Psychon Bull Rev
DOI 10.3758/s13423-014-0675-5

BRIEF REPORT

Verbal labeling, gradual decay, and sudden death in visual short-term memory

Chris Donkin · Robert Nosofsky · Jason Gold · Richard Shiffrin

Abstract Zhang and Luck (*Psychological Science*, *20*, 423–428, 2009) found that perceptual memories are lost over time via sudden death rather than gradual decay. However, they acknowledged that participants may have instead lost memory for the locations of objects. We required observers to recall only a single object. Although the paradigm eliminated the need to maintain object–location bindings, the possibility that observers would use verbal labels increased. To measure the precision of verbal labeling, we included explicit verbal-labeling and label-matching trials. We applied a model that measured the contributions of sudden death, gradual decay, and verbal labeling to recall. Our model-based evidence pointed to sudden death as the primary vehicle by which perceptual memories were lost. Crucially, however, the sudden-death hypothesis was favored only when the verbal-labeling component was included as part of the modeling. The results underscore the importance of taking into account the potential role of verbal-labeling processes in investigations of perceptual memory.

Keywords Visual working memory · Short-term memory · Mathematical models · Working memory

In the present research, we explored the way that visual short-term memories are lost over time. Zhang and Luck (2009) provided evidence that the precision of memory for the continuous value of visual objects is lost in an all-or-none fashion ("sudden death"), rather than gradually. According to this view, the initial memory that is formed is maintained in its entirety until some moment in time, at which it is suddenly and completely lost.

Zhang and Luck (2009) used a *continuous-recall paradigm* (Wilken & Ma, 2004; Zhang & Luck, 2008). On each trial, observers saw a brief visual display of three colored squares. Following a variable retention interval, a single location of the visual display was probed. The observer was required to recall the color at that location by clicking on the appropriate portion of a continuous color wheel.

Zhang and Luck (2009) developed a formal model for predicting observers' recall judgments. The model provided separate estimates of (1) the probability that a memory representation for the color existed at the time that it was probed and (2) the precision of that representation. In brief, perceptual memory for the original color was presumed to follow a bell-curve probability distribution centered on the true value of the color. Gradual decay was modeled in terms of increased variance of that distribution. By contrast, in the event that there was sudden death of the memory representation, observers would be forced to randomly guess the value of the original color. Using this model, Zhang and Luck found that the probability that a representation for the color existed in memory was a decreasing function of the length of the retention interval. However, the precision of that representation was invariant with time; that is, they found no evidence for a role of gradual decay.

As was acknowledged by Zhang and Luck (2009, p. 427), observers may have sometimes forgotten the appropriate feature–location bindings (cf. Bays, Catalao, & Husain, 2009). If, with some probability, observers report the color of an item from a different location than the one that was probed, then application of their model would yield results consistent with random guessing.

Electronic supplementary material The online version of this article (doi:10.3758/s13423-014-0675-5) contains supplementary material, which is available to authorized users.

C. Donkin (✉)
School of Psychology, University of New South Wales, Matthews Building, Kensington, NSW 2052, Australia
e-mail: christopher.donkin@gmail.com

R. Nosofsky · J. Gold · R. Shiffrin
Indiana University, Bloomington, IN, USA

Published online: 26 June 2014

To address this limitation, we conducted a study like that of Zhang and Luck (2009) to assess whether perceptual memories are lost due to sudden death or gradual decay. However, in our paradigm, on each trial there was only one object to be remembered. Although a single-object paradigm eliminated the need for observers to bind color and location, it increased the possibility that observers might verbally encode the study item with a label and augment their judgments with memory of the label.

We addressed this possibility by measuring explicitly the precision of memory associated with a verbal label and incorporated the memory for labels in an extended version of the recall model. On some trials, observers were explicitly required to produce a verbal label for the presented stimulus. To measure the precision of label memory, the observers were presented with their label three trials later and asked to reproduce the continuous value of the original stimulus by making use of their label. We used a delay of three trials between the production of the verbal label and the subsequent reproduction of the color corresponding to the label in order to minimize the contribution of any remaining perceptual memory for the original stimulus. Thus, these label-matching trials would provide a reasonable estimate of the precision allowed by verbal-labeling processes alone. The extended model allows one to estimate the separate contributions of perceptual memory, guessing, and verbal labeling to the continuous-recall process and to test how these components are influenced by the passage of time.[1]

To anticipate, we found evidence that under the present conditions, observers did indeed make extensive use of verbal labeling. Furthermore, modeling the verbal-labeling component was crucial to our drawing inferences about whether perceptual memories were lost via sudden death or gradual decay. We emphasize at the outset that we are not suggesting that verbal labeling is used as prevalently in other visual-memory paradigms as in the present one. Instead, our measurement and modeling of verbal labeling was used as a vehicle in the present work to help assess the nature of perceptual-memory loss—that is, whether it arises due to sudden death or gradual decay. As we suggest in our General Discussion, however, the extent to which verbal labeling may influence performance in other visual-memory paradigms is an extremely important question, and the present methods could contribute to addressing it.

Experiment

Method

Participants The participants were eight members of the Indiana University community reimbursed $10 per session, plus a bonus of up to $3 for good performance. All had normal or corrected-to-normal vision, and all reported having normal color vision.

Stimuli The stimuli, similar to those described in Zhang and Luck (2008, 2009), were 2° × 2° filled colored squares presented on a gray background. On each trial, a single square could appear in one of eight possible locations equally spaced around a centrally displayed virtual circle with radius 4.5°. Responses were indicated by a position selected from a color wheel containing 181 colors that were evenly spaced around a circle in the L*a*b* color space (L = 50, a = 10, b = 10, with a radius of 40 units). To decouple color-based and location-based responding, the color wheel was randomly rotated between 0° and 360° on each trial. Further details regarding the stimulus characteristics are provided in the online Supplement.

Procedure The structure of the experiment is depicted in Fig. 1. We manipulated presentation duration (0, 0.1, 0.5, or 2 s)[2] and the delay between study and test (0.1, 0.5, 1, 4, or 10 s). All trials began with a 500-ms fixation cross, followed by the presentation of a single randomly selected stimulus. On standard trials, following the retention interval the color wheel was presented, and the participant used the mouse to click on the part of the wheel that corresponded to the studied item. Participants were then given feedback on how closely their response matched the study item (see the Supplement). Labeling trials began like standard trials. However, following

[1] van den Berg, Shin, Chou, George, and Ma (2012) and Fougnie, Suchow, and Alvarez (2012) proposed variable-resources models to account for visual working memory limitations in designs involving multi-element displays. According to their models, in cases in which an item is given minimal encoding resources, it may be associated with a highly diffuse perceptual distribution, resulting in what is essentially guessing behavior. Such a model might be adapted to the present paradigm by assuming highly variable rates of perceptual decay with the passage of time. In our view, if "gradual decay" of a perceptual representation is taken to include the sudden generation of a highly diffuse perceptual representation, then there is little functional distinction between the sudden-death and gradual-decay hypotheses. In our present inquiry, we limited consideration to cases in which gradual decay results in perceptual representations that are at least as precise as what can be achieved through verbal labeling.

[2] Because guessing is a major component of the sudden-death model, we also included a set of catch trials in which the participant was presented with no study item (i.e., the study duration was 0 s). These trials were identical in every way to standard trials, except that instead of a study item, a gray outline of a square was presented for one frame. Participants were informed at the outset of the experiment that on some trials, items would be flashed so quickly that they would hardly perceive them, but to try their best to respond accurately on all trials. The purpose of this manipulation was to measure whether participants tended to guess with particular colors or locations on the response device, in the absence of any perceptual information. We observed that a common behavior on those trials was for participants to click on the top location of the color wheel; however, that behavior did not appear to translate to the standard trials. Possibly the forms of guessing that take place when observers believe that they once knew the identity of an item are different from those that take place on the "never-knew" trials.

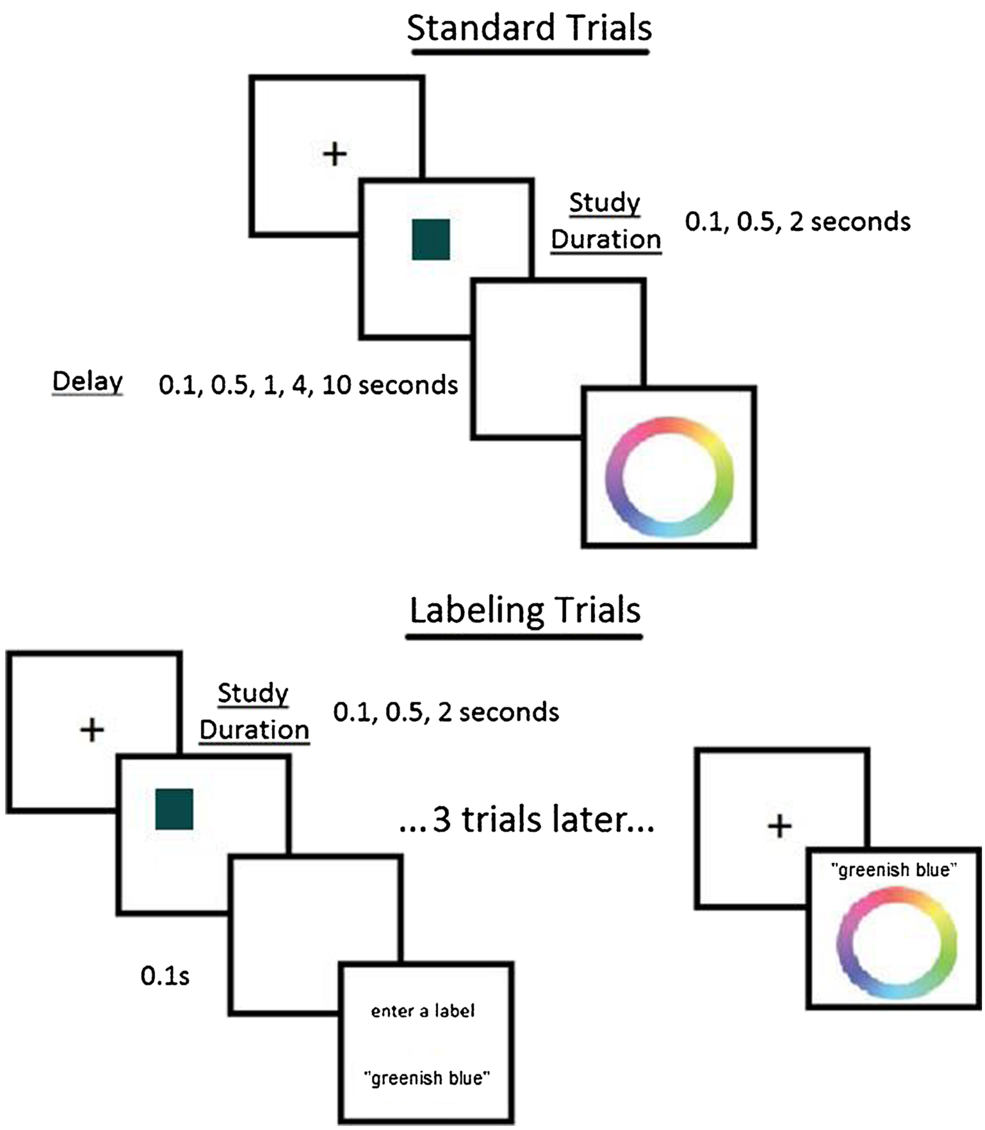

Fig. 1 Visual depiction of the trial structure on standard sample-matching and label-matching trials. The study-duration and delay-interval conditions (the 0-s study duration is not shown) are also listed

presentation of the stimulus and a 0.1-s delay, instead of recalling the stimulus, participants were asked to provide a label for the studied color by typing on a computer keyboard. Three trials later, participants were presented with the label (in text on the screen) and clicked on the part of the color wheel that best matched this label. Feedback was the same as on the standard trials. Our assumption was that following three intervening trials, any remaining perceptual memory for the original color would be minuscule. Therefore, these label-matching trials would provide a good estimate of the precision allowed by verbal-labeling processes alone.

Participants completed 300 standard trials and 75 labeling trials in each of six sessions, with each condition occurring equally often. For each participant, this produced 90 observations per combined study-duration/retention-interval condition for standard trials, and 150 observations per study-duration condition for labeling trials.

Results

We analyzed and modeled the data in terms of the distribution of responses around the value of the to-be-remembered stimulus (termed *zero*). Figure 2 plots the distribution of responses on labeling trials, aggregated across individuals. It is clear from inspection that as the study duration increased, the labeling distributions for the colors grew more precise (i.e., less variable).

Figure 3 plots the aggregated distribution of responses on standard trials for each study duration and delay interval. The variance of responses decreases as a function of increasing

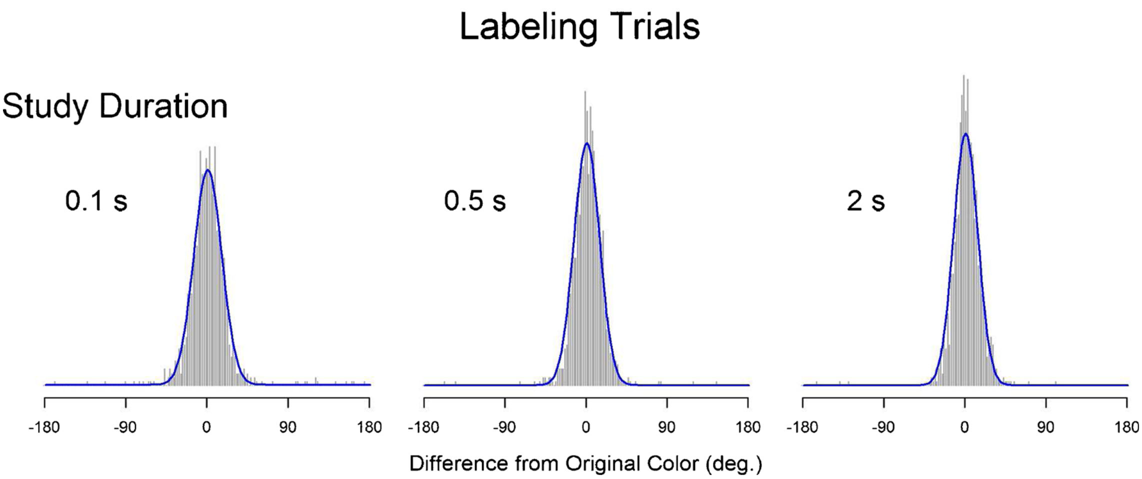

Fig. 2 Aggregated distributions of responses on labeling trials as a function of study duration. The best-fitting mixture of a normal and uniform distribution is shown as a solid line. The precision of the normal distribution fit to labeling trials was used to predict the precision of responses based on labeling on standard trials. Note that the scales of the *y*-axes are identical for all distributions

study duration—that is, as one moves from left to right across the figure. The variance of responses also increases as a function of increasing delay interval—that is, as one moves from top to bottom of the figure—though the increase is most pronounced for the 4- and 10-s delays.

Model-based analysis

The formal model

Our model extends that of Zhang and Luck (2009) by assuming that responses are a mixture of three distributions: one based on visual memory, one based on random guesses, and one based on verbal labeling. We assumed that, at time of test, the studied item would be in visual memory with probability p, in which case the response generated by the participant would come from a normal distribution with mean 0 and standard deviation σ.[3] Otherwise, there were two possibilities: With conditional probability q, the verbal label was used to generate the response, on the basis of a normal distribution with mean 0 and standard deviation γ; and with conditional probability $1 - q$, the responses were assumed to represent guessing. The distribution of guessing errors was modeled as a uniform distribution across the stimulus range (from −180° to 180°).

In our primary analyses, we assumed that the verbal labels would not be forgotten (or decay in quality) over the course of 10 s (see the General Discussion for subsidiary analyses that support this assumption). As such, the conditional probability that the verbal label was used, q, and the standard deviation of the labeling distribution, γ, were held constant across all delay intervals. We did allow the probability of generating a label and the precision of that label to vary with study duration.

Thus, the probability density of a response deviation of magnitude x in the ith study-duration condition and the jth delay-interval condition $D_{ij}(x)$ was given by

$$D_{ij}(x) = p_{ij}\cdot \mathrm{N}\left(x\middle|0,\sigma_{ij}\right) + \left(1-p_{ij}\right)\left[q_i\cdot \mathrm{N}\left(x\middle|0,\gamma_i\right) + (1-q_i)\cdot \mathrm{U}(x)\right], \quad (1)$$

where $\mathrm{N}(x \mid 0, b)$ is a normal distribution with mean zero and standard deviation b, and $\mathrm{U}(x)$ is a uniform density across the range of tested stimuli.

We fit four main versions of the model above based on the combination of the following two factors: (1) The models either used labeling (the q_is were free parameters) or did not use labeling (the q_is were fixed at zero), and (2) the models either assumed "sudden death" of visual memory (p varied and σ was fixed across delay intervals j) or "gradual decay" of visual memory (p was fixed and σ varied across delay intervals j). We refer to the sudden-death and gradual-decay models that used labeling as SD_L and GD_L, respectively, and the versions of those models that did not use labeling are denoted SD_{NL} and GD_{NL}. In all cases, the models allowed that study duration might influence the encoding of the study item (and so influence p, σ, q, and γ). To reduce the number of free parameters, we assumed that p_{ij} was given by

$$p_{ij} = p_{Si} \times p_{Dj}, \quad (2a)$$

[3] Note that Zhang and Luck (2009) had used a von Mises distribution instead of a normal distribution. The von Mises distribution is a normal distribution that is wrapped around a circle. Although such a distribution is theoretically more appropriate, we found that the precision of participants' responses was great enough that the von Mises distribution added unnecessary computational complexity. A number of "spot checks," wherein we refit individuals with the von Mises distribution, suggested that our conclusions are not dependent on which distribution was used.

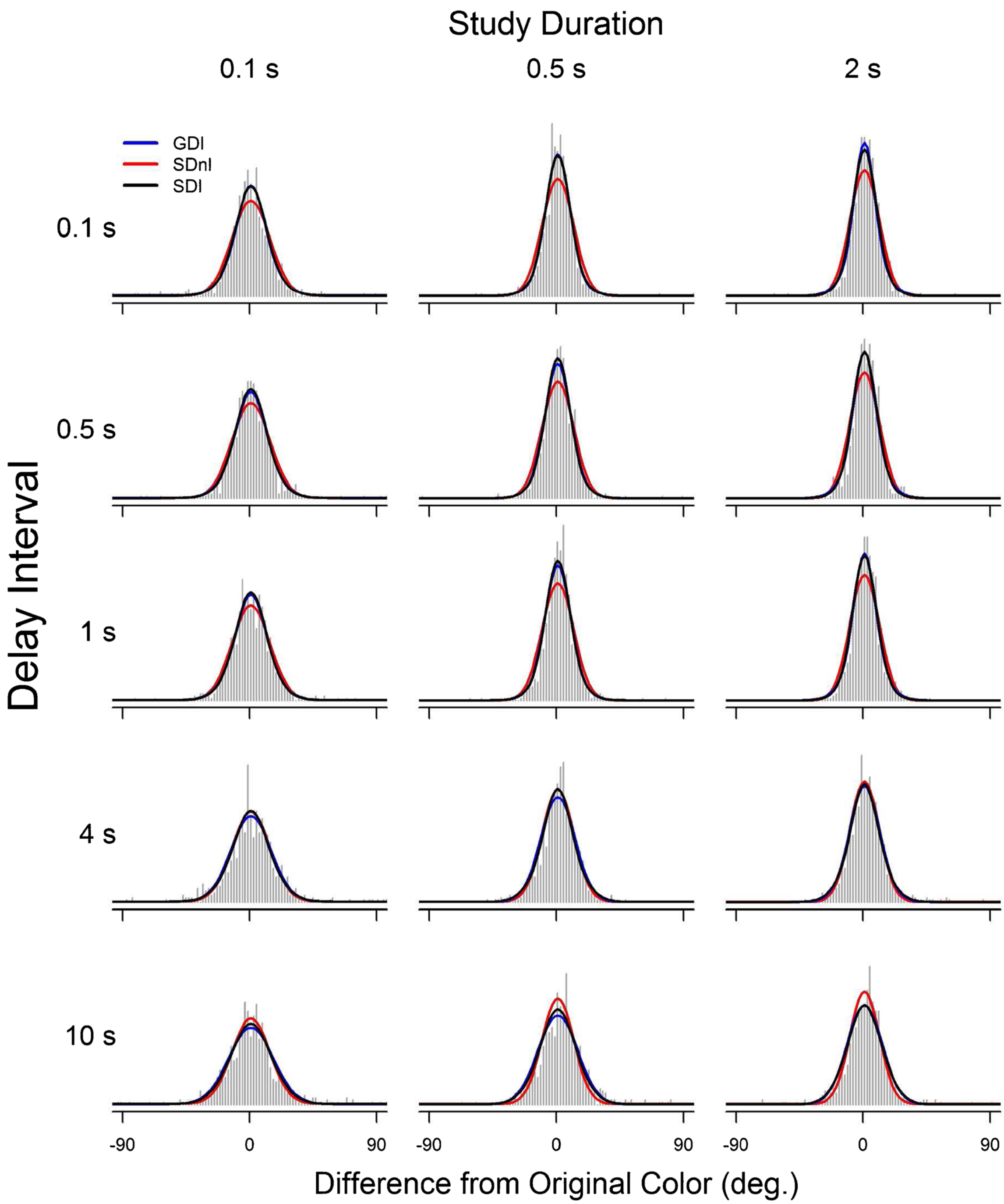

Fig. 3 Distributions of responses for standard sample-matching trials as a function of study duration (columns) and delay interval (rows). The predictions of the gradual-decay model with labeling (GDl) and the sudden-death model with and without labeling (SDl and SDnl, respectively) are shown in separate lines. These plots zoom in on the response errors from –90 to 90 deg because response errors beyond that range were extremely rare. Note that the scales of the *y*-axes are identical for all distributions

where p_{Si} $(0 < p_{Si} \leq 1)$ depends only on study-duration level *i*, and p_{Dj} $(0 < p_{Dj} \leq 1)$ depends only on delay interval *j*. Analogously, we assumed that σ_{ij} was given by

$$\sigma_{ij} = \sigma_{Si} \times \sigma_{Dj}, \quad (2b)$$

where $0 < \sigma_{Si}$ and $0 < \sigma_{Dj}$. Furthermore, we assumed that *p* could only decrease and that σ could only increase with increasing delay interval. Importantly, our conclusions do not depend on whether the full or the constrained versions of the models were used.

Finally, rather than freely estimating the precision of verbal memory γ from standard trials, we use the precision of responses made on labeling trials to fix the values of γ used in the model.

Recall that we used three study-duration conditions and five delay-interval conditions. Thus, the SD_{NL} model had ten free parameters (three σ_{Si} parameters, three p_{Si} parameters, and four p_{Dj} parameters; without loss of generality, p_{D1} can be held fixed at one). The GD_{NL} model also had ten free parameters (three σ_{Si} parameters, four σ_{Dj} parameters, and three p_{Si} parameters). The SD_L and GD_L models each had an additional three free parameters: a q_i parameter for each study duration.

Criterion of fit

The models were fit to each participant's response distributions using standard maximum-likelihood methods (see the Supplement). To penalize models for using additional free parameters, we then transformed the log-likelihood (ln L) values into Akaike information criterion (AIC) values:

$$\mathrm{AIC} = -2 \ln L + 2n_p,$$

where n_p is the number of free parameters in the model. The model that yields the smallest AIC is considered to provide the most parsimonious account of the data.[4]

Model-fitting results

The AIC values for each of the four models for each individual are reported in Table 1. First, note that making allowance for labeling yielded an improved AIC for the GD model in seven of eight cases and an improved AIC for the SD model in eight of eight cases. For the SD model, these improvements in AIC were dramatic. These model-fitting results provide convincing evidence for the role of a verbal-labeling process.

Furthermore, assuming that one makes allowance for labeling, the SD model is clearly favored as compared to the GD model. In six of eight cases, the AIC fit for the SD_L model is better than that for the GD_L model, and in most of these cases the advantage is clear cut (i.e., greater than or equal to five AIC points). By contrast, in only one case does the GD_L model yield a clearly smaller AIC than does the SD_L model. The AIC summed across participants is far smaller for the SD_L model than for the GD_L model. Thus, the balance of evidence favors the sudden-death hypothesis.

[4] We conducted extensive model-recovery analyses to test whether the AIC or an alternative, the Bayesian information criterion (BIC) statistic, was a more appropriate model-selection tool in the present situation. Those recovery analyses pointed decidedly toward the AIC statistic—see the Supplement for details.

It is instructive to note that had we not made allowance for labeling, the conclusions would have been dramatically reversed. Restricting consideration to the no-labeling models, in almost all cases the GD_{NL} model yields far better AIC fits than does the SD_{NL} model. The SD model without verbal labeling is unable to account for the increase in variance of responses without random guesses. This result underscores the critical importance of taking into account possible verbal-labeling processes in investigations of perceptual memory.

The aggregated predicted response curves from the GD_L, SD_L, and SD_{NL} models are plotted as solid lines, along with the aggregated data, in Fig. 3. Visual inspection suggests that the SD_{NL} model provides the worst account of the data, predicting too much variance in the response distributions at short delays, and too little variance at long delays. The aggregated predictions from the SD_L model appear to be slightly better than those of the GD_L model.

Hybrid model For completeness, we also fitted a hybrid model to the data that included verbal labeling and that assumed that both sudden death and gradual decay occurred as the retention interval increased. The hybrid model always yielded worse AIC fits to the data than did the best SD model. Although the worse fits of the hybrid model do not rule out the possibility that gradual decay played a role, it appears that sudden death played the dominant role under the present testing conditions.

Best-fitting parameters

The averaged values of the best-fitting parameters from the SD_L model are shown in Fig. 4. The conditional probability of using verbal labeling increased with study duration, and was extremely high in the 0.5-s and 2-s study-duration conditions. Also, the probability of using visual memory decreased with increasing delay intervals, although this effect was most pronounced for delay intervals of 4 and 10 s. The standard deviations of the perceptual error distributions tended to grow smaller with increased presentation durations. The standard deviations of the verbal-labeling distributions were greater than those of the perceptual distributions.

General discussion

Summary

Our analyses suggest the roles of three discrete states of memory. One state is based on perceptual memory and has high precision that does not decay until it dies in an all-or-none fashion. A second state has intermediate precision, which we presume is based on verbal labeling. A pure

Table 1 AIC values for each participant

	Participant								
Model	1	2	3	4	5	6	7	8	Sum
GD_{NL}	1,942	1,963	2,413	2,279	2,005	1,688	1,546	1,619	15,455
GD_{L}	1,942	**1,953**	2,411	2,269	1,993	**1,688**	1,550	1,618	15,424
SD_{NL}	1,956	1,989	2,403	2,295	2,011	1,721	1,595	1,625	15,595
SD_{L}	**1,935**	1,962	**2,387**	**2,265**	**1,981**	1,691	**1,545**	**1,608**	**15,374**

GD = gradual decay, SD = sudden death, NL = no labeling, L = labeling. Boldface entries denote the best-fitting model for each participant

guessing state is used when neither other form of memory is available.

That the intermediate memory state is related closely to verbal labeling is strongly suggested by the fact that our model for regular trials did well when using the precision estimated from the labeling trials. Moreover, making provision for the verbal-labeling component was crucial to our subsequent inferences about whether short-term perceptual memory for color was lost due to sudden death or gradual decay. In particular, the sudden-death hypothesis was favored only when the verbal-labeling component was included as part of the model. Such results underscore the importance of taking into account the potential role of verbal-labeling processes in investigations of perceptual memory.

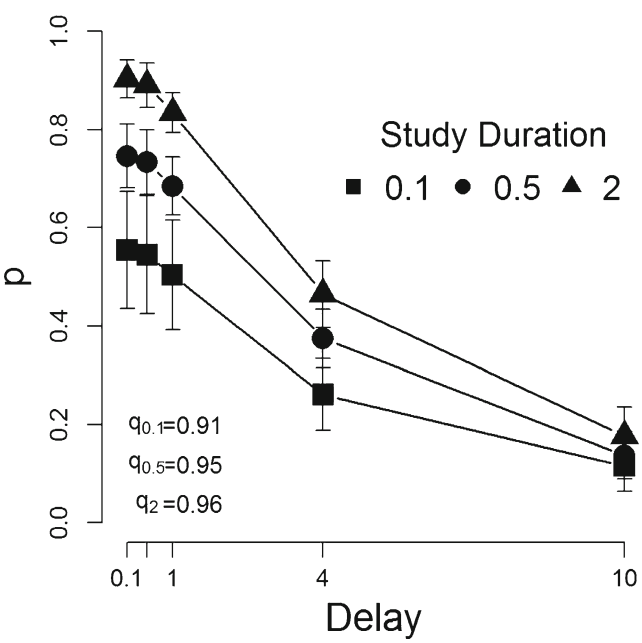

Fig. 4 The p parameters of the SD_L model are plotted as a function of study duration and averaged over individuals. The conditional probability of using verbal labeling, q, is also reported for each study-duration condition. Error bars represent standard errors of the means. The average standard deviation parameters, σ_{Si}, for durations of 0.1, 0.5, and 2 s are 11.65 (SE = 2.4), 8.61 (SE = 0.71), and 8.88 (SE = 0.75) deg. The average standard deviation parameters for verbal labels, γ_i, as estimated on labeling trials, were 15.6 (SE = 1.2), 13.9 (SE = 0.99), and 13.3 (SE = 0.87)

Alternative modeling assumptions

Although one might posit alternative mechanisms by which perceptual memory, verbal labeling, and guessing are combined and operate, the bottom line is that, under the present conditions, the present formulation already provides a significant improvement over the standard two-component model (based on only perceptual memory plus guessing). Thus, the present extensions involving the potential role of verbal labeling take the field an important step forward.

We acknowledge that our conclusions pertaining to sudden death and gradual decay, like all such conclusions, are model-dependent and that future alternative models could point in different directions. In follow-up analyses, we did consider two major alternatives. First, recall that in our primary modeling analyses we assumed that if a verbal label was formed at the onset of the trial, that verbal label would not be forgotten over the course of a 10-s retention interval. In one set of follow-up analyses, we considered more complex models in which the probability of retaining the verbal label was allowed to decay over the course of the retention interval (see the Supplement for details). As it turned out, those more complex models tended to yield worse AIC fits to our data than did the primary model that was the focus of article. Furthermore, application of those models did not change our conclusions about whether perceptual memory loss operated in accord with sudden death versus gradual decay.

Second, recall that our primary model assumed that the precision afforded by verbal labeling was constant over the 10-s retention interval. That is, assuming that the verbal label is formed and retained, the precision to which it gives rise remains the same. An alternative view is that the verbal label might somehow allow the observer to partially reconstruct the original perceptual image itself. If so, then the precision to which the verbal label gives rise might vary with the delay interval. To investigate this possibility, we fitted more complex models in which the verbal-label precision was allowed to vary with delay. Again, these models yielded worse AIC fits to our data than did our primary model and did not result in changed conclusions about whether perceptual memory is lost due to sudden death or gradual decay (see the Supplement for details).

Finally, yet another possibility, which we have not formally investigated, concerns our assumption that the perceptual error distributions are normal in form. van den Berg et al. (2012) argued for the merits of a variable-precision model in which the variance of the error distributions is itself variable across items and trials, leading to distributions that are not normal. It is an open question whether application of such types of variable-precision models might yield differing conclusions about the operations of sudden death versus gradual decay in our paradigm.

Issues for future research

Converging evidence for a role of verbal labeling It is important that future research seek converging evidence for the verbal-labeling interpretation of the results. One approach might be to conduct experimental manipulations that would be expected to selectively interfere with observers' ability to generate verbal labels for the objects. For example, observers might be required to engage in articulatory suppression or in concurrent verbal working memory tasks at the same time that they attempted to maintain visual memories. If those manipulations had a selective influence on the estimated label-use and label-precision parameters (q and γ), this would provide converging evidence for our verbal-labeling interpretation. In addition, comparison conditions should also be conducted in which an explicit requirement to produce verbal labels was not included. Possibly, the verbal-labeling trials that we included in our experiments might have promoted more widespread use of that strategy than would have occurred under more neutral testing conditions. Finally, future research might also investigate more extensively our assumption that following three intervening trials, any perceptual memory for the original color was minuscule, and that the precision estimated from the label-matching trials provides a reasonable estimate of verbal-labeling precision. For example, the number of trials between the construction of the verbal label and when a response was made using that label could be systematically manipulated.

To reiterate our caveat in our introduction, we do not suggest that verbal labeling is as prevalent in other visual-memory paradigms as apparently occurred in ours. Nevertheless, it seems reasonable to us that it could have at least *some* influence in other paradigms, and that obtaining measures of verbal-labeling precision is of general importance. To take just one example, Brady, Konkle, Gill, Oliva, and Alvarez (2013) compared the precision of long-term memory to that of working memory. In their Experiment 2, observers were presented with 180 working memory trials in which a single colored object was presented for 3 s on each trial. After a 1-s delay, observers attempted to recall the color on the color wheel. In a comparison long-term memory condition, observers viewed a complete list of 180 colored objects and engaged in continuous recall of the colors only after presentation of the complete list. Application of the Zhang and Luck (2009) measurement model revealed both dramatically increased guessing in the long-term memory condition and lower precision for remembered colors. Although the lowered precision might be taken as evidence for a role of gradual decay, we note here that the researchers did not obtain explicit measures of the precision that could be achieved through verbal labeling. In the working memory condition, with only a 1-s delay, observers presumably almost always relied on their perceptual memories. It seems plausible to us, however, that observers might often have relied on memory for verbal labels in the long-term memory condition, which would have a profound effect on the measures of perceptual precision that were obtained.[5]

Multiple mechanisms of visual-memory loss Our present research was limited to an investigation of visual-memory loss in a single domain, namely color. It is an open question whether similar results would be observed in other domains. For example, although colors are generated by varying a single physical attribute, color is nevertheless a multidimensional psychological attribute. Furthermore, it varies qualitatively on a metathetic continuum, in contrast to unidimensional psychological attributes such as brightness, that vary quantitatively on prothetic continua (Stevens & Galanter, 1957). Furthermore, it appears that observers are able to generate a very large number of distinct labels for verbally coding different colors, in contrast to what seems possible for unidimensional prothetic attributes. Possibly, the dominant mechanisms of visual-memory loss may be influenced by any of the above-mentioned factors.

Alternative paradigms for measuring gradual decay and sudden death Finally, although the continuous-recall paradigm provides a highly creative approach to disentangling the contributions of gradual decay and sudden death, it will be important to seek converging evidence through the use of alternative paradigms. One potential problem with the continuous-recall paradigm is that the presentation of the continuous response device (e.g., the color wheel) may in itself be highly interfering of the original visual memories. In our color-recall experiment, we included retention intervals

[5] Brady et al. (2013, p. 987) briefly mentioned a control experiment in which participants performed a verbal interference task and in which similar estimates of precision were obtained; however, participants might still be able to form and remember verbal labels in the presence of such interference.

of 0.1, 0.5, and 1 s because we hypothesized that the operation of gradual-decay mechanisms might predominate at those short intervals. (Indeed, at 0.1-s and 0.5-s delays, iconic memory might be involved.) However, the presentation of the color wheel might lead to sudden interference with fine-grained visual memories, which could explain why the response distributions were nearly invariant across those intervals. Possibly, the use of the more standard discrimination and change-detection paradigms, combined with information regarding change-detection *decision times* (e.g., Donkin, Nosofsky, Gold, & Shiffrin, 2013; Pearson, Raskevicius, Bays, Pertzov, & Husain, 2014), would provide more diagnostic information about these detailed characteristics of visual short-term memory.

Acknowledgements The work was supported by a Project Development Team within ICTSI NIH/NCRR Grant Number TR000006 to Robert Nosofsky, and an ARC Discovery Projects Scheme DE130100129 to Chris Donkin.

References

Bays, P. M., Catalao, R. F. G., & Husain, M. (2009). The precision of visual working memory is set by allocation of a shared resource. *Journal of Vision, 9*(10), 7.1–711. doi:10.1167/9.10.7

Brady, T. F., Konkle, T., Gill, J., Oliva, A., & Alvarez, G. A. (2013). Visual long-term memory has the same limit on fidelity as visual working memory. *Psychological Science, 24,* 981–990. doi:10.1177/0956797612465439

Donkin, C., Nosofsky, R. M., Gold, J. M., & Shiffrin, R. M. (2013). Discrete-slots models of visual working-memory response times. *Psychological Review, 120,* 873–902. doi:10.1037/a0034247

Fougnie, D., Suchow, J. W., & Alvarez, G. A. (2012). Variability in the quality of visual working memory. *Nature Communications, 3,* 1229. doi:10.1038/ncomms2237

Pearson, B., Raskevicius, J., Bays, P. M., Pertzov, Y., & Husain, M. (2014). Working memory retrieval as a decision process. *Journal of Vision, 14*(2), 2:1–15. doi:10.1167/14.2.2

Stevens, S. S., & Galanter, E. H. (1957). Ratio scales and category scales for a dozen perceptual continua. *Journal of Experimental Psychology, 54,* 377–411.

van den Berg, R., Shin, H., Chou, W. C., George, R., & Ma, W. J. (2012). Variability in encoding precision accounts for visual short-term memory limitations. *Proceedings of the National Academy of Sciences, 109,* 8780–8785. doi:10.1073/pnas.1117465109

Wilken, P., & Ma, W. J. (2004). A detection theory account of change detection. *Journal of Vision, 4*(12), 1120–1135. doi:10.1167/4.12.11

Zhang, W., & Luck, S. J. (2008). Discrete fixed-resolution representations in visual working memory. *Nature, 453,* 233–235. doi:10.1038/nature06860

Zhang, W., & Luck, S. J. (2009). Sudden death and gradual decay in visual working memory. *Psychological Science, 20,* 423–428. doi:10.1111/j.1467-9280.2009.02322.x