Cognition 181 (2018) 127–134

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/cognit

Original Articles

Implicit updating of object representation via temporal associations

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ARTICLE INFO

Keywords:
Statistical learning
Updating
Transfer
Object representation
Temporal prediction

ABSTRACT

The cognitive system can flexibly update the representations of objects upon changes in the physical properties of the objects. Can the changes ripple to the representations of other associated objects that are not directly observable? We propose that statistical learning allows changes in one object to be automatically transferred to related objects. Observers viewed a temporal sequence with pairs of colored circles where the first circle always preceded the second. When the first circle increased or decreased in size, the second circle was judged to be larger (or smaller), suggesting that changes were automatically transferred to the second object (Experiment 1). When the second circle changed in size, the first circle was unaffected (Experiment 2). The strength of transfer seemed to depend on the conditional probability between objects (Experiment 3). The findings were replicated using pairs of faces that changed in expressions (Experiments 4&5). Importantly, no observer was explicitly aware of the pairs. Thus, statistical learning enables automatic and implicit updating of object representations upon changes to temporally associated objects.

1. Introduction

The environment is constantly changing over time. For example, light intensity fluctuates throughout the day from dawn to dusk, rendering objects in the environment brighter or darker; the shape of the moon changes from full to crescent over monthly cycles; and children change in body size as they develop over the years. However, at any given moment in time, we can only observe changes in a limited number of objects, and yet, the cognitive system can quickly and spontaneously update changes in other related objects in an efficient manner. For example, the increasing size of headlights at night signals an approaching car, even when the body of the car is not fully visible. Thus, the question is: What cognitive mechanisms support the updating of the representations of objects that are not directly observable?

We propose that statistical learning is a basic mechanism that supports the automatic updating of object representations in the environment. Statistical learning is a cognitive process that extracts the relationships among individual objects in terms of how likely they are to co-occur over space or time (Fiser & Aslin, 2001; Saffran, Aslin, & Newport, 1996). Such extraction occurs implicitly, without conscious intent or awareness (Turk-Browne, Jungé, & Scholl, 2005; Turk-Browne, Scholl, Chun, & Johnson, 2009). This learning process operates in multiple sensory modalities and feature dimensions (Conway & Christiansen, 2005; Fiser & Aslin, 2001; Saffran et al., 1996; Turk-Browne, Isola, Scholl, & Treat, 2008), draws attention implicitly and persistently to the co-occurring objects themselves (Yu & Zhao, 2015; Zhao, Al-Aidroos, & Turk-Browne, 2013), interferes with summary perception (Hall, Mattingley, & Dux, 2015; Zhao, Ngo, McKendrick, & Turk-Browne, 2011), and facilitates the compression of information (Brady, Konkle, & Alvarez, 2009; Zhao & Yu, 2016).

Learning the co-occurrences among objects can shape the representations of these objects. For example, statistical learning renders the neural representations of temporally co-occurring objects more similar (Schapiro, Kustner, & Turk-Browne, 2012), increases visual short-term memory (Brady et al., 2009), and reduces the perceived numerosity of the co-occurring objects (Zhao & Yu, 2016). In all these studies, participants remained unaware of the co-occurrences between objects. This suggests that statistical learning may result in the implicit grouping of co-occurring objects, unitizing individual objects. If co-occurring objects are represented as one unit, then changes in one object may be automatically transferred to its co-occurring partner, even though the partner is not directly observable. Such transfer can be efficient because the cognitive system can update the representations of other associated objects without directly observing these objects, facilitating the propagation of representational changes.

The goal of the current study was to examine how the cognitive

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https://doi.org/10.1016/j.cognition.2018.08.015
Received 15 June 2016; Received in revised form 22 August 2018; Accepted 23 August 2018

system updates the representations of objects upon changes to associated objects. In four experiments, observers first viewed a temporal sequence of objects while performing a cover task during the exposure phase. Unbeknownst to the observers, the sequence contained object pairs, where one object reliably followed another in each pair. After exposure, one object in the pair changed in size (Experiments 1&2) or facial expression (Experiments 4&5). Upon seeing this change, observers were asked to recall the size of the partner circle (Experiments 1 &2) or rate the expression (Experiments 4&5) of the face that was paired with the changed face. Importantly, the size change or expression change was irrelevant to the partner object, and observers were encouraged to recall or perceive the partner object as accurately as possible. We were interested to see whether the recalled size or the rated facial expression of the partner object was influenced by the incidental changes of the other object in the pair. We also examined whether the strength of updating depended on the conditional probability between objects (Experiment 3).

2. Experiment 1

The goal of the experiment was to examine whether new information about one object can be transferred to an associated object.

2.1. Participants

Forty-two undergraduate students (26 female, mean age = 20.5 years, SD = 3.4) from the University of British Columbia (UBC) participated for course credit. Participants in all experiments had normal or corrected-to-normal vision, and provided informed consent. All experiments have been approved by UBC Behavioral Research Ethics Board. We conducted a power analysis using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007). Based on a previous paradigm that used similar color circles as stimuli (Zhao & Yu, 2016), the effect size was η_p^2 of 0.11 obtained from a main effect of condition (structured vs. random in Experiment 1). Given this effect size and the 2 × 2 within-subjects design in the current experiment, a minimum of 42 participants were required to achieve 95% power.

2.2. Stimuli

The stimuli consisted of 12 colored circles in 12 distinct colors. The colors were (R/G/B values): red (255/0/0), green (0/255/0), blue (0/0/255), yellow (255/255/0), magenta (255/0/255), cyan (0/255/255), gray (185/185/185), orange (248/155/43), brown (139/69/19), violet (148/0/211), lime (208/255/20), and black (0/0/0). The circle diameter subtended 2.2° of visual angle (or 60 pixels). Eight out of the 12 circles were randomly assigned for every participant into four 'color pairs' and were constant throughout the experiment. In each pair, the first color appeared first, which was always followed by the second color. The remaining four circles were random and not paired with any other circle. That is, the random circle did not reliably follow any given circle, but appeared randomly between the color pairs.

2.3. Procedure

The experiment contained three phases: exposure, size recall, and test. During the exposure phase, participants viewed a continuous temporal sequence of colored circles. In each trial, one circle appeared at the center of the screen for 500 ms, followed by an inter-stimulus interval (ISI) of 500 ms. Unbeknownst to the participants, the sequence contained four color pairs and four random circles (Fig. 1A). Participants performed a 1-back task where they judged as quickly and accurately as possible whether the current color was the same as the previous one (by pressing the "/" or "z" key for same or different, respectively, key assignment counterbalanced). For the 1-back task, each color had a 20% chance of repeating the previous color. This 1-back task served as a cover task which was irrelevant to the color pairs, in order to conceal the true purpose of the study and to ensure that learning of the color pairs was incidental. Due to the 20% chance of repetition of each color, the second object in a color pair only followed the first one for 80% of the time (e.g., Pr(B|A) = .8 in an AB pair). Each color pair and each random circle was repeated 30 times to form the sequence in a pseudorandom order with the constraint that no color pair could repeat back-to-back. Since there were four pairs and four random circles and each color could repeat itself 20% of the time, the probability of a random circle following the second object in the pair, or following another random circle was 0.8 × 1/7 = .11 (e.g., Pr(random|B) = .11 or Pr(random 1|random 2) = .11).

After exposure, participants completed a size recall task (Fig. 1B). In each trial, the first circle in each pair was presented for 1000 ms, followed by a 3000 ms blank screen. Importantly, for two pairs, the first circle was presented in a larger size (the diameter subtended 4.4°, or 120 pixels). For the other two pairs, the first circle was presented in a smaller size (the diameter subtended 1.1°, or 30 pixels). After the blank screen, either the second circle in the same pair or a random circle that never followed the first circle was presented on the screen. The recall of the random circle served as a baseline comparison to account for the anchoring effect of recalling a larger or smaller size after seeing a larger or smaller previous circle. Either circle was presented as a probe circle with a diameter subtending 0.55° (or 15 pixels). Participants were asked to recall the size of the second circle in the pair or the random circle, as it initially appeared in the exposure phase, by using the mouse to adjust the size of the circle. They were told that the first circle was irrelevant to the recall, and they should try to report the original size of the probe circle. The first circle in each pair was presented 10 times resulting in 40 trials in total (the second circle appeared for 5 trials and the random circle for 5 trials).

After the size recall task, participants completed a surprise two-alternative forced choice (2AFC) test phase to examine whether they had successfully learned the color pairs. In each trial, two sets of circles were presented one set after another. Each circle appeared for 1000 ms followed by a 750 ms ISI, and each set was separated by a 1000 ms pause. Participants judged whether the first or second set looked more familiar based on what they saw in the exposure phase. One set was a color pair presented in exposure, and the other 'foil' set contained one color from the pair, and one color from a different pair. The colors in the foil had never appeared one after another in that order. Each pair was tested against two foils: the first foil contained one color from the pair, and the second foil contained its other color. Each pair-foil combination was tested twice, creating 16 trials (order randomized). Each pair and each foil were presented the same number of times at test. Thus, to discriminate the pair from the foil, participants needed to know which two particular colors followed each other during exposure.

After the test phase, a debriefing session was conducted at the end of all experiments, where participants were asked if they had noticed any colored circles that appeared one after another in any pattern. For those who responded yes, we further asked them to specify which color followed which color. The participant had to correctly identify both colors in a pair to be counted as correctly identifying one pair.

2.4. Results

During the test phase, the color pairs were chosen as more familiar than foils for 66% (SD = 20.6%) of the time, which was reliably above chance (50%) [$t(41) = 4.96$, $p < 0.001$, $d = 0.76$]. This indicates that participants have successfully learned the temporal co-occurrences between the two colors in a pair. During debriefing, six participants reported noticing color pairs, but none correctly reported which specific colors followed each other. This suggests that participants had no explicit awareness of the color pairs.

The reported size of the circle during the size recall task was presented in Fig. 1D. A 2 (the second circle in the pair vs. random circle) ×