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Brief article

Prolonged focal attention without binding: Tracking a ball for half a minute without remembering its color

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ABSTRACT

Conventional theories of cognition focus on attention as the primary determinant of working memory contents. However, here we show that about one third of observers could not report the color of a ball that they had just been specifically attending for 5–59 s. This counterintuitive result was obtained when observers repeatedly counted the passes of one of two different colored balls among actors in a video and were then unexpectedly asked to report the color of the ball that they had just tracked. Control trials demonstrated that observers' color report performance increased dramatically once they had an expectation to do so. Critically, most of the incorrect color responses were the distractor ball color, which suggested memory storage without binding. Therefore, these results, together with other recent findings argued against two opposing theories: object-based encoding and feature-based encoding. Instead, we propose a new hypothesis by suggesting that the failure to report color is because participants might only activate the color representation in long-term memory without binding it to object representation in working memory.

1. Introduction

As perceivers, people intuitively believe that they remember information as detailed as they had just experienced, which is exemplified by the adage "Seeing is believing". However, researchers have concluded that we remember what is attended, given evidence that attention plays crucial roles in working memory storage and maintenance (e.g., Awh, Vogel, & Oh, 2006; Chun, 2011; Gazzaley & Nobre, 2012; but see Fougnie, 2009), and without attention, people often failed to report clearly visible stimuli (e.g., a gorilla) or changes (e.g., person substitution) (e.g., Mack & Rock, 1998; Most, Scholl, Clifford, & Simons, 2005; Rensink, O'Regan, & Clark, 1997; Simons & Chabris, 1999; Simons & Levin, 1998).

Nonetheless, there is a debate concerning how an attended object is represented in memory. One hypothesis suggests that we obligatorily encode all features of an object into working memory irrespective of their task relevance (i.e., *object-based encoding hypothesis*; Gao, Gao, Li, Sun, & Shen, 2011; Luck & Vogel, 1997; Shen, Tang, Wu, Shui, & Gao, 2013; Vogel, Woodman, & Luck, 2001).

An alternative hypothesis is *feature-based encoding*, which argues that participants often encode only the task-relevant feature of a stimulus and filter out its task-irrelevant features (e.g., Awh et al., 2006; Olivers, Meijer, & Theeuwes, 2006; Woodman & Vogel, 2008), or encode distinct features of the same object independently (Fougnie & Alvarez, 2011).

One way to reconcile these hypotheses is to assume that object-based encoding occurs when the capacity limitation of cognitive processing is not met, while feature-based encoding constrains memory when capacity is exceeded and information must be prioritized. fMRI data (Xu, 2010) supported this hybrid hypothesis by showing object-based encoding in a low, but not a high working memory load condition.

However, this hybrid hypothesis was challenged by Chen and Wyble (2015a) which showed that observers often failed to report obvious attributes (e.g., color and identity) of an object in response to an unexpected question, even though they had just selectively paid attention to only that object, which should be well below the capacity of focal attention and working memory[1]. However, Chen and Wyble's paradigm may have yielded a momentary form of memory because the stimulus duration was at most 250 ms and

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[1] Note that Eitam, Yeshurun, and Hassan (2013) showed a similar failure to report one color of an attended stimulus, although participants may have treated the stimulus as two objects (Eitam, Shoval, & Yeshurun, 2015).

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participants only attended briefly. Such fleeting representations are assumed to be more susceptible to proactive interference or rapid forgetting (Nee & Jonides, 2013; Oberauer, 2002).

There are cases of change blindness for longer duration stimuli such as actor swaps (Levin & Simons, 1997; Levin, Simons, Angelone, & Chabris, 2002; Simons & Levin, 1998). However, the two actors' overall appearance in these studies were typically similar and attention to the actors might have been intermittent, which may have contributed to the failures to detect changes. In fact it was suggested that failures to detect changes might not occur for individuals with dramatically different appearance (e.g., Simons & Levin, 1998, p. 648). Furthermore, subjects might have failed to perform a memory comparison despite having formed memory representations (Levin et al., 2002).

Therefore, it remains an open question whether prolonged focal attention to a simple object for several seconds will necessarily produce a robust memory of that object's highly discriminable attributes that is sufficient for report immediately afterwards in response to an unexpected question. To investigate this question, we forced observers to track one of two colored balls in a video for multiple seconds repeatedly and then asked an unexpected question about the attended ball's color. Color was a salient and distinguishing feature of that ball, despite not being necessary for the tracking task.

2. Method

2.1. Participants

Sixty observers from the Pennsylvania State University psychology department subject pool participated in exchange for course credits. Four observers were replaced because their counting performance on pre-surprise trials was more than 2.5 SD below the mean.

2.2. Apparatus

Stimuli were presented on a 17-in. CRT monitor (1024 × 768, 75 Hz) with MATLAB and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Observers sat 50 cm from the screen, and responded via keyboard.

2.3. Stimuli and procedure

Trials started with a black central fixation cross (1.03°) for 200 ms, which was replaced by a 500 ms black word "Ready" followed by a recorded video of size 22 × 13° (640 × 360 pixels, 25 fps) wherein two different colored balls (e.g., red and blue) were passed among six actors[2] who walked continuously (Fig. 1). The balls were selected from a set of four colored balls (i.e., red, green, blue, and purple, 0.65° to 1.94° diameter according to position). The ball that was passed *first* at the beginning of each video was designated as the target, while the other ball was designated as the distractor. Observers were instructed to count the passes of the target ball from one actor to another while ignoring the distractor ball. The number of passes differed between the target and distractor balls in 87.5% of videos (average 2.3 passes difference). After the video a 200 ms fixation screen preceded a two alternative forced-choice numbers (e.g. 19 or 20 passes) and observers responded by pressing either the 1 or 2 key in an unspeeded response.

There were 12 types of videos based on the color combinations of the four balls with each combination having 3 durations (short duration: average 8 s, 3 or 4 passes; medium duration: average 26 s, 10 or 11 passes; and long duration: average 44 s, 19 or 20 passes). Each observer saw one video of each color combination at each of the three durations, for one of the two pass numbers, chosen randomly, totaling 36 trials (12 video types × 3 duration conditions) in a randomized order. On the first 31 pre-surprise trials, observers reported the number of target-ball passes with feedback.

On the 32nd trial (i.e., surprise trial), immediately after the 200-ms fixation following the video, observers were unexpectedly presented with a forced-choice recognition test array consisting of four words (RED, GREEN, BLUE, and PURPLE) in black along with this question "*This is a surprise memory test! Here we test the "Color" of the target ball, Press a corresponding number to indicate the "Color" of the target ball*". The four color words were presented in a random order alongside the numbers 1–4. Observers were then asked to report the number of passes. The surprise trial was followed by four control trials that were identical to the surprise trial. The Surprise trial videos were evenly distributed among the three video durations across participants, but video duration had no effect on accuracy.

3. Results

Pre-surprise trials had an average of 10% pass-counting errors indicating that observers could track the target ball. However, on the surprise question, 37% (22/60) of these observers failed to select the ball's correct color (Fig. 2). Interestingly, for these 22 *incorrect observers*, 73% (16/22) of them selected the distractor ball color, which is significantly more than chance, (73% vs. 33%, χ^2 (1, $N = 44$) = 7.379, $p = .007$, $\varphi = .41$).

Critically, on the trial immediately after the surprise trial (i.e., control trial 1), when observers now expected that they might have to report the ball's color, color-report errors dropped to 17% (10/60), which was significant (17% vs. 37%, χ^2 (1, $N = 120$) = 6.136, $p = .013$, $\varphi = .23$). Color report error in the following three control trials remained consistently low (13%, 13%, and 12% errors). On erroneous control trials participants reported the distractor color 88% of the time, indicating that tracking the wrong ball was the source of most errors on control and presurprise trials.

For pass-counting, performance on the control trials (8%, 15%, 13%, and 17% errors) was similar to the pre-surprise trials (10% error), suggesting that observers could remember the ball's color without much cost. Performance in the surprise trial (28% error) was worse than other trials, which is likely because the pass-counting question occurred after the surprise question, which might have caused forgetting of the pass count. Pass counting performance remained stable during the pre-surprise trials, averaging 12% error in the 6 trials prior to the surprise.

To ensure that this effect is robust, we replicated the experiment with two minor modifications to reduce the probability of tracking the wrong ball. We removed 11 videos which consistently produced poor pass-counting (more than 15% errors) and we paused the first frame of the video for one second prior to the video start.

We replicated the results. 19 of 60 (32% error) participants were incorrect in color report on the surprise trial, and 15 of these 19 (79%) incorrect participants reported the distractor ball color instead, which is significantly more than guessing (79% vs. 33%, χ^2 (1, $N = 38$) = 7.836, $p = .005$, $\varphi = .45$). The color report error dropped to 7% in the first control trial which was significant (7% vs. 32%, χ^2 (1, $N = 120$) = 12.102, $p < .001$, $\varphi = .32$) and remained low (Fig. 3). Pass counting errors were also low (4% pre-surprise, 8.8% control), except for the surprise trial (30%) which mirrored the previous experiment.

[2] The actors were assigned to two groups, one for each ball. This grouping of the actors changed at random per trial.

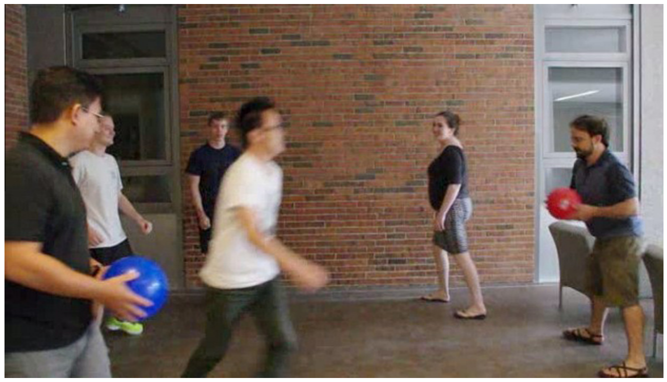

Fig. 1. An example frame of the video from a trial using the red and the blue ball. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

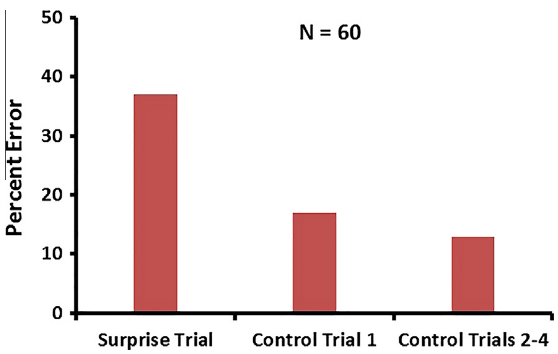

Fig. 2. The error rates for the color report question.

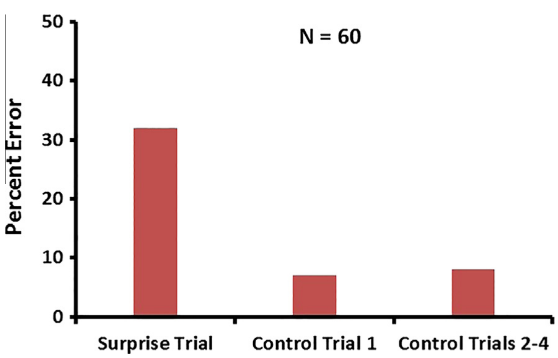

Fig. 3. The error rates for the color report question in the replication.

Note that errors could result from tracking the wrong ball. We corrected the proportion of distractor ball reports by removing an estimated number of subjects who had presumably tracked the wrong ball, as determined by the probability of reporting the distractor ball color on control trials, which was 12% and 7% in the two experiments. Thus, 7 and 4 participants were removed and after this conservative correction, 60% (9/15) and 73% (11/15) of participants still reported the distractor ball in the first and replication experiments respectively. The noisier data in the first experiment did not reveal a difference compared to chance performance (33%; $p = .15$) but in the replication experiment the cleaner data reveals a significant difference after the correction ($p = .028$) as do the combined data of both experiments ($p < .01$).

4. Discussion

Our results show that observers frequently failed to report the highly distinguishable color of a ball despite having had just focused specifically on that ball for multiple seconds, provided that they did not expect to report the color. These results extend previous change blindness studies (Levin & Simons, 1997; Levin et al., 2002; Simons & Levin, 1998) in several important ways. In this study, the attended stimuli were simple objects with categorically distinct colors and observers were required to attend continuously to the ball for the duration of the video. Thus, the present experiment provides even stronger constraints on theories of how attention and memory interact.

In another relevant study, Eitam et al. (2015) showed accurate report for the irrelevant feature of a single object, which differs from our results. However their study used more stimulus values and fewer presurprise trials, which might have reduced both proactive interference and the strength of the task set at the time of the surprise trial. To determine how our result is related to experience in the task, we ran a control experiment, in which the surprise test was on the first trial and found fewer color report errors and no change relative to the first control trial (4/20 = 20% error in both). Also, this experiment had 30 control trials after the surprise, which revealed consistently high color-report performance (average 10% error). This indicates that once an expectation to report color is established, participants have no trouble continuing to remember the color, despite proactive interference.

4.1. Object-based encoding hypothesis

According to the object-based encoding hypothesis, observers obligatorily extract features of a selected stimulus and encode an integrated object into working memory. In contrast our results show that observers did not have a clear memory of the color of the ball they had just been tracking. Previous studies suggest a weaker version of object-based encoding which occurs for basic features (e.g., color and shape; Gao et al., 2011), or when working memory load was low (Xu, 2010). However, even this weaker version cannot explain the present finding, since our participants tracked only one simple object and reported its color. Furthermore, the result that most of incorrect color reports were of the distractor ball color as well as Chen and Wyble (2015a)'s findings argue strongly against the hybrid hypothesis.

4.2. Feature-based encoding hypothesis

The feature-based encoding hypothesis assumes that observers selectively extract information into working memory. If observers treated the color of the balls as irrelevant, this theory predicts that observers should have no memory of those colors. However, this prediction was not supported since 90% (54/60) of observers reported the color of one of the two balls on the surprise trial, indicating that almost all observers have some memory of the ball colors. Furthermore, feature-based encoding has difficulty explaining why participants could rarely report the task-relevant features of a target in Chen and Wyble (2015a).

4.3. A new hypothesis: Expectancy-based binding

Since neither object-based nor feature-based encoding provide a satisfactory explanation for these results we propose a new hypothesis which attempts to reconcile these findings. Memory models propose that there are different levels of information storage (e.g., Cowan, 1995, 1999; LaRocque, Lewis-Peacock, & Postle, 2014; LaRocque et al., 2015; Nee & Jonides, 2013; Oberauer, 2002, 2008; Eitam & Higgins, 2010). In the context of these models, we propose that information that participants expect to be useful later is bound to the object representation in working memory, while information that will not be useful later is stored as an activated trace in long-term memory (Oberauer, 2002) or stimulated state (Eitam & Higgins, 2010), regardless of whether it has been relevant for the task[3]. This latter representation does not support the ability to link specific objects to specific features at report but could still generate familiarity signals Oberauer, 2002, 2008) that might be able to influence both behavioral and neurophysiological responses. We termed this hypothesis expectancy-based binding.

We propose that some observers have activated color representations of both target and distractor balls in long-term memory, but have not linked those colors to the ball representations in working memory. Thus, those observers have difficulty when asked to retrieve the color of a specific ball. Nonetheless, the activated long-term memory traces enable them to choose either the target or distractor colors more often than a non-present color on that trial.

However, it could also be possible that participants encoded the color into working memory but forgot it before answering the surprise question. We argue against this possibility because in a different experiment, participants who are forced to encode a color into memory are able to report that color in a surprise question (Chen & Wyble, in press).

This expectancy-based binding hypothesis can also explain other findings. For example, the *irrelevant-change-distracting effect* (an influence of task-irrelevant feature changes on performance, Gao et al., 2011; Shen et al., 2013), which is usually cited as evidence for object-based encoding, can be explained if we assume that irrelevant information is represented as activated long-term memory which allows irrelevant changes to influence participants' performance. Our binding hypothesis also predicts that because the activated representation in long-term memory is not bound to object representations in working memory, the *irrelevant-change-distracting effect* should only be triggered by changing the irrelevant feature to a new one, but not by switching the location of irrelevant features which is consistent with Gao et al. (2011).

Moreover, Chen and Wyble (2015a) found that observers failed to report a task-relevant feature of an attended object if they had no expectation to report it. This is compatible with expectancy-based binding, which predicts that even a task-relevant feature that is not expected to be useful afterward could be activated in long-term memory without being bound to the object representation in working memory. This implication was also supported by another series of experiments that show consistent binding errors when reporting task-relevant features of a single object (Chen, Carlson, & Wyble, in preparation).

[3] As an example of information that is relevant but not useful at a later point we refer to Chen and Wyble (2015a)'s key attribute (i.e., target-defining attribute) that participants have to use to locate the target but do not need to report.

5. Conclusion

The present study showed a striking inability to report an obvious color of a ball that had been tracked for multiple seconds. This demonstration, together with other recent findings (e.g., Chen & Wyble, 2015a, 2015b, in press; Eitam et al., 2013) suggests that an attended object is neither stored completely in memory as an integrated object, nor are only task-relevant features stored. Instead, we propose that information that is expected to be useful later is more likely to be bound to the object representation in working memory, while the remaining information is only activated in long-term memory regardless of its momentary task relevance.

Author contributions

Hui Chen and Brad Wyble developed the study concept. Hui Chen performed the programming, data collection, analysis, interpretation, and most of the writing. Brad Wyble and Garrett Swan contributed data interpretation, writing, and editing. All authors approved the final version of the manuscript for submission.

Declaration of conflicting interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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