repeated. A repeat detection task differs from a continuous recognition task in that it aims to see whether participants can detect a familiar item after repetition to see how robust recognition is. Their findings support the notion that we recover temporal context by scanning along a timeline to retrieve information with the same explanation offered by Bright et al. (2022). Lastly, Scofield et al. (2020) also researched this interpretation of the recency effect. Interestingly, they did not only look at behavioural data but also at electrophysiological correlates. Their behavioural findings again support the previous interpretations. Additionally, ERPs revealed that along with reaction times in ‘old’ trials, the delay of the left parietal old/new ERP effect increased as the lag increased. The left parietal old/new ERP effect is an ERP correlate associated with the occurrence of successful recollection (Vilberg & Rugg, 2008).

The idea that we scan our mental timeline to locate memories is intriguing because it entails that we engage in strategies about the temporal context of information for memory retrieval that individuals might, to a certain degree, be able to engage in voluntarily. The extent to which we engage in such a strategy might have implications for our understanding of the relevance of cueing the context for memory retrieval and practical consequences for educational, personal or business settings. Our experiment is constructed in a way that one of the two experimental variants, namely our variant ‘Cued at Retrieval’, aims to address the questions brought about by Coppes and Kruijne (2023) in the discussion of their results. Our second experimental variant, ‘Cued at Encoding’, also addresses engaging in strategies benefitting memory retrieval when provided with a cue at encoding instead of retrieval. The present study asks whether the presence of such cues related to the duration of a retention interval influences the accessibility of memories over time. Moreover, we hope to shed some light on possible differences between the two variants and whether individuals engage with the cues provided differently depending on their presentation.

Method

Participants

A total of 127 students from the University of Groningen (Rijksuniversiteit Groningen) participated in this study (121 after filtering on performance, discussed below). The sample comprised 99 women, 27 men, and one person who chose not to disclose. Participants were between 17 and 35 years old. Sixteen indicated being left-handed, while 111 indicated being right-handed. Additionally, 124 participants reported normal or corrected-to-normal vision, while three reported having diagnosed degraded vision that was uncorrected at the time. Participants received study credit for participation. Based on set criteria outlined by the Ethics Committee of Psychology at the University of Groningen, the study was deemed low-risk and exempt from full ethical review. Participants provided informed consent before participating.

A power calculation analysis determined the sample size based on a separate pilot sample of 23 participants. The power analysis was performed using the simr package in R (Green & MacLeod, 2016). Effects on Hit Rate were evaluated separately per variant. Unexpectedly, the current study achieved the required participant count ahead of schedule. Once the desired sample size was reached, we tested another 76 participants, who were already scheduled to participate, in a follow-up experiment with longer retention intervals. No preliminary power analysis was conducted for this second experiment. The conclusions drawn from this second experiment will only briefly be discussed in the discussion section (for results, see appendix).

Study Procedure

Upon arriving in the lab, participants were given a verbal rundown of the study procedure and were asked to read the information and consent forms. They were then seated in a dimly lit, sound-attenuated cubicle at approximately 70 cm viewing distance from the screen. After consent was provided, task instructions were presented on the screen, indicating the structure of the experiment. Participants performed a continuous recognition task of 13 blocks of 100 trials each, separated by self-timed breaks between blocks. Participants were split into two groups, partaking in one of two different experimental variants. Variants and their differences will be detailed below. Group membership was counterbalanced and pseudo-randomly allocated by assigning variant types to even and odd participant numbers. A continuous sequence of items drawn from a set of American city names was shown during the task. Most items were shown once as a study trial and again at a different point in the sequence as a test trial. The overall sequence of items was constructed by considering the interval between study and test: Items were repeated after a short (after 8 – 13 trials) or long (after 20 – 25 trials) interval in the sequence.

Variant 'Cued at Encoding'

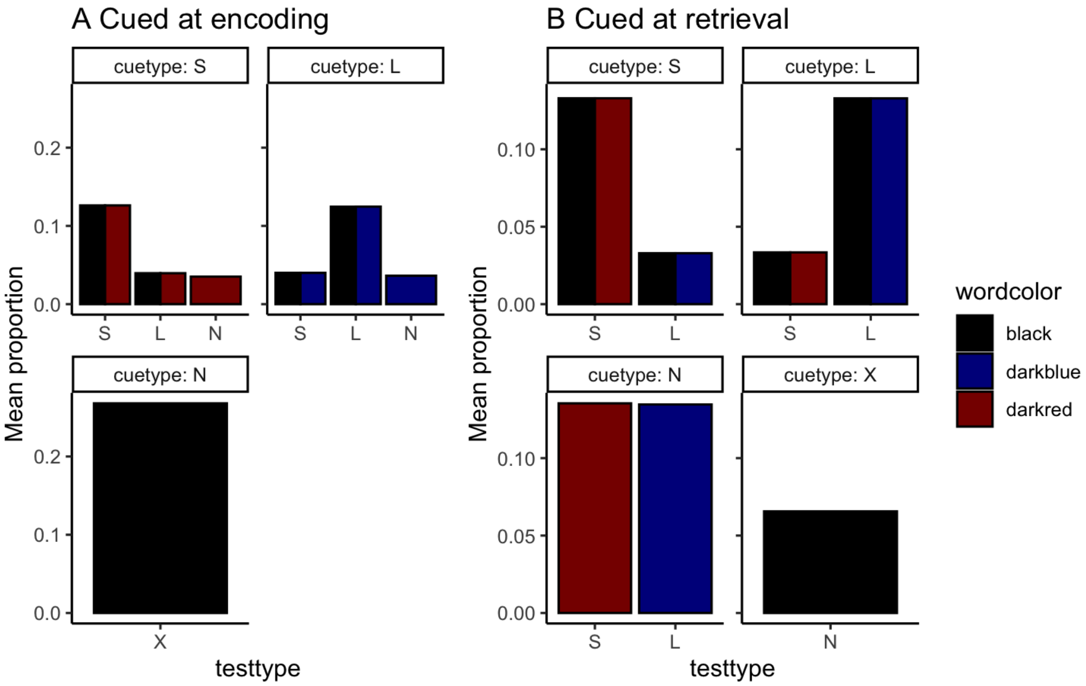
Within the variant 'Cued at Encoding', study items were either cued to be tested early or tested late. This cue was indicated to the participant via the colour (dark red vs dark blue) and position (above or below fixation) of the study item. The meaning of the colours and positioning was counterbalanced across participants. From now on, this will be referred to as the cue type. Test items were always shown in black, in the centre of the screen. Items could be tested after a short or long interval or as a singular test item without prior study at any point in the sequence. From now on, this will be referred to as test type. The encoding cue was usually valid. However, there was a proportion of items that were never cued but still tested, as well as cases where an early cue resulted in a late test and vice versa. The experimental trial sequences were constructed by positioning trials of various types within the sequence until the entire experiment sequence was filled. Not all trial types occurred equally often for each participant due to the individual construction of the sequence. Figure 1 shows how frequently, on average, combinations of cue and test type and singular lures occurred in the trial sequence. In variant ‘Cued at Encoding’ for cue type ‘short’, 25.2 % were valid cue type and test type pairs, 7.9 % were invalid pairs, and 3.5 % were not presented as pairs but as unique lures. For cue type ‘long’, 25.0 % were valid pairs, 8.0 % were invalid pairs, and 3.6 % were unique lures. 26.8 % were items that were never cued and only tested.

Variant ‘Cued at Retrieval’

The variant ‘Cued at Retrieval’ was almost identical to the variant ‘Cued at Encoding’, with the major difference that items were presented in black, at the centre of the screen, upon their first presentation but were cued (red/blue placed above/below fixation) at their second presentation. This means that participants were cued for having seen the item previously (at study) either a short or long interval back in time. Like the 'Cued at Encoding' variant, there were instances where certain items were studied but not tested, along with instances where items cued ‘short’ indicated that an item was studied long ago and vice versa. In variant ‘Cued at Retrieval’, Figure 1 illustrates that for cue type ‘short’, 26.6 % were valid pairs, and 6.6 % were invalid pairs. Additionally, 13.5 % were new items never studied but cued ‘short’ and, therefore, tested, and 13.5 % were new items never studied but cued ‘long’ and tested. For cue type ‘long’, 26.6 % were valid pairs, and 6.6 % were invalid pairs. 6.6 % were items that were solely studied.

Figure 1

Cue and test type combinations and singular lures on average



Note. In segment A, cue types are denoted as follows: 'S' indicates a cue for a short retention interval, 'L' for a long retention interval, and 'N' for never cued. Test types are represented by 'S' for testing after a short interval, 'L' after a long interval, 'N' for never tested, and 'X' for items only tested.

In segment B, cue types are similarly indicated: 'S' for ‘short’ cues, 'L' for ‘long’ cues, 'N' for items never studied, and 'X' for items never cued. Test types mirror those in segment A.

On each trial, participants had to indicate whether the item was ‘New’ (one they had not seen before) or ‘Old’ (one they had seen before). ‘New’ and ‘Old’ responses were given with the Z and M key on the keyboard. The meaning of the key was counterbalanced across participants. Participants were instructed to respond as fast and accurately as possible. Participants had a break between blocks where they were shown a screen containing information about their accuracy and average response time. Before the experiment, participants completed a practice block to familiarise themselves with the task. This trial block incorporated a predetermined sequence of 25 more widely recognised city names. In the practice block, all items were presented in black in the centre of the screen.

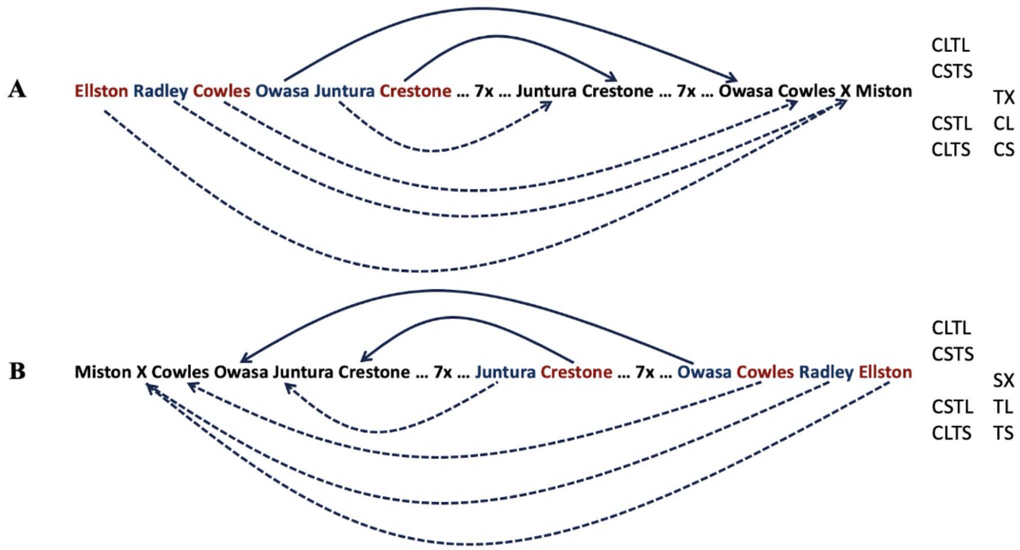
Sequence Presentation

Figure 2 illustrates a partial sequence of trials for both variants. For the sake of simplicity, Figure 2 illustrates a scenario where all cued (coloured) and non-cued (black) items appear consecutively. However, in reality, the sequence was much more mixed. Figure 2 A illustrates the variant ‘Cued at Encoding’. In this figure, dark red items represent ‘short’ retention interval cues, while dark blue items indicate ‘long’ retention interval cues. The direction of the arrows indicates the temporal meaning of the cues. Most cues are valid (solid arrows). For instance, ‘Owasa’ was cued ‘long’ and tested after a long interval (CLTL; valid pair). Invalid cues are shown with dotted arrows, for example, ‘Juntura’ cued ‘long’ yet tested after a short interval (CLTS; invalid pair). Additionally, some trials remain untested and are only presented as cues. For instance, consider ‘Ellston’, initially cued ‘short’ but never tested (CS; cue singles). Lastly, some items were never cued during the study phase but emerged as black, centrally presented new items. An illustrative example is ‘Miston,’ which is not featured as a study item but exclusively appears as a test item (TX; test singles).

For the Variant ‘Cued at Retrieval’ (B; Figure 2), the direction of the arrows illustrates that cues presented at test are informative about the retention interval that has just passed rather than what is to come. Overall, the labelling of study-test trial pairs and singularly presented items is identical to the variant ‘Cued at Encoding’.

Figure 2

Representation of a sequence for both variants



Note. Variant 'Cued at Encoding' (A) and variant 'Cued at Retrieval' (B).

Dark red represents cue type 'short'. Dark blue represents cue type 'long'.

Solid arrows indicate valid study-test pairs, dotted arrows indicate invalid study-test pairs and unique lures.

Stimuli

Stimulus Selection

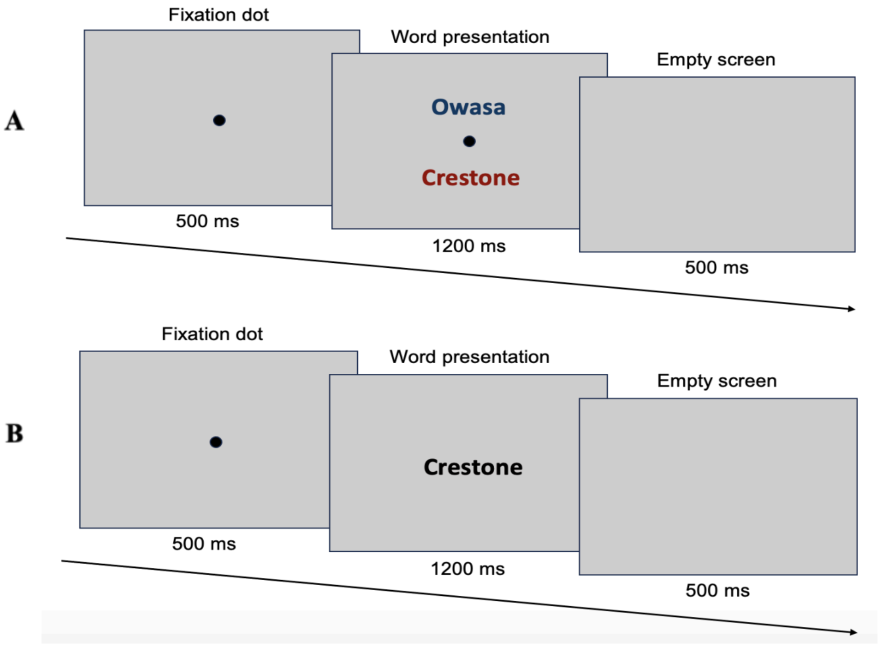
We employed identical stimuli and selection procedures per the methodology outlined by Coppes and Kruijne (2023). The items to remember during the continuous recognition task were American city names, which were pulled from a US Cities Database (https://simplemaps.com/data/us-cities). The list of cities was filtered based on several criteria: The population of each city had to be higher than ten, city names could not contain non-alphabetic characters, and the length of the city name had to be between five and ten characters. The 25 cities with the highest populations were used for the practice block. The 1200 cities with the lowest population count were used in the main experiment. Then, city names were randomly sampled across participants for both the practice and experimental blocks.

Presentation

The items were presented on a 768 x 1024 LCD screen. A grey screen served as a background, and text was presented in black unless it was a cue. The text was presented in mono font at a 22p font size. Figure 3 shows the trial structure for the 'cued trials' (A) and the 'non-cued trials' (B) separately to show what differentiates them. Participants were initially shown an instruction screen that explained the task objective, the meaning of the cues, and the pairing of the 'Z' and 'M' keys. At the beginning of each trial, an empty screen with a fixation dot appeared for 500 ms. Next, a city name appeared. Cued items were either dark red or blue and positioned above or below the fixation dot. On other trial types, items were presented in black. The city name remained on the screen for 1200 milliseconds, followed by an empty screen for 500 milliseconds. Responses had to be provided within a 1700-millisecond window after stimulus onset. Following this interval, a fixation dot onset signalled the start of a new trial.

Figure 3

Trial Sequence for 'cued' vs 'non-cued' trials



Note. For ‘cued trials’ (A), the word was presented either above or below the fixation dot and displayed in dark red or blue. For ‘non-cued trials’ (B), the word was initially presented in black in the middle.

Exclusion Criteria

Participants were excluded if they displayed outlier responses in more than 15% of the trials. Outliers were identified per participant separately. This was defined by computing log(RT) for each response and then determining cut-offs at three median absolute deviations away from the median. Four participants were excluded based on this analysis. Secondly, if the participant’s hit rate dropped below 43% (chance level performance), they were also excluded from the analysis. Thereby, two more participants were excluded.

Results

Hit Rate and Correct Rejections

Figure 4 provides an overview of the hit rate (HR) and correct rejections (CR) for the relevant study and test items. The HR is the proportion of trials where a participant correctly indicated an item as ‘old’. CR are trials where the participant correctly identified ‘new’ items. For HR and CR, a logistic regression model analysis was performed for both variants separately to examine the effects of cue type and test type and their interaction.

Variant ‘Cued at Encoding’

Table 1 summarises our model selection for HR based on the Akaike information criterion (AIC) for the Variant ‘Cued at Encoding’. The AIC is calculated from the number of free parameters and the maximum likelihood estimate, and a lower value indicates a better model. If a model is lower than another by 2 AIC unit points, the model with the lower AIC unit points is considered better.

For the analysis of HR of this variant, the best model is the interaction model of test type and cue type (Mtxc; see Table 1). We report statistics for individual predictors by excluding them with respect to this best model and comparing the models using a chi-square likelihood ratio test. Test type had a significant effect on HR (Mtxc vs Mc; $\chi^2(1) = 67.742$, $p < 0.001$). This test type effect is due to the recency of an item and is linked to forgetting. Figure 4 shows this effect in the higher HR for short than long retention intervals. Cue type significantly affected HR (Mtxc vs Mt; $\chi^2(1) = 8.893$, $p < 0.01$). Figure 4 shows this effect regarding whether items were cued 'short' or 'long', with a trend for 'long' cued items to have higher HR on average. The interaction between cue type and test type had a significant effect on HR (Mtxc vs Mtc; $\chi^2(1) = 4.927$, $p = 0.026$). Using a Tukey t-test on the estimated marginal means of the full model Mtxc, we specifically conclude that there is a significant cue type effect for items tested late, with long-cued items leading to a higher HR ($z = -2.990$, $p < 0.01$). This was not the case for items tested early ($z = 0.237$, $p = 0.995$).

For the analysis of CR of this variant, the best model includes a main effect of cue type (Mc; see Table 3). We concluded that there is a significant cue type effect (Mc vs M0; $\chi^2(1) = 735.280$, $p < 0.001$). Using the Tukey t-test on the estimated marginal means of the model Mc, we add to these results that the contrast between items cued 'short' and items presented in black ($z = 18.991$, $p < 0.001$) as well as items cued 'long' and items presented in black ($z = 17.671$, $p < 0.001$) influences this significant cue type effect. The contrast between cued 'short' and 'long' was not significant ($z = 1.315$, $p = 0.387$). These results can be seen as illustrated in the bar graph in Figure 4.

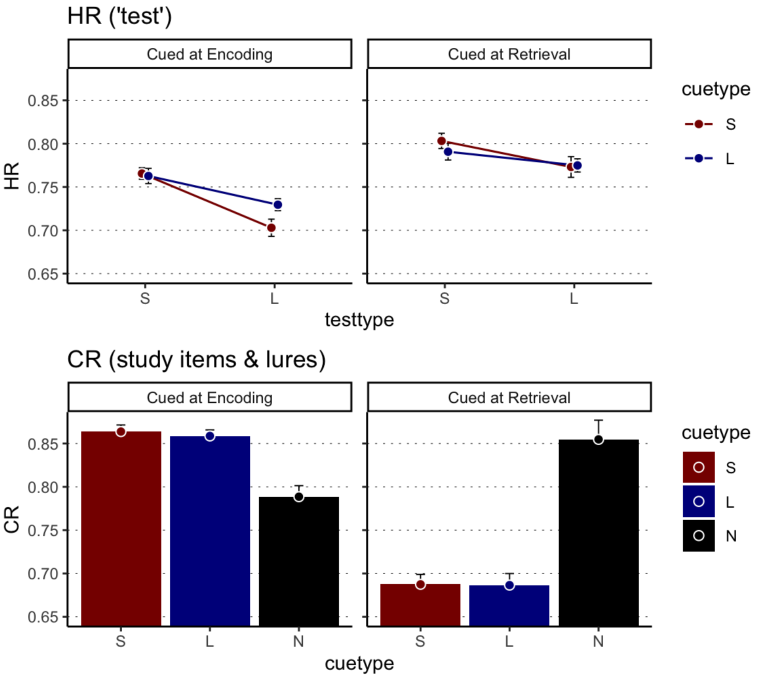
Variant 'Cued at Retrieval'

Table 2 again summarises our model selection based on the AIC for the Variant 'Cued at Retrieval'. For this variant, the best model includes only a main effect of test type (Mt; see Table 2). We report statistics for individual predictors by including or excluding them with respect to this best model and comparing the models using a chi-square likelihood ratio test. Test type had a significant effect on HR (Mt vs M0; $\chi^2(1) = 11.531$, $p < 0.001$), with higher HR for short than long retention intervals. Neither cue type (Mt vs Mtc; $\chi^2(1) = 0.999$, $p = 0.317$) nor the interaction between cue type and test type (Mt vs Mtxc; $\chi^2(1) = 1.039$, $p = 0.595$) had a significant effect on HR.

For the analysis of CR of this variant, the best model includes a main effect of cue type (Mc; see Table 4). This cue type effect was significant (Mc vs M0; $\chi^2(1) = 493.1$, $p < 0.001$), and the Tukey t-test on the estimated marginal means of the model Mc revealed that this effect entailed a significant contrast between 'short' cued items and items presented in black ($z = 36.383$, $p < 0.001$), as well as 'long' cued items and items presented in black ($z = 37.354$, $p < 0.001$). The contrast between 'short' and 'long' cues was not significant ($z = -1.110$, $p = 0.683$).

Figure 4

HR and CR for both variants



Note. 'S' denotes short, and 'L' denotes long retention intervals For test type. For cue type, 'S' represents cued ‘short’, 'L' represents cued ‘long’, and 'N' represents black items.

Error bars depict 95% confidence intervals.

Table 1

Model Selection HR ´Cued at Encoding’

Model		AIC
M0	correct ~ (1 | sub_id)	26203
Mc	correct ~ cue type + (1 | sub_id)	26199
Mt	correct ~ test type + (1 | sub_id)	26140
Mtc	correct ~ test type + cue type + (1 | sub_id)	26138
Mtxc	correct ~ test type * cue type + (1 | sub_id)	**26135**

Note. Model Selection here and in all subsequent tables based on AIC. Best model consists of the interaction effect (Mtxc).

Table 2

Model Selection HR ‘Cued at Retrieval’

Model		AIC
M0	correct ~ (1 | sub_id)	-10657
Mc	correct ~ cue type + (1 | sub_id)	-10657
Mt	correct ~ test type + (1 | sub_id)	**-10667**
Mtc	correct ~ test type + cue type + (1 | sub_id)	-10666
Mtxc	correct ~ test type * cue type + (1 | sub_id)	-10664

Note. Best model consists of the main effect of test type (Mt).

Table 3

Model Selection CR ´Cued at Encoding’

Model		AIC
M0	correct ~ (1 | sub_id)	42530
Mc	correct ~ cue type + (1 | sub_id)	**42038**

Note. Best model includes the main effect of cue type (Mc).

Table 4

Model Selection CR ‘Cued at Retrieval’

Model		AIC
M0	correct ~ (1 | sub_id)	42530
Mc	correct ~ cue type + (1 | sub_id)	**42038**

Note. Best model includes the main effect of cue type (Mc).

Signal Detection Theory

In the following, we use Signal Detection Theory (SDT) as an additional theoretical framework. Our CR analysis showed a strong response bias tied to the cued items. Therefore, we want to expand on this analysis and disentangle the specifics that underlie the participants' decision-making. We use an adapted version of SDT to analyse our data further. We do not have false alarm (FA) rates for both variants across all conditions. The variable 'test type' is undefined for FAs (‘new’ items). Therefore, we use the FA rate for the two cue type conditions as a basis of the SDT. Figure 5 illustrates results for beta (the criterion or bias), d’ (d prime; the sensitivity), a measure of sensitivity and A’ (a prime; estimate of discriminability), a nonparametric measure of sensitivity, for both variants.

Beta was calculated in R using the formula:

$$-0.5 * (ZHR + ZFA) \tag{1}$$

D’ was calculated in R using the formula:

$$ZHR - ZFA \tag{2}$$

Lastly, A’ was calculated in R using the formula:

$$0.5 + ((HR - FA) * (0.5 + HR - FA)) / (4 * HR * (1 - FA)) \tag{3}$$

In all three formulas, ZHR and ZFA represent the z-scores of HR and FA, respectively. For beta and d’, z-scores were computed using (HR-0.001) and (FA+0.001). This adjustment was necessary due to a minority of two participants achieving a HR of 100%, rendering the computation of z-scores for Signal Detection Theory (SDT) unfeasible due to the span of the normal distribution. To address this challenge, we applied a minor adjustment by subtracting or adding a small value (0.001) to HR and FA. This approach preserved these extreme cases at the ends of the normal distribution while minimally impacting the z-scores of other participants. This was not necessary for the nonparametric A'.

Variant 'Cued at Encoding'

For the Variant 'Cued at Encoding', note that we only have a single FA rate to use in the SDT computations, as all 'Hits' are defined by trials of a neutral, black colour. Therefore, the resulting scores for d' and beta are numerically equivalent. We analysed each SDT parameter employing repeated measures ANOVAs on test type and cue type and their interaction for the different parameters of SDT, where the statistics for d' and beta are identical. We will focus on A' primarily as a measure of memory performance.

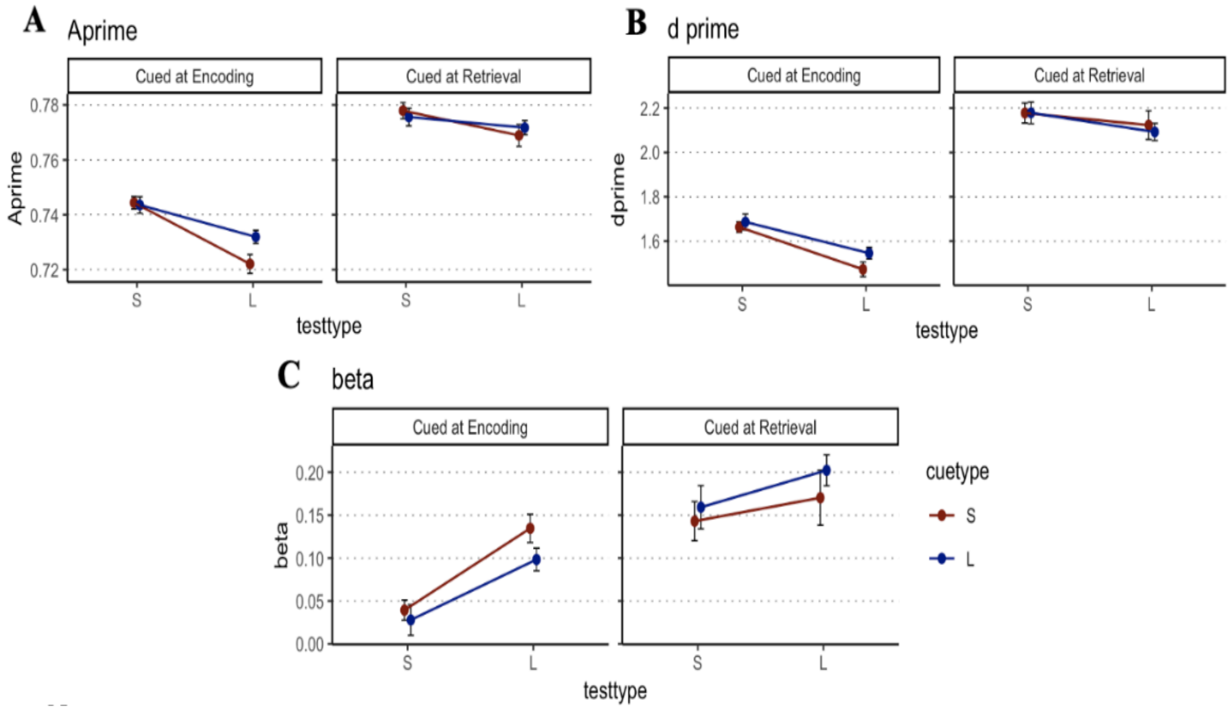
For A', we found a significant effect of test type ($F(1, 59) = 66.300$, $p < 0.001$), as well as cue type ($F(1, 59) = 5.610$, $p = 0.021$). We also found a significant interaction effect ($F(1, 59) = 7.250$, $p = 0.009$). These results mirror the HR results and can be seen in Figure 5. For d' and beta, we found significant effects of test type ($F(1, 59) = 63.500$, $p < 0.001$) and cue type ($F(1, 59) = 5.960$, $p = 0.018$). However, there was no significant interaction effect ($F(1, 59) = 1.150$, $p = 0.288$).

Variant 'Cued at Retrieval'

We followed the same analysis strategy for the variant 'Cued at Retrieval'. For A', we found test type effects ($F (1, 60) = 5.980$, $p = 0.017$) but no cue type effects ($F (1, 60) = 0.012$, $p = 0.913$). Lastly, we did not find significant results for the interaction term ($F(1, 60) = 2.010$, $p = 0.161$). These results mirror our HR analysis and can also be seen in the graph in Figure 5. For d' and beta, we concluded that there is a significant test type effect ($F(1, 60) = 3.830$, $p = 0.055$). but not for cue type ($F(1, 60) = 0.140$, $p = 0.710$). Lastly, we did not find significant results for the interaction term (F(1, 60) = 0.280, p = 0.597). We conclude that looking at A' in our SDT analysis mirrors our HR analysis in both variants.

Figure 5

Depiction of A'prime, d'prime and beta per test type - cue type condition for both variants



Note. Connotation of test and cue type is as in previous graphs. Error bars indicate 95 % confidence intervals.

Reaction Time

Figure 6 provides an overview of the reaction time (RT) for the hits per condition for both variants. HR results showed that in variant 'Cued at Encoding', patterns are driven by both test type, cue type and their interaction. We only found a test type effect for variant 'Cued at Retrieval'. Now, we turn to RT results and follow the same analysis strategy as for HR. The RT analysis is done using linear mixed-effects regression on log(RT) for both variants to account for the skew in the RT distribution.

Variant 'Cued at Encoding'

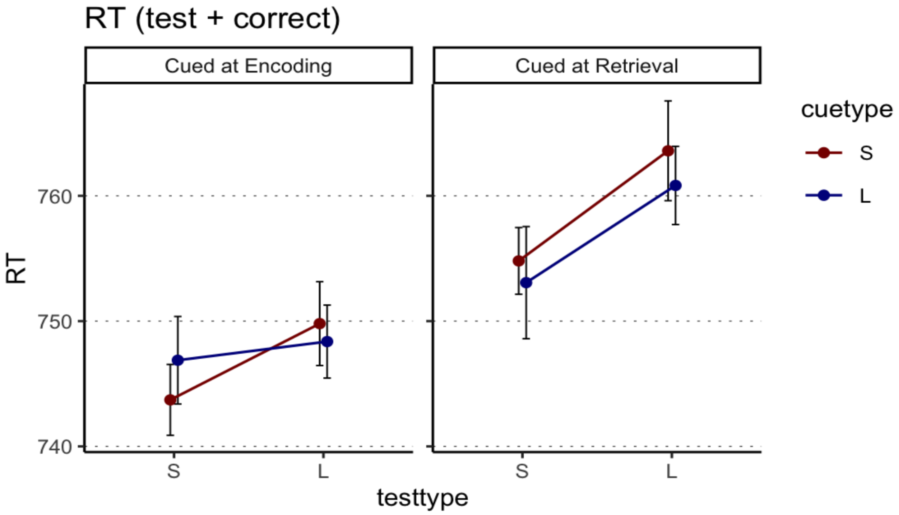
Table 5 summarises our model selection based on the AIC for the Variant 'Cued at Encoding'. The best model includes only a main effect of test type (Mt; see Table 5). Using the chi-square likelihood ratio tests, we compare statistics to this best model (Mt; see Table 5). We conclude that test type significantly affected RT (Mt vs M0; $\chi^2(1) = 10.266$, $p = 0.001$). This was not the case for cue type (Mt vs Mtc; $\chi^2(1) = 0.013$, $p = 0.911$) or the interaction term (Mt vs Mtxc; $\chi^2(1) = 0.413$, $p = 0.814$).

Variant 'Cued at Retrieval'

Table 6 again summarises our model selection based on the AIC for the Variant 'Cued at Retrieval'. The best model again only includes a main effect of the test type main effect (Mt; see Table 6). Accordingly, from the chi-square likelihood ratio test, we conclude that there is a main effect of test type on RT (Mt vs M0; $\chi^2(1) = 11.531$, $p < 0.001$). This was not the case for cue type (Mt vs Mtc; $\chi^2(1) = 0.999$, $p = 0.317$) or the interaction term (Mt vs Mtxc; $\chi^2(1) = 1.040$, $p = 0.595$). Although no significant results for cue type can be seen, our RT results indicate a trend for faster RT for 'long' cues, as can be seen in Figure 6.

Figure 6

RT for the hits per condition for both variants



Note. Connotation of test and cue type is as in previous graphs.

RT is depicted in milliseconds. Error bars indicate 95 %

confidence intervals.

Table 5

Model Selection Variant ´Cued at Encoding'

Model	Model	AIC
M0	log(RT) ~ (1 | sub_id)	-14705
Mc	log(RT) ~ cue type + (1 | sub_id)	-14706
Mt	log(RT) ~ test type + (1 | sub_id)	**-14713**
Mtc	log(RT) ~ test type + cue type + (1 | sub_id)	-14711
Mtxc	log(RT) ~ test type * cue type + (1 | sub_id)	-14710

Note. Best model includes the main effect of test type (Mt).

Table 6

Model Selection Variant 'Cued at Retrieval'

Model	Model	AIC
M0	log(RT) ~ (1 | sub_id)	-10657
Mc	log(RT) ~ cue type + (1 | sub_id)	-10657
Mt	log(RT) ~ test type + (1 | sub_id)	**-10667**
Mtc	log(RT) ~ test type + cue type + (1 | sub_id)	-10666
Mtxc	log(RT) ~ test type * cue type + (1 | sub_id)	-10664

Note. Best model includes the main effect of test type (Mt).

To summarise, test type, cue type, and their interaction significantly affected the HR in variant 'Cued at Encoding'. Only the test type significantly affected the HR in variant 'Cued at Retrieval'. Moreover, cue type significantly affected CR, driven by the difference between 'cued items' (colour) and 'non-cued items' (black) in both experimental variants. Based on our CR results, we conducted SDT analysis. Here, we concluded that our findings for HR are mirrored by A' for both variants. There was a significant test type effect on RT irrespective of the experimental variant. Lastly, our RT results indicate a trend in the variant 'Cued at Retrieval'. RT results here seemed to point to faster retrieval for 'long' cues.

Discussion

Recent research has demonstrated that retrieving information might depend on retrieving the temporal context for the relevant information by scanning our mental timeline. Using this strategy to judge the recency of an item or event allows individuals to find and retrieve the required information. The recovery of this temporal context depends on recency and increases with the time between encoding and retrieval (Bright et al., 2022; Scofield et al., 2022; Singh et al., 2017). By introducing retention interval cues, our study focused on whether the presence of such cues influences the accessibility of memories over time and whether our two experimental variants differ in how participants used the retention cues for encoding and retrieval. We conducted a continuous recognition experiment in which participants were asked to indicate whether the items presented were ‘new’ or ‘old’. We sought to gain insight into the strategy individuals use to retain information by providing retention interval cues (signalling ‘short’ or ‘long’ retention intervals) either at encoding (variant ‘Cued at Encoding’) or at retrieval (variant ‘Cued at Retrieval’). Cues were either valid or invalid.

Forgetting

Looking at our HR results, we saw that test type significantly affected HR, one finding common to both of our experimental variants. Specifically, for both variants, the ability of participants to correctly indicate an item as ‘old ’ decreased with an increase in the interval between study and test items. Moreover, our RT results showed a significant test type effect on RT for both of our experimental variants. The time it took participants to respond correctly increased with the retention interval. These findings align with the idea that memories are forgotten with time.

Variant ‘Cued at Encoding’

On the one hand, we aimed to investigate how participants use retention interval cues at encoding to make inferences about when an item will be needed again, which was reflected in our HR results for the variant ‘Cued at Encoding’, showing a significant cue type effect: Items cued ‘long’ prompted participants to hold onto the item longer, significantly improving HR for these cues compared to items cued ‘short’. This suggests three things: Firstly, the presentation of the cue made a difference. Participants used the cues to determine how long an item needed to be retained. Secondly, ‘long’ cued items made an individual's memory more robust. In other words, it made those items better retrievable after a longer delay. Thirdly, this potentially suggests that participants exert some voluntary control over identifying the necessity of retaining information. Participants might have put some extra effort into labelling items as needing to be kept in memory for longer at encoding. They were then successful at retrieving them because of this strategy.

Interestingly, this cue type effect interacted with the test type effect, and our analysis showed that there were significant HR effects for the long retention interval, with participants being able to more frequently correctly indicate an item as ‘old ’ when they had received a ‘long’ cue. When participants received an invalid ‘short’ cue but were tested after a long retention interval, they were less successful in correctly indicating items as ‘old’ than when they received a ‘long’ cue. This suggests that the participant’s use of the retention interval cues might have exceeded just the notion of putting in effort to remember when an item will be needed in the future. Our results suggest that participants might have bound the cue to a context for either short or long retention, which helped them access the right information at retrieval. An example of this is that the context for remembering where you parked your car for one hour when you go to the supermarket is a different one than remembering where you parked your car before going on vacation for a week. This would explain why participants had similar hit rates for both cues at short retention intervals (context matters less here) but more frequently correctly indicated an item as ‘old ’ when they had received a ‘long’ cue. As this result was not seen for the HR in the variant ‘Cued at Retrieval’, individuals might employ a strategy during encoding as reflected by the HR in the variant ‘Cued at Encoding’ to anticipate the temporal context required for memory retrieval. Here, the temporal context reflects participants' judgment about how long information needs to be retained and when it is expected to be needed. Through the cue, individuals understand that they have to hold on to information for either a short or long time, affecting their ability to retrieve the items later.

In addition to our HR analysis, we also analysed CR. This analysis showed a strong response bias tied to the cued items compared to the black items. Importantly, no response bias was tied to the contrast between ‘short’ and ‘long’ cues, showing that participants could discriminate between the two cues and use them accordingly. Due to this response bias towards cued items, we wanted to expand on our analysis by using Signal Detection Theory to disentangle specifics about decision-making. As explained in the results section, we used an adapted version of Signal Detection Theory. Using A’ as a measure of memory performance, we found our HR results consistent with this analysis's outcomes, indicating that the HR results observed for variant ‘Cued at Encoding’ were not solely driven by bias, accentuating the discussion of results so far.

Variant ‘Cued at Retrieval’

On the other hand, we were also interested in seeing how participants use retention interval cues at retrieval to make inferences about when an item was encountered previously. Our analysis of RT results for the variant ‘Cued at Retrieval’ did not directly show a significant cue type effect as expected. Still, we identified a trend that should not be overlooked: Participants seemed quicker to give correct responses for items cued to have been seen a ‘long’ time ago over those cued to have been seen a ‘short’ time ago (see Figure 6). A possible explanation for this trend in RT is that participants try to recover the temporal context of the item by scanning along their mental timeline (Bright et al., 2020; Scofield et al., 2022; Singh et al., 2017). In our case, participants might have used the information from the cue at retrieval to scan their mental timeline and find the point at which it was first presented. Interestingly, participants seemed to be faster for items they had seen a long time ago, possibly indicating that they exerted some voluntary control over keeping the item in mind more strongly. This might explain why the ‘scanning process’ was shorter for these items, as they were more easily located on the mental timeline and then retrieved more quickly, as reflected by RT. As we did not observe any cue type effects or trends in the variant ‘Cued at Encoding’, we suggest that RT results for the variant ‘Cued at Retrieval’ reflect a strategy at retrieval in dealing with the temporal context of an item, namely scanning our mental timeline for required information.

These results mirror the results obtained by Coppes and Kruijne (2023) on RT, with the critical difference that our study provided the retention interval cues at retrieval and encoding separately and not at both encoding and retrieval in the same experiment. In their research paper, the authors analysed their data using the EZ-Diffusion model, which can combine RT and HR results in a single model. The analysis indicated that cue type influenced non-decision time, which showed that memory processes not directly involved in decision-making differed between ‘short’ and ‘long’ cued items. Coppes and Kruijne (2023) interpreted this finding on non-decision time in the same way we interpreted our RT results. We did not follow the same analysis strategy for our study as there was too much response bias towards cued items, and the EZ-Diffusion Model assumes no existing bias. However, the trend towards a cue type effect in our experiment might point towards the same explanation provided by Coppes and Kruijne (2023).

Additionally, we observed that in the 'Cued at Retrieval' variant, both HR and RT were higher overall than in the 'Cued at Encoding' variant. Unlike the 'Cued at Encoding' variant, where no cues were provided at test, resulting in a HR solely for items presented in black, the 'Cued at Retrieval' variant involved cues provided at test, leading to a HR for items presented in colour. The overall increase in HR and RT suggests that participants required additional time to process the meaning of the cues, which ultimately benefited the correct identification of items as 'old'. This increase in HR and RT not only suggests a boost in performance due to participants taking more time but also indicates an improvement in overall discriminability (A'), as seen in SDT. This observation is crucial as it suggests that the performance boost was not solely attributable to bias.

Follow-up Experiment

As mentioned in the methods section, we conducted a second experiment with longer retention intervals between items. Items here were tested after a short interval (after 20-25 trials) or a long interval (after 30-35 trials). The graphs from this experiment were combined with those from the first experiment, where the long interval in the first experiment and the short interval in the second experiment were combined into a new ‘medium’ category. These graphs were made on the results obtained for HR and RT and can be found in the Appendix (Figures 1 and 2). In the second experiment, we saw a noteworthy trend in the HR for the 'Cued at Encoding' variant. Figure 1 in the Appendix shows that items cued 'long' exhibited an intriguing pattern during the medium retention interval, as the HR drops here. Taken together, these experiments suggest that a ‘long’ cue might aid in retaining trials at a 20 to 25 item interval compared to a ‘short’ cue. However, no clear benefits exist at either longer or shorter retention intervals. Currently, we lack an explanation for this trend, and therefore, we anticipate that future research might be able to shed more light on this. Additionally, we observed a noticeable difference in RT for the 'Cued at Retrieval' variant. As previously mentioned, we identified a trend towards an effect of cue type on RT in our initial experiment. Figure 2 in the Appendix suggests this trend is even more pronounced here. While we did not conduct formal statistical analysis on these results, the graph shows a potentially significant cue type effect. Taking into account the considerations made above, this might be additional support for the ideas proposed by Bright et al. (2022), Scofield et al. (2020) and Singh et al. (2017) on how we recover the temporal context of relevant items at retrieval.

General Discussion

Collectively, our findings give rise to the idea that HR and RT may reflect different memory processes for dealing with retention interval cues and identifying the temporal context of the required information. We make this inference based on the observation that only one of the experimental variants appeared to show expected cue type effects for each dependent variable. Individuals seem to employ different strategies for encoding and retrieval when using retention interval cues. At encoding, we suggest that individuals bind a context to the information that needs to be retained and use this context to their advantage at retrieval. Using the retention interval cues provided, individuals can judge how long information needs to be retained and when it is expected to be needed. At retrieval, we suggest that individuals scan their mental timeline in order to contextualise the retention interval cue and its relevance, as suggested by Bright et al. (2022), Scofield et al. (2020) and Singh et al. (2017), using the information of the retention interval cue as introduced by Coppes and Kruijne (2023) and refined in this experiment.

Returning to the example of the German law students mentioned in the introduction, we asked whether providing cues regarding the duration of material retention or the academic year from which the material is sourced would help German law students access the right knowledge at the right moment. Our study shows that specificity about exact moments might not even be necessary, but providing a general timeframe in which information was learned might already be enough. In other words, providing German law students with a broad timeframe regarding the duration of maintenance of information, when it is initially learned or how long information has been retained when it is tested could suffice to grasp the temporal context of the required information and leverage this understanding to their advantage. In our experiment, we only provided intervals spanning five items, so we encourage future research to investigate longer timeframes, potentially even in real-life settings, to gain better insight into this proposition.

Limitations

Importantly, in conducting and analysing our experiment, we critically drew some conclusions about our study's limitations. Due to our design's structure, we could not use Signal Detection Theory in its full capacity. For both variants, we did not have FA rates across all conditions. Moreover, for beta and d’, we had to adapt z-scores due to participants’ performance, which affected all z-scores when calculating the two. This did not influence the experiment, making our data analysis harder to interpret.

Moreover, we could not analyse our data using the EZ-Diffusion Model as in Coppes and Kruijne’s (2023) research because participants' bias towards cued items was too high. The EZ-Diffusion model assumes that participants' responses are unbiased. This hindered our ability to directly compare results between our research and those of Coppes and Kruijne (2023).

Future Directions

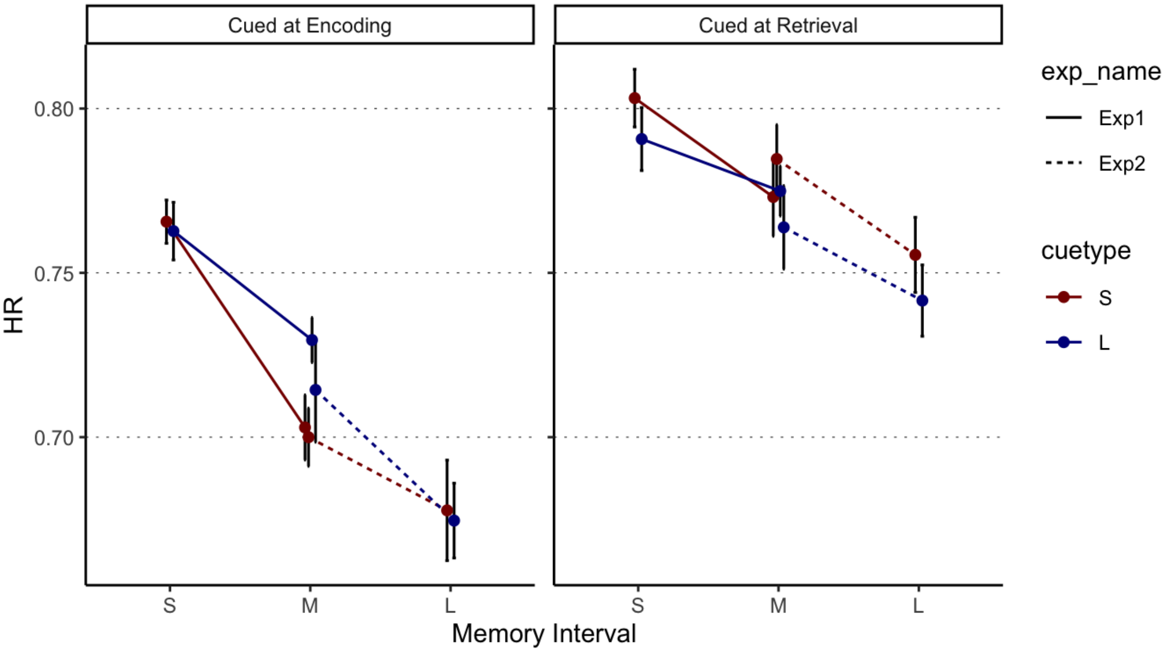
In the future, it might be interesting to look more specifically at the possibility that individuals choose a strategy of dealing with the temporal context of memory either at encoding, as revealed by the cue type effects on HR in our study, or at retrieval, as proposed by the trending cue type effect on RT. In our study, we could only show the existence of differing strategies towards our retention interval cues at encoding and retrieval. It is unclear whether individuals could prefer either strategy if they were given the opportunity to choose. This preference could be based on experience or learned behaviour or might not exist at all. In any case, it seems intriguing for future research to dive into these strategies more thoroughly based on these findings.

Moreover, it might be interesting for future research to look more closely at the discrepancy between RT and HR results. Our results give rise to the impression that HR and RT might reflect different processes in memory even though they seem to co-occur often. Future research could aim to isolate RT and HR results using electrophysiological measures to help look into specific components that might influence long-term memory processes to see if the discrepancy persists. Finally, future research might manipulate the retention interval cues by adding more intervals or changing the length of intervals, as well as investigating the use of these cues in real-life settings, such as in schools or the workplace, to determine if our findings persist under these conditions.

Appendix

Figure 1

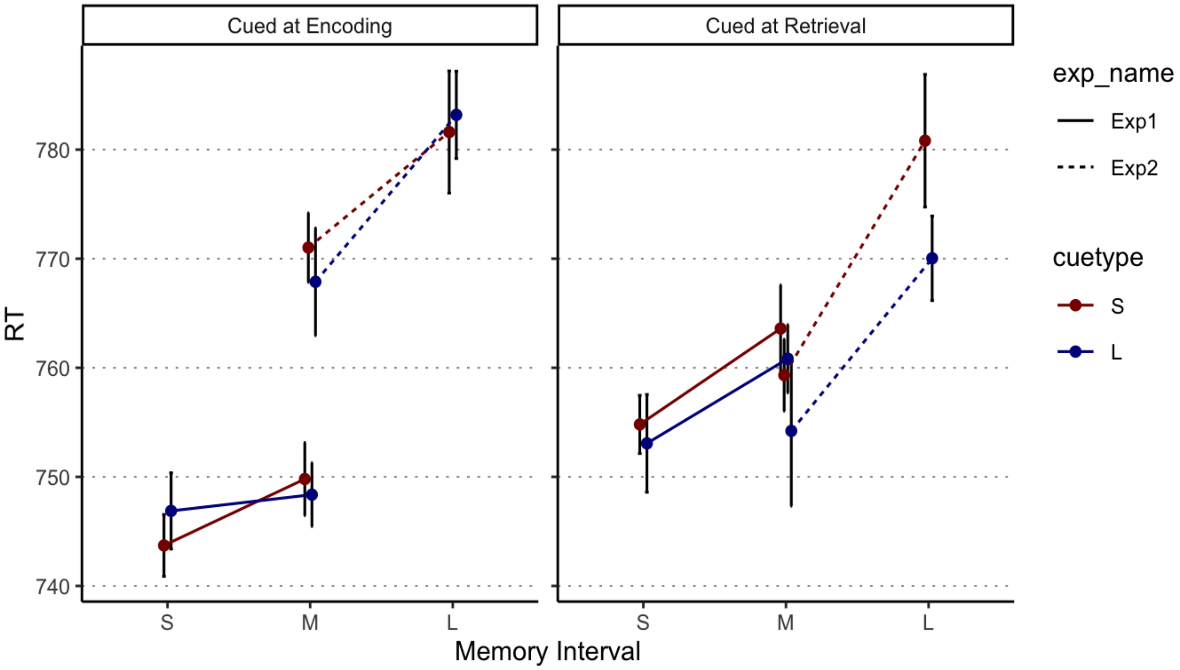
HR results across Experiments 1 and 2



Note. 'S' denotes short, ‘M’ denotes medium and 'L' denotes long retention intervals for test type. For cue type, 'S' represents cued ‘short’ and 'L' represents cued ‘long’. Error bars depict 95% confidence intervals.

Figure 2

RT results across Experiments 1 and 2



Note. 'S' denotes short, ‘M’ denotes medium and 'L' denotes long retention intervals for test type. For cue type, 'S' represents cued ‘short’ and 'L' represents cued ‘long’. RT is depicted in milliseconds. Error bars depict 95% confidence intervals.

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