The loss of short-term visual representations over time: Decay or temporal distinctiveness?

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ABSTRACT

There has been much recent interest in the loss of visual short-term memories over the passage of time. According to decay theory, visual representations are gradually forgotten as time passes, reflecting a slow and steady distortion of the memory trace. However, this is controversial and decay effects can be explained in other ways. The present experiment aimed to re-examine the maintenance and loss of visual information over the short-term. Decay and temporal distinctiveness models were tested using a delayed discrimination task, where participants compared complex and novel objects over unfilled retention intervals of variable length. Experiment 1 found no significant change in the accuracy of visual memory from 2 to 6 s, but the gap separating trials reliably influenced task performance. Experiment 2 found evidence for information loss at a 10 s retention interval, but temporally separating trials restored the fidelity of visual memory, possibly because temporally isolated representations are distinct from older memory traces. In conclusion, visual representations lose accuracy at some point after 6 s, but only within temporally crowded contexts. These findings highlight the importance of temporal distinctiveness within visual short-term memory.

Keywords: Visual memory, decay, temporal distinctiveness, forgetting, short-term memory.

Visual short-term memory (VSTM) is responsible for maintaining small amounts of visual information over brief periods of time (Christophel, Hebart, & Haynes, 2012). In recent years, there has been extensive effort to understand the characteristics and nature of visual short-term and working memory, including capacity limitations (e.g. Luck & Vogel, 2013; Vogel, Woodman, & Luck, 2001), the role of attention (e.g. Johnson, Hollingworth, & Luck, 2008; Kuo, Stokes, & Nobre, 2012) and consolidation processes (e.g. Mance, Becker, & Liu, 2012; Vogel, Woodman, & Luck, 2006). Yet there is uncertainty concerning how the passage of time affects the precision and fidelity of VSTM. One possibility is that visual information is slowly lost from memory as time passes, with the representation becoming steadily less accurate. For example, Ricker and Cowan (2010) employed a delayed discrimination task and asked participants to determine whether a probe stimulus matched any of three target stimuli. The retention interval (RI) between the target stimuli and the probe was 1.5, 3, or 6 s. The stimuli themselves were abstract and unconventional, which minimized the influence of verbal encoding and labelling. Ricker and Cowan found a significant decline in recognition performance as the RI was lengthened.

Such time-based loss of VSTM is consistent with trace decay, which proposes that visual representations lose precision over time. This could be a result of memories becoming more "noisy" and distorted as time passes (e.g. Sakai & Inui, 2002). Importantly, other evidence is consistent with the decay process (e.g. Hesse & Franz, 2010; Salmela, Mäkelä, & Saarinen, 2010; Tsuda & Saiki, 2013). However, there are differing ideas about how such decay operates. Some authors have proposed that visual information is randomly distorted over time (e.g. Kinchla & Smyzer, 1967), whereas Gold, Murray, Sekuler, Bennett, and Sekuler (2005) argue that visual memory decay actually results from deterministic changes to the representation. If so, finely resolved visual information is progressively lost over the

passage of time in a non-random fashion. Alternatively, visual information may be lost very abruptly (an effect termed sudden death), rather than via a gradual decline (Zhang & Luck, 2009; see also Gao & Bentin, 2011, Experiment 4, for evidence of a sharp decline in recognition accuracy).

Irrespective of whether VSTM loss occurs gradually or rapidly, decay theory emphasizes the importance of the *absolute* amount of time that has passed, with longer RIs leading to greater forgetting. But some findings are incompatible with this suggestion. For instance, memory for simple visual attributes can be perfectly retained for periods exceeding 10 s (Magnussen, Greenlee, Baumann, & Endestad, 2010). Magnussen and Greenlee (1999) reported that memory for spatial frequency is as accurate at 10-30 s as it as at 1 s, challenging decay. VSTM for motion also appears to be resistant to temporal decay (Blake, Cepeda, & Hiris, 1997; Poom, 2012; Zokaei, Gorgoraptis, Bahrami, Bays, & Husain, 2011). Such findings initially appear surprising, but within the *verbal* short-term and working memory literature, decay is highly controversial and has been challenged in numerous studies (see Lewandowsky, Oberauer, & Brown, 2009; Oberauer & Lewandowsky, 2013). As such, decay may not necessarily be the best interpretation of the loss of visual information over the passage of time.

Temporal distinctiveness theories provide an alternative explanation for the time-based loss of VSTM. These accounts explain forgetting through proactive interference and confusability. Unlike decay theory, which emphasizes the passage of absolute time, distinctiveness models highlight the role of *relative* time, or the amount of time that has elapsed in relation to other events. According to the distinctiveness perspective, memories are more easily confused as time passes, particularly if they are temporally proximate (Brown & Lewandowsky, 2010). Similarly, memories that are temporally isolated should be easier to

recall than temporally crowded memories, since they are more distinct from their neighbors (Unsworth, Heitz, & Parks, 2008).

One way of conceptualizing temporal distinctiveness is through the ratio-rule (e.g. Bjork & Whitten, 1974). This idea postulates that memory recall is influenced by the ratio between the inter-item interval and each item's RI (Oberauer & Lewandowsky, 2008). From this perspective, it is not simply the total duration of the RI that is important, but the ratio of the RI to the interval separating events on different trials (Cowan, Saults, & Nugent, 1997).

Many of the different ideas surrounding temporal distinctiveness have been formally incorporated into Brown, Neath, and Chater's (2007) SIMPLE model. This account indicates that items are retrieved from memory in relation to their temporal location and are forgotten if they become confused with other items. Within SIMPLE, items are represented along a temporal dimension, but this is logarithmically compressed. As a result, items in the past are more crowded and less distinct than more recent items (Geiger & Lewandowsky, 2008). They are therefore harder to retrieve, but this is a result of inter-item confusion, rather than decay. Indeed, it is the predicted absence of decay that introduces such proactive interference over longer intervals.

Intriguingly, there is some support for temporal distinctiveness models within the context of nonverbal memory. Guerard, Neath, Suprenant, and Tremblay (2010) presented series of dots in different spatial locations. The interval between dots was varied (0 – 4 s) and at recall participants were asked to reconstruct the order in which the stimuli had occurred. Dots that were temporally isolated from their neighbors were more likely to be correctly recalled. Shipstead and Engle (2013) also documented temporal isolation effects in the visual arrays task, so time-based forgetting in VSTM may actually result from a loss of distinctiveness at longer RIs, rather than decay. More specifically, participants may have

difficulty distinguishing the current visual memory from previous (interfering) representations, especially at the longest intervals.

This is plausible, since research indicates that visual information from the recent past can influence current visual memories (e.g. Huang & Sekuler, 2010). Thus, the present study aimed to examine the importance of temporal distinctiveness within the context of VSTM for novel objects. Specifically, this study assessed how the temporal proximity of stimuli from previous trials affected recognition performance on the current trial. Rather than decay, the decline of VSTM accuracy over time was predicted to be a result of lost distinctiveness. As such, heightening the distinctiveness of visual information was expected to preserve the fidelity of the memory.

EXPERIMENT 1

The delayed discrimination task was used (e.g. Ricker & Cowan, 2010), but the length of the inter-trial interval (ITI) was also varied to manipulate the distinctiveness of the visual memories. Stimuli were drawn from a set of unfamiliar and complex objects known as "Fribbles" (see http://www.tarrlab.org/). Fribbles were selected instead of simpler stimuli for several reasons. Firstly, whilst Fribbles are unusual and novel, they usefully mimic real-world stimuli in terms of their structure and complexity (Barry, Griffith, De Rossi, & Hermans, 2014). Secondly, it is possible to manipulate Fribbles in a highly systematic and controlled way. Finally, since Fribbles are more complex than the stimuli used in many previous studies (e.g. colours or simple shapes), they may be more susceptible to forgetting. For example, complex objects are more difficult to remember (e.g. Alvarez & Cavanagh, 2004) and may place greater demands on memory capacity (Eng, Chen, & Jiang, 2005).

On each trial, a target Fribble was displayed and followed by a test Fribble after a RI of 2 or 6 s. Participants had to determine whether the two stimuli differed. The ITI was either half that of the RI (creating temporal crowding and *low distinctiveness*) or double the length of the RI (creating temporal isolation and *high distinctiveness*). This arrangement allowed better comparability across conditions: in the low distinctiveness conditions, the RI:ITI ratio was 1:0.5, whereas in the high distinctiveness condition this ratio was 1:2. Distinctiveness itself was assessed relative to the test Fribble. It should be easier to discriminate the target and test Fribbles at short RIs, as recent events are expected to be less confusable and more distinct than distant events (Brown et al., 2007; Brown & Lewandowsky, 2010). Distinctiveness models would therefore expect better performance at the 2 s than the 6 s RI. Decay theory also predicts RI to influence performance; hence discriminatory ability should decline from 2 to 6 s. But the two accounts can be differentiated according to their hypotheses regarding the ITI. At shorter ITIs, the target Fribble on trial *N* is temporally close to the test Fribble from trial *N*-1, reducing distinctiveness and making the discrimination more difficult. At longer ITIs, the events on the two trials are temporally separated and so the test Fribble is more distinct. As such, distinctiveness theory predicts significantly better performance at the longer ITI, for both 2 and 6 s RIs. Conversely, decay theory does not expect the ITI to have any effect.

Method

Participants. 25 individuals (23 female) aged between 19 and 41 (*M* = 22.56, *SD* = 4.83) completed this experiment. Responses from another individual were not correctly recorded and hence excluded from further analysis. Participants were volunteers from the

Institute of Psychology at the University of Wolverhampton and reported normal or corrected-to-normal vision.

Materials. The Fribbles used in this study are abstract and unconventional stimuli that consist of a body and four different appendages (Barense, Gaffan, & Graham, 2007). They have been described as non-nameable due to their complex yet novel appearance (Hartshorne, 2008). There are three different Fribble families, labeled A, B and C, and each family contains four different species. Species within a family share the same body, but have very different appendages. In total, there are 12 broad types of Fribble, each with 81 exemplars. Seventy-two members of each Fribble family were randomly selected for the experimental trials, with an additional 30 used on practice trials (stimulus images courtesy of Michael J. Tarr, Center for the Neural Basis of Cognition, Carnegie Mellon University, http://www.tarrlab.org/). Within each family, 18 members of the four species were chosen, ensuring that all Fribble types were equally represented. In total, 246 Fribbles were employed.

Each condition included 18 "same" trials and 18 "different" trials, and stimuli from the full range of Fribble species were included (i.e. 12 trials per species). On trials when the stimuli differed, two appendages were changed in the test stimulus (see Figure 1). Within each condition, all possible changes to the appendages of the Fribbles occurred three times. In addition, a post-perceptual mask was created consisting of a series of overlapping circles of different textures and was designed to eliminate any lingering contribution from sensory memory (Vogel et al., 2006).

Crucially, each trial contained unique Fribbles, so stimuli were consistently novel between trials. Such variation in the stimuli was designed to prevent the formation of long-term memories and minimize verbal encoding or labelling strategies. These manipulations

have been successful in the study of other forms of nonverbal memory (see McKeown &

Mercer, 2012).

The experiment was designed and conducted using a PC running SuperLab software

(version 4.5). Participants were seated approximately 60 cm from a HannsG HP191 19" LCD

monitor. All stimuli were displayed in the center of the screen and participants entered their

responses using a keyboard.

"Figure 1 about here"

Design and Procedure. A 2x2 repeated measures design was employed, with RI and

ITI as independent variables. Performance on the task and response times were recorded.

Each trial began with the presentation of a fixation cross positioned in the center of the screen

for 0.1 s. A target Fribble was then shown for 1.5 s and participants were instructed to

remember it. After an unfilled 0.25 s delay, the mask was shown for 0.1 s. The second Fribble

was shown after a 1.65 or 5.65 s gap and remained on screen until participants made a

response. Individuals were told to respond quickly but without sacrificing accuracy. They

were also asked to press the 'S' key if they believed the stimuli were identical and the 'D' key

if they noticed any difference. The ITI following this response was either half or double the

length of the RI. This created four conditions according to the combination of the RI and ITI:

2:1, 2:4, 6:3 and 6:12.

Trials were completed in separate blocks for different conditions, since a blocked

arrangement was needed to preserve the RI:ITI ratio throughout the experiment. The two

conditions with a 2 s RI were undertaken in one block, whereas the two conditions with a 6 s

RI were divided into smaller trials blocks. 6:3 was completed in two blocks, each containing

18 trials, and 6:12 was divided into three blocks, consisting of 12 trials. This was designed to

reduce the likelihood that any effects were due to the amount of time required to complete all

of the trials in a condition, rather than the experimental manipulations. Half of the

participants began the experiment with 2 s blocks, followed by 6 s, and the other participants

underwent the reverse order. Trials within a block were randomized. Participants completed

10 practice trials prior to undertaking the main procedure and there were opportunities for

breaks. The experiment lasted approximately 45 minutes.

Results

"Table 1 about here"

Preliminary analyses. Mean response times were examined and participants generally

responded rapidly. However, there were some instances of delayed responding and

participants' data were subjected to closer scrutiny if 3 x SD exceeded 2.5 s. This marker was

chosen as it was effective in detecting trials on which participants had responded unusually

slowly, in comparison with their responses to other trials. Nine individuals were affected and

trials on which their response times exceeded 3 SDs were removed. This did, however,

represent only 3.7 % of collected data. One participant was consistently very slow to respond

in the 2:4 condition ($M = 4921.79$ ms) and emerged as an outlier. Her response time in this

condition was far greater than the upper quartile of scores plus 3 x IQR. Her data were

therefore removed from further analysis. A second individual was excluded due to chance

performance ($M = .49$) and the final analysis was based upon 23 individuals.

Recognition accuracy. Hits (correctly responding "same" on same trials) and false

alarms (incorrectly responding "same" on different trials) were calculated for each condition

and are shown in Table 1. To assess these data further, A' values were calculated using

Snodgrass, Levy-Berger, and Haydon's (1985) formula. The hit and false alarm rates were used to generate *A'* for each participant. *A'* provides a bias-free measure of sensitivity, with a score of 0.5 indicating chance performance. *A'* was chosen since there may have not have been sufficient data points in each condition to calculate a reliable *d'* (Miller, 1996). The means for each condition can be seen in Figure 2.

A 2 (RI: 2 s vs. 6 s) x 2 (ITI: half RI vs. double RI) repeated measures ANOVA was then employed to assess the data. There was a significant effect of ITI, $F(1, 22) = 6.82$, *MSE* $= .003$, $p = .02$, $\eta_p^2 = .24$, indicating that participants were more accurate when the ITI was double the length of the RI ($M = .87$), rather than half its duration ($M = .84$). Conversely, there was no significant effect of RI, $F(1, 22) = 1.19$, *MSE* $= .003$, $p = .29$, $\eta_p^2 = .05$, and no significant interaction, $F(1, 22) = .09$, *MSE* $= .01$, $p = .93$, $\eta_p^2 = 0$.

"Figure 2 about here"

Discussion

Experiment 1 found that the ability to discriminate two visual stimuli was significantly better when the gap separating trials was extended. The advantageous effect of a longer ITI supported the predictions of distinctiveness models and indicated that the accuracy of visual representations can be affected by the temporal proximity of stimuli in the recent past. When items from the previous trial were temporally close to the target stimulus on the current trial, there was a greater likelihood of forgetting as manifested by a decline in recognition ability.

In contrast to the effect of ITI, RI had no reliable impact upon task performance. This seems problematic for decay theory, which proposes that memories decline as time passes. Distinctiveness models also expect a drop in performance at longer RIs (at least when the ITI

is short), since over time it becomes harder to distinguish items in memory (Brown & Lewandowsky, 2010). Hence a target Fribble should be less distinct after 6 s has elapsed, than after 2 s. However, the RIs used in the present experiment may have been too short. Participants were only required to remember one stimulus on each trial, and this limited set size may have permitted the representation to persist beyond 6 s. Indeed, evidence suggests that the precision of visual memories decreases as the number of items being maintained increases, (e.g. Bays, Catalao, & Husain, 2009; Bays & Husain, 2008), but individual stimuli can be retained with a high level of detail (Magnussen & Greenlee, 1999). Additionally, Fougnie, Suchow, and Alvarez (2012) have reported that the quality of visual memory varies within an individual, and this variability changes according to the number of stimuli that must be remembered (in their experiment, memory variability increased as the set size was expanded from one to three items, and from three to five items). Time-based forgetting of single Fribbles may not be manifested over 6 s intervals, but lengthening the RI may make retention more difficult.

Alternatively, decay may have occurred before the shortest RI (see Campoy, 2012, for evidence of fast-acting decay) or the 1.5 s encoding time may have allowed the creation of a more durable representation. Memory for complex visual objects may benefit from long encoding times (Eng et al., 2005), potentially allowing improved performance (although consolidation in VSTM may naturally occur quickly, see Vogel et al., 2006). In Experiment 2, the target stimulus was shown for 0.75 s, reducing encoding time to that used in Ricker and Cowan's (2010) study. The length of the RIs was also altered in order to maximize the chances of detecting decay.

EXPERIMENT 2

Experiment 2 used three different RIs: 1.5, 5 and 10 s. The shortest gap should allow

fast-acting decay to be manifested, whereas the longer 10 s interval created a broader

timeframe for the detection of forgetting. For all three RIs, the ITI was 0.75 s. Decay theory

would expect a drop in performance as the RI was extended from 1.5 to 5 and 10 s, due to the

loss of memory fidelity. Distinctiveness theory also anticipates a decline in performance at

longer RIs, since items in the past are less distinct and more easily confused with other items,

particularly at short ITIs. However, an additional two conditions were added to Experiment 2.

These conditions had a 10 s RI, but ITIs of either 5 or 20 s. Decay theory does not predict any

difference in performance at the 10 s RI according to ITI duration, whereas distinctiveness

theory expected recognition accuracy to improve as the ITI was lengthened, due to reduced

temporal crowding. Indeed, distinctive representations should retain a high level of detail.

Method

Participants. 30 individuals (26 female) aged between 18 and 43 ($M = 20.93$, $SD =$

4.57) participated in the experiment. Participants were volunteers from the Institute of

Psychology at the University of Wolverhampton and reported normal or corrected-to-normal

vision.

Materials. Fribbles from the three different families were randomly selected for this

experiment. In total, 180 Fribbles were used and these reflected an equal balance of the

different families and species (an additional nine Fribbles were used on the six practice

trials). Each condition included 12 "same" trials and 12 "different" trials, and stimuli from

the full range of Fribble species were included within all conditions. Between-trial variation

of the stimuli meant that Fribbles were constantly varied and the same Fribble was never

employed on more than one trial. This was designed to prevent the formation of long-term

memories and minimize the use of verbal encoding and maintenance. All other arrangements matched Experiment 1.

Design and Procedure. The design of Experiment 2 was similar to that of Experiment 1, although the target Fribble was shown for just 0.75 s. This made the presentation time more congruent with that typically used in the delayed discrimination task (e.g. Ricker & Cowan, 2010). The RI separating the two Fribbles was 1.5, 5 or 10 s, and participants were asked to make their same-different response as quickly as possible. For these three RIs, the ITI was 0.75 s, creating conditions labeled 1.5:0.75, 5:0.75 and 10:0.75. Two other conditions were also added to the design. These conditions had a 10 s RI but an ITI of either 5 s (10:5) or 20 s (10:20).

In total, there were five different conditions completed in separate stimulus blocks. The 1.5 s RI condition was completed in a single block of trials. Similarly, the 5 s RI condition was completed within an independent block, but the 10:0.75 and 10:5 conditions had to be divided into two (independent) blocks, each containing 12 trials. The 10:20 condition was divided into four blocks, each comprising 6 trials. The order of the blocks was randomized, as were the trials within a block. Participants completed six practice trials prior to undertaking the main procedure and were given three breaks during the course of the experiment. The study lasted approximately 45 minutes.

Results

"Table 2 about here"

Preliminary analyses. Trials on which participants pressed an invalid button (i.e. neither 'S' nor 'D') were excluded, but these were very rare (< 0.2 % of all trials). Analysis

of response times showed that 3 x *SD* was greater than 2.5 s for all participants and, following Experiment 1, trials on which response times exceeded 3 *SD*s were omitted from the analysis. This affected less than 4.5 % of the total collected data.

Recognition accuracy. Hits and false alarms were calculated in the manner described for Experiment 1 and are shown in Table 2. Following Experiment 1, hits and false alarms were used to calculate *A'* for each participant in each condition, and then the overall mean scores were computed. These data are displayed in Figure 3. Recognition performance showed a slight and unexpected increase from 1.5 to 5 s, but dropped substantially at 10:0.75. However, there was a recovery in task accuracy as the ITI in the 10 s conditions was increased. A one-way repeated measures ANOVA found a significant effect of condition, $F(4, 116) = 3.47$, $MSE = .01$, $p = .01$, $\eta_p^2 = .11$, and simple within-subject contrasts were then carried out. The 1.5 s condition was employed as the baseline category. There was no change in performance from 1.5 to 5 s ($p = .54$, $\eta_p^2 = .01$), although there was a significant decline in accuracy in the 10:0.75 condition when compared to 1.5 s ($p = .01$, $\eta_p^2 = .2$). The 10:5 and 10:20 conditions did not differ from 1.5 s ($p = .37$ and .64, respectively).

To further assess this effect, a second repeated measures ANOVA was used to compare the three conditions with a 10 s RI. There was another significant main effect, $F(2, 58) = 3.91$, $MSE = .01$, $p = .03$, $\eta_p^2 = .12$. Šidák pairwise comparisons were used to explore differences between the three 10 s conditions and this confirmed that performance in the 10:0.75 condition was significantly worse than 10:20 ($p = .04$), but not 10:5 ($p = .3$). The 10:5 and 10:20 conditions did not differ ($p = .52$).

"Figure 3 about here"

Discussion

The results from Experiment 2 presented a more complex picture of the maintenance of VSTM over the passage of time. There was a significant drop in recognition performance from 1.5 to 10 s when the ITI was 0.75 s, suggesting a loss of fine details in the representation. But this effect was removed by lengthening the ITI for the 10 s condition, with accuracy in the 10:20 condition being significantly better than 10:0.75. The beneficial effect of ITI is readily compatible with temporal distinctiveness models, which predict that isolating stimuli on successive trials will boost task accuracy by protecting the memory from proactive interference. Yet such ITI effects are harder to reconcile with decay theory. Nonetheless, Experiment 2 did not find any significant change in recognition accuracy between 1.5 and 5 s RIs – a finding that conflicts with both decay and distinctiveness accounts. The latter would predict a decline in performance since distinctiveness in the 5:0.75 condition was lower than 1.5:0.75. Within SIMPLE, this effect arises due to the logarithmic transformation of time, with temporally distant items becoming compressed and less isolated (Brown et al., 2007). The target item should therefore be harder to remember at longer RIs, unless some attempt is made to preserve distinctiveness. But these findings are analogous with Experiment 1: the ITI significantly affected task performance and there was little change in accuracy over RIs lasting between 1.5 and 6 s. Indeed, despite halving the presentation time of the target Fribble from 1.5 s to 0.75 s in Experiment 2, there was a high degree of consistency between performance in the present experiments (1.5:0.75 $A' = .81$, 2:1 $A' = .84$, 5:0.75 $A' = .83$, 6:3 $A' = .83$). This could be a result of rapid consolidation of the target Fribbles (Vogel et al., 2006), but it is encouraging that the broad pattern of results was consistent across the two experiments, despite the change to encoding time.

GENERAL DISCUSSION

The present study aimed to examine the precision with which visual information was maintained over the short-term. Particular attention was given to the fidelity of VSTM and whether accuracy was lost as time passed. The results from two experiments offered support for temporal distinctiveness models, as the ITI played an important role. In Experiment 1, the ability to discriminate the stimuli was improved when the ITI was twice the length of the RI, rather than half its duration. Experiment 2 found a significant decline in performance when the RI was extended from 1.5 to 10 s, but accuracy was restored by increasing the ITI. As such, separating stimuli on trial *N* from their recent neighbors alleviated the loss of trace accuracy and reduced short-term forgetting. These findings also demonstrated that visual information is influenced by stimuli from the recent past, which is consistent with existing work highlighting the potent influence of residual visual memories (e.g. Huang & Sekuler, 2010; Shipstead & Engle, 2013).

Distinctiveness models can easily explain the positive influence of temporal isolation reported in Experiments 1 and 2. At longer ITIs, items in memory are much less likely to be confused with other items, so proactive interference is lessened. Importantly, the decline from 1.5:0.75 to 10:0.75 is also explicable by distinctiveness theory, since items in memory are compressed as time passes. This can only be overcome by lessening temporal crowding (e.g. via extending the ITI). Conversely, the effects of ITI were not anticipated by decay theory. According to this account, the absolute passage of time determines forgetting, so ITI should not have any influence. This prediction was challenged by both experiments, and the significant improvement from 10:0.75 to 10:20 – where the RI was identical – was particularly problematic for models incorporating decay. Nonetheless, it is worth considering whether an elaboration of decay theory could account for these findings. Some authors have conceptualized decay as a way of reducing proactive interference, allowing redundant

information to be removed from memory through a decay process (e.g. Altmann & Gray, 2002). Within the context of the present study, extending the ITI may have allowed representations from previous trials to decay, reducing proactive interference and boosting recognition performance. However, this revised account actually places more emphasis on proactive interference as the cause of forgetting, with decay serving to *reduce* interference from previous stimuli. As such, this model would predict that decay is not the major source of forgetting of an actively maintained visual representation (if potentially interfering residual information has been removed, the current representation should persist over long periods of time). Additionally, whilst it would be useful to assess whether residual visual information is subjected to decay, this revised model may be difficult to distinguish from the predictions of temporal distinctiveness. In relation to the decay model tested here (with its emphasis on absolute time), it was unable to explain the effects of ITI. Yet the temporal distinctiveness model also had difficulty with some of the findings.

Specifically, the stability of visual memory over 6 s periods was unexpected and contradicted some previous findings. As noted previously, Ricker and Cowan (2010) reported a drop in the fidelity of VSTM over RIs lasting between 1.5 and 6 s. The present study shared some similarities with Ricker and Cowan, including the use of novel and unfamiliar stimuli, but there were differences in the size of the visual arrays. In the present experiments, individual objects were shown on each trial, whereas Ricker and Cowan employed three target stimuli. Such differences in set size are likely to be important, since it may be harder to remember multiple items over RIs (Bays et al., 2009; Bays & Husain, 2008). This could explain why Ricker and Cowan found more rapid time-based forgetting over RIs up to 6 s, whereas the present study did not.

Nonetheless, whilst the set size used in the present study appears limited in comparison with some previous experiments, the differences that participants were asked to identify were

quite subtle and required the detection of changes to particular features. The present stimuli
were also more complex than those typically used in visual memory studies, consisting of 3D
objects with a body and four different appendages. Such images may be more difficult to
retain in visual memory than simpler ones (Eng et al., 2005; Luria, Sessa, Gotler, Joicœur, &
Dell'Acqua, 2010), yet forgetting was not significantly manifested until the RI had exceeded
6 s.

VSTM for individual complex stimuli can persist with a high degree of accuracy over
short periods of time, which was not anticipated by decay or distinctiveness models. Yet the
primary contribution of the present study has been to show that VSTMs are affected by their
temporal proximity to other representations. The importance of considering temporal
distinctiveness has also been highlighted within the wider memory literature. For example,
the advantageous effect of temporal isolation has been reported in verbal memory under
certain conditions (e.g. Geiger & Lewandowsky, 2008; Lewandowsky, Nimmo, & Brown,
2008; Morin, Brown, & Lewandowsky, 2010), but temporal distinctiveness models have also
been challenged, since many studies have failed to uncover temporal isolation effects (see
Farrell, Wise, & Lelièvre, 2011). Similarly, evidence challenging temporal distinctiveness –
but supporting trace decay – has been reported for abstract auditory short-term memory. Two
recent studies of acoustical memory did not find any temporal isolation effects using a
delayed two-tone comparison task, indicating that distinctiveness cannot explain the loss of
auditory representations over the passage of time (McKeown & Mercer, 2012; Mercer &
McKeown, 2014). Most recently, Mercer and McKeown (2014, Experiment 2) asked
participants to compare two abstract complex tones varying in timbre. The tones were
separated by RIs of 2 and 32 s, with the ITI being 2 or 34 s. There was a significant decline in
task performance as the RI was extended, but ITI duration was irrelevant. Perhaps there are
fundamental differences between auditory and visual memory (but see Visscher, Kaplan,

Kahana, & Sekuler, 2007), although the ITI duration used in this tone discrimination experiment may have been too short to reveal any performance advantage at 32 s intervals. In the present Experiment 2, the ITI was particularly beneficial when it was *double* the duration of the RI. This is congruent with distinctiveness models where the ratio of the RI to the ITI is important (Brown et al., 2007). A 64 s ITI might have conferred a similar advantage in the 32 s condition of Mercer and McKeown. Alternatively, decay for individual visual objects may not manifest itself until a very long period of time has passed. Finally, it is possible that both distinctiveness and decay effects can be found, and future studies could more thoroughly explore this issue by using a variety of RIs and ITIs, including intervals greatly exceeding the 10 s used in Experiment 2.

It would also be of interest to examine the changes that occur to the visual representations as time passes. In the present experiment participants had to detect alterations to individual features within the target and test Fribbles. Intriguingly, Fougnie and Alvarez (2011) have shown that items within visual memory are not necessarily represented as integrated objects and different features comprising an object can be forgotten independently. The forgetting observed in the present study could have been due to failure to remember specific features of the Fribble stimuli, particularly within temporally crowded contexts. Further investigation to the type of changes occurring within the visual representations would be beneficial, particularly if explored using a distinctiveness framework.

In summary, whilst the temporal distinctiveness account could not explain the full set of findings reported here, it provided a useful explanation of the influence of ITI. Visual representations endured in a highly resolved state for at least 10 s, if they were temporally isolated from their neighbors. Whilst this finding was problematic for decay theory, with its reliance on the passage of absolute time, this study suggested that temporal distinctiveness models might provide a valuable framework for understanding visual memory and forgetting.

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TABLES

Table 1.

Mean Hit and False Alarm Rates in Experiment 1

Condition (RI:ITI)	Hits (*SD*)	False alarms (*SD*)
2:1	.78 (.15)	.27 (.18)
2:4	.85 (.11)	.25 (.15)
6:3	.77 (.13)	.28 (.17)
6:12	.81 (.19)	.24 (.16)

Table 2.

Mean Hit and False Alarm Rates in Experiment 2

Condition (RI:ITI)	Hits (*SD*)	False alarms (*SD*)
1.5:0.75	.73 (.16)	.23 (.13)
5:0.75	.72 (.17)	.23 (.15)
10:0.75	.67 (.16)	.33 (.16)
10:5	.76 (.12)	.34 (.20)
10:20	.84 (.16)	.34 (.19)

FIGURE CAPTIONS

Figure 1. Example Fribble stimuli. Items on each row show examples of the three Fribble families (A, B and C, respectively). The two Fribbles on each row are drawn from the same family and species, but differ in two of their four appendages.

Figure 2. Mean *A'* in each condition of Experiment 1. Errors bars show +/-1 *SE*, corrected for the repeated measures design.

Figure 3. Mean *A'* in each condition of Experiment 2. Error bars show +/-1 *SE*, corrected for the repeated measures design.
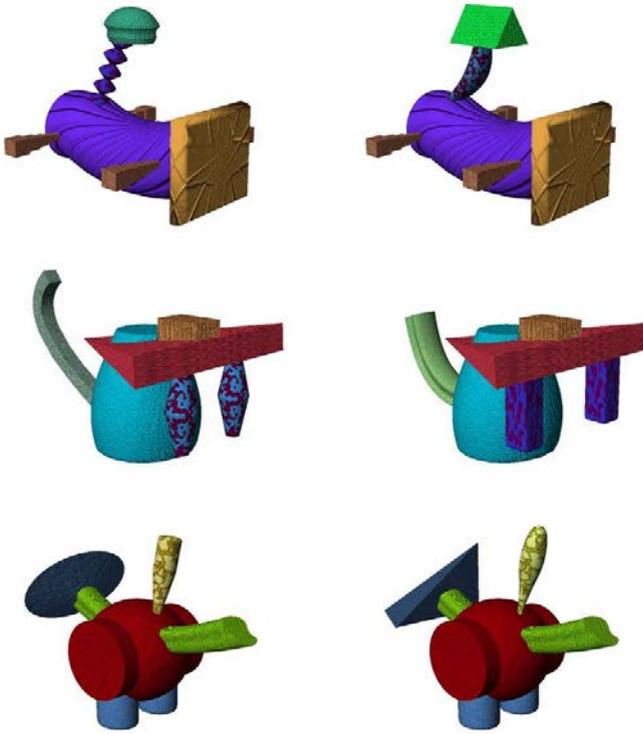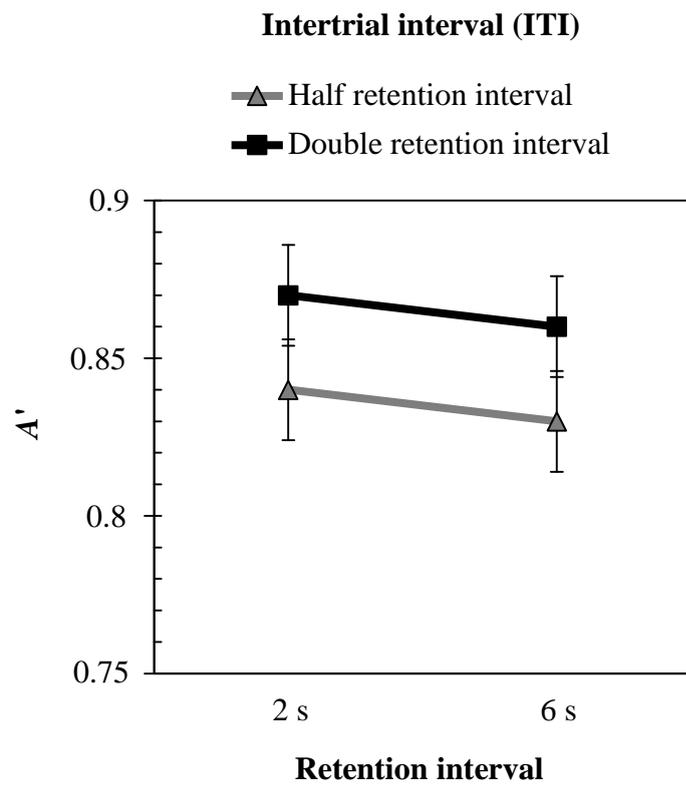
Figure 1.

Figure 2.

Intertrial interval (ITI)

Figure 3.

0.75 s iTI

e 5 s ITI

A 20 s ITI

Retention interval