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Original Articles

Implicit updating of object representation via temporal associations

Ru Qi Yu[a], Jiaying Zhao[a,b,*]

[a] Department of Psychology, University of British Columbia, Canada
[b] Institute for Resources, Environment and Sustainability, University of British Columbia, Canada

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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

* Corresponding author at: Department of Psychology, Institute for Resources, Environment and Sustainability, University of British Columbia, Vancouver, B.C. V6T 1Z4, Canada.
E-mail address: jiayingz@psych.ubc.ca (J. Zhao).

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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 $0.8 \times 1/7 = .11$ (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) ×

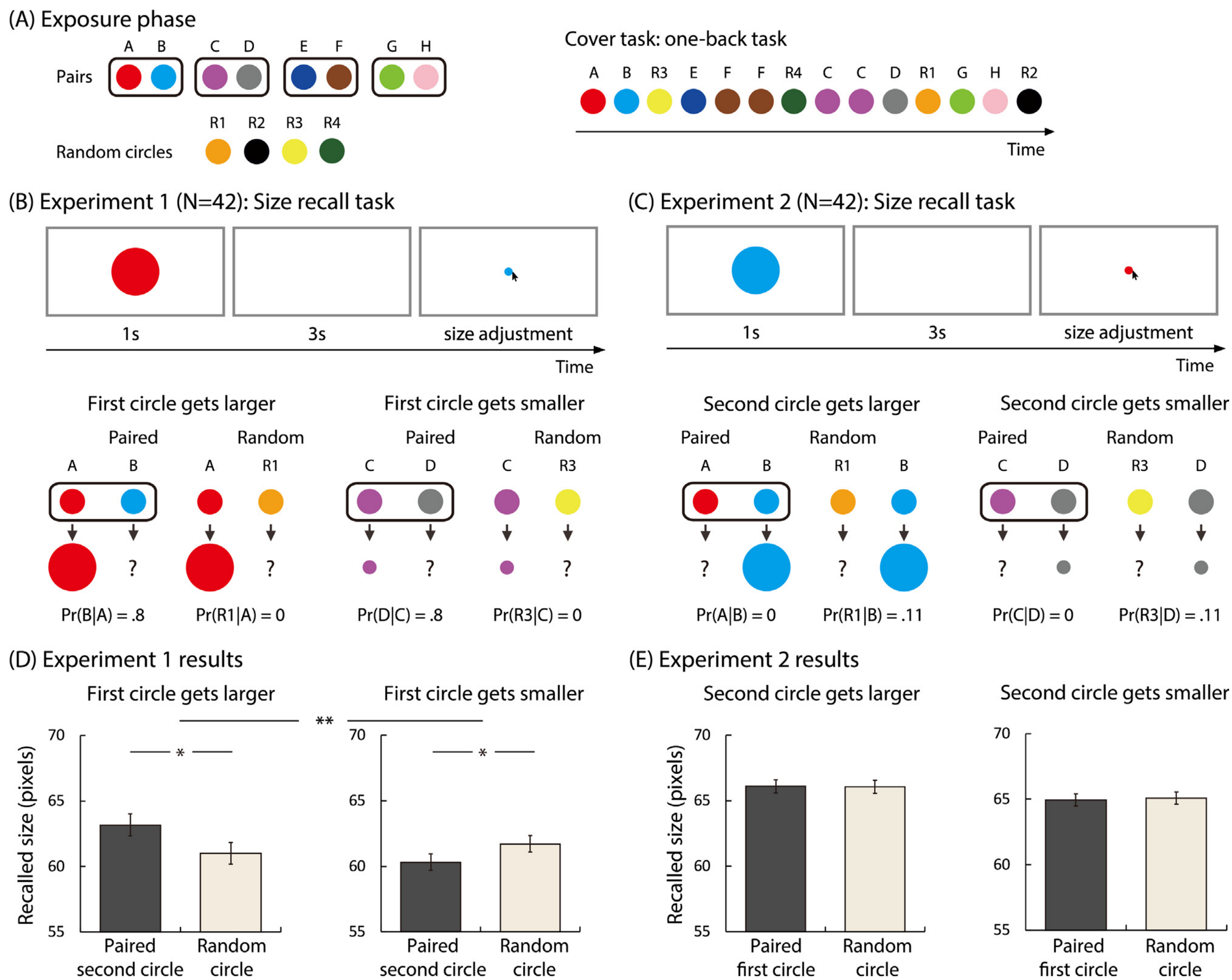

Fig. 1. *(A) Exposure phase.* Observers viewed a continuous sequence of colored circles consisting of four color pairs and four random circles. To ensure incidental encoding of the pairs, observers performed a cover one-back task over the sequence. The specific colors that are assigned to the pairs and random circles are only for illustration. The colors were randomly assigned into pairs for each participant. *(B) Experiment 1.* After exposure, observers completed a size recall task, where they briefly viewed a distorted first circle in each pair. Specifically, the first circle was larger or smaller than that during exposure. After the first circle, a blank screen appeared for 3 s. Then observers reported the size of either the second circle in the pair, or a random circle that never appeared after the first circle. Of the four pairs, the first circle was larger in two pairs and was smaller in the other two pairs. *(C) Experiment 2.* Experiment 2 was identical to Experiment 1, except that observers briefly viewed a distorted second circle in each pair. Specifically, the second circle was larger or smaller than that during exposure. Observers reported the size of either the first circle in the pair, or a random circle that never appeared before the second circle. *(D) Experiment 1 results.* When the first circle became larger in the recall task, the reported size of the second circle in the pair was reliably larger than that of the random circle. Likewise, when the first circle became smaller in the recall task, the reported size of the second circle in the pair was reliably smaller than that of the random circle. There was also a reliable two-way interaction between the change in the first circle and the type of recalled circle. *(E) Experiment 2 results.* When the second circle became larger in the recall task, there was no difference in the reported size of the first circle in the pair and that of the random circle. Likewise, when the second circle became smaller in the recall task, there was no difference in the reported size of the first circle in the pair and that of the random circle. There was no two-way interaction between the change in the second circle and the type of recalled circle. (Error bars represent within-subjects SE, *$p < 0.05$, **$p < 0.01$).

2 (the first larger vs. smaller circle) repeated-measures ANOVA revealed a significant two-way interaction [$F(1,41) = 9.29$, $p < .01$, $\eta_p^2 = 0.18$]. Critically, after seeing a larger first circle, the reported size of the second circle in the pair was reliably larger than that of the random circle [$t(41) = 2.64$, $p = .01$, $d = 0.09$]. Likewise, after seeing a smaller first circle, the reported size of the second circle in the pair was reliably smaller than that of the random circle [$t(41) = 2.20$, $p = .03$, $d = 0.07$]. The results showed that the size change in the first circle had a stronger impact on the representation of the second circle than that of the random circle. This suggests that changes in the first circle in the pair were automatically transferred to the second circle in the pair, even if participants were not explicitly aware of the color pair. Thus, the visual system implicitly and automatically updates the representations of objects upon changes to a temporally associated object.

3. Experiment 2

Experiment 1 suggests that changes in one object can be transferred to the object that reliably follows. This transfer may be facilitated by the fact that the first circle preceded the second circle in the pair, such that people automatically anticipate the second object upon seeing the first one (Turk-Browne, Scholl, Johnson, & Chun, 2010). Alternatively, the transfer can reflect a source of surprise when seeing a random object after the first object in the pair. The violation in expectation may inhibit the transfer of changes from the first object to the random object. To tease these ideas apart, in Experiment 2 the second circle in the pair changed in size, and participants recalled either the size of the first circle or the size of a random circle. The probability of seeing the first circle after the second was 0 and would be a violation of expectation (e.g., Pr(A|B) = 0). The probability of seeing the random circle after the second was .11 (e.g., Pr(random|B) = .11), thus no violation of expectation. If the transfer was stronger from B to random than from B to A, then this would suggest that the previous finding in Experiment 1 was driven by a violation of expectation. But if the transfer was equal, then this would suggest the previous finding in Experiment 1 was due to the temporal association between two objects in a pair (i.e., Pr(B|A) = .8).

3.1. Participants

To be consistent with the first experiment, a new group of 42 undergraduate students (29 female, mean age = 20.3 years, SD = 2.2) from the University of British Columbia (UBC) participated for course credit.

3.2. Stimuli and procedure

The stimuli and the procedure were identical to those in Experiment 1, except for a critical difference. In the size recall task, the second circle was presented in a larger or smaller size, and participants were asked to recall either the first circle in the same pair or a random circle that never preceded the second circle (Fig. 1C).

3.3. Results

During the test phase, the color pairs were chosen as more familiar than foils for 71% (SD = 17.2%) of the time, which was reliably above chance (50%) [$t(41) = 7.96$, $p < 0.001$, $d = 0.82$], indicating that participants have successfully learned the temporal co-occurrences between the two colors in a pair. During debriefing, eight participants reported noticing color pairs, but none correctly reported which specific colors followed each other. This again 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. 1E. A 2 (the first circle in the pair vs. random circle) × 2 (the second larger vs. smaller circle) repeated-measures ANOVA revealed that there was no two-way interaction [$F(1,41) = 0.05$, $p = .82$, $\eta_p^2 < 0.01$]. Critically, after seeing a larger second circle, the reported size of the first circle in the pair was not different from that of the random circle [$t(41) = 0.07$, $p = .94$, $d < 0.01$]. After seeing a smaller second circle, the reported size of the first circle in the pair was not different from that of the random circle [$t(41) = 0.25$, $p = .80$, $d = 0.01$]. Moreover, across the two experiments, there was a reliable three-way interaction [$F(1,82) = 6.26$, $p = .01$, $\eta_p^2 = 0.07$], as revealed by a 2 (Experiments 1 vs. 2) × 2 (paired vs. random circles) × 2 (larger vs. smaller circles) ANOVA. There was no main effect of experiment [$F(1,82) = 2.15$, $p = .15$, $\eta_p^2 = 0.03$]. These results showed that the size change in the second circle had no impact on the representation of the first circle in the same pair. This suggests that changes in the second circle were not successfully transferred to the first circle, despite the fact that participants expressed robust learning of the color pair at test. The results from the two experiments suggest that changes in the first circle can be transferred to the second circle in the pair, but not vice versa. In other words, when an object precedes another, changes in the object are automatically transferred to the object that reliably follows.

4. Experiment 3

Experiment 2 showed that there was no difference in the transfer of changes from B to A (a violation of expectation) than from B to random (no violation). This suggested that the violation of expectation itself had minimum impact on the strength of transfer. It also implied that the weaker transfer of changes from A to random (a violation of expectation) than from A to B (no violation) in Experiment 1 was not solely driven by the violation of expectation. However, Experiments 1 and 2 were conducted with different samples of participants, and used different paradigms. To replicate these findings in the same sample and to demonstrate that the strength of transfer could depend on the conditional probability of the objects, we conducted Experiment 3, where participants recalled the size of B after seeing changes in A in an AB pair (Pr(B|A) = .8), recalled the size of D in a different CD pair after seeing changes in A (Pr(D|A) = 0), or recalled the size of a random circle after seeing changes in a different random circle (Pr(R4|R1) = .11). Using this setup, we can directly compare the recall of objects when there is a violation of expectation (i.e., Pr(D|A) = 0) and when there is no violation of expectation (i.e., Pr(R4|R1) = .11 and Pr(B|A) = .8).

4.1. Participants

Given the new paradigm in this experiment, we conducted a power analysis using G*Power (Faul, et al., 2007). An effect size of 0.07 was found in Experiment 1. Using the effect size, at least 100 participants were needed to have 95% power to detect an effect in our design. Thus, we recruited 130 undergraduate students (103 female, mean age = 19.7 years, SD = 1.64) from UBC in this experiment.

4.2. Stimuli and procedure

The stimuli and procedure were the same as those in Experiment 1, except for three important differences: 1. in the size recall task, the first circle in each trial always increased in size; 2. for half of the trials in the size recall task, the first circle in a pair increased in size, and participants recalled the size of the paired second circle (10 trials, condition 1 where Pr(B|A) = .8) or a second circle in a different pair (10 trials, condition 2 where Pr(D|A) = 0); and 3. for the other half of the trials in the size recall task, the first circle was one random circle that increased in size, and participants recalled the size another random circle (20 trials, condition 3 where Pr(R4|R1) = .11, Fig. 2A).

4.3. Results

During the test phase, the color pairs were chosen as more familiar than foils for 67% (SD = 19.4%) of the time, which was reliably above chance (50%) [$t(1\,2\,9) = 10.11$, $p < 0.001$, $d = 0.89$], indicating that participants successfully learned the temporal co-occurrences between the two colors in a pair. During debriefing, twelve participants reported noticing color pairs, but only one participant correctly identified at least two out of the four pairs. This again suggests that most participants had no explicit awareness of the color pairs.

A repeated-measures ANOVA revealed that there was a main effect of condition [$F(2,258) = 4.29$, $p = .01$, $\eta_p^2 = 0.03$]. Post-hoc Tukey analysis showed that the recalled size in condition 1 was reliably larger than that in condition 2 [$p = .01$]. No other comparisons were significant. These results replicated the findings in Experiments 1 and 2, and suggested that the strength of transfer seemed to depend on the conditional probability between the two objects.

We further explored the relationship between the strength of transfer and conditional probability across all experiments reported in the study (Table 1). We tabulated the conditional probabilities between the objects and the effect sizes. We found that a larger effect in transfer was associated with a higher conditional probability.

5. Experiment 4

The first three experiments demonstrated that the changes in simple features such as size in one object can be transferred to an associated object. Can such transfer occur in other feature dimensions? Thus, this experiment examined if the same results can be replicated with more complex stimuli such as faces.

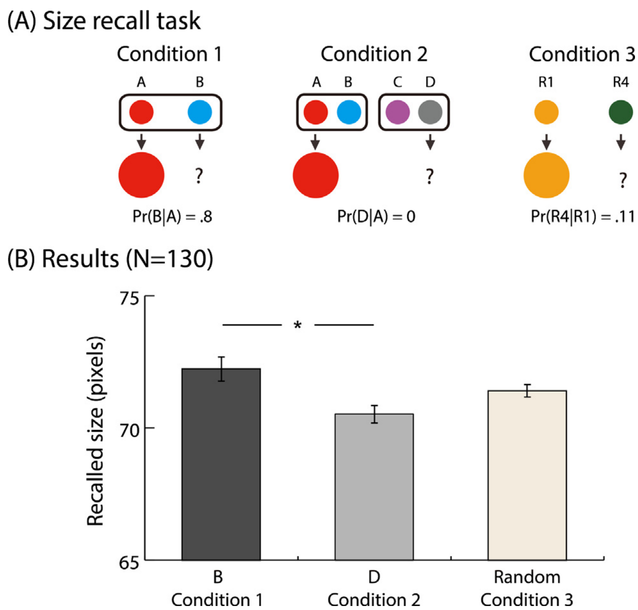

Fig. 2. *(A) Size recall task.* After exposure, observers completed the size recall task. The first circle in each recall trial always increased in size. There were three within-subjects conditions in this task. In condition 1, participants recalled the paired second circle after the first circle in the pair. In condition 2, participants recalled the second circle of a different pair after the first circle in the pair. In condition 3, participants recalled a random circle after another random circle. *(B) Results.* The reported sizes of the paired second circle, the second circle in a different pair, and the random circles were compared. The recalled size of the paired second circle was reliably greater than that of the second circle in a different pair. No other pair-wise comparisons were reliable. (Error bars represent within-subjects SE, $^*p < 0.05$).

Table 1

Summary of the effect sizes in Experiments 1 to 5. This table summarizes the recall task effect sizes across all experiments in the study. The first column lists the specific experiments. The second column lists the type of change in the object. The third column lists the comparisons of the recall trials. The fourth column lists the conditional probabilities. The last column lists the effect sizes in terms of Cohen's d (Experiments 1–2, and 4–5), or partial eta square (Experiment 3).

Exp.	Type of change	Comparisons	Conditional probabilities	Effect size
1	A gets larger	A → B vs. A → R1	.8 vs. 0	0.09
1	C gets smaller	C → D vs. C → R3	.8 vs. 0	0.07
4	A gets sadder	A → B vs. A → R1	.8 vs. 0	0.24
2	B gets larger	B → A vs. B → R1	0 vs. .11	< .01
2	D gets smaller	D → G vs. D → R3	0 vs. .11	0.01
5	B gets sadder	B → A vs. B → R1	0 vs. .11	0.03
3	A gets larger or R1 gets larger	A → B vs. A → D vs. R1 → R4	.8 vs. 0 vs. .11	0.03

5.1. Participants

As this experiment involved the ratings of facial expressions, we collected two pilot studies to modify the previous paradigm. We again used G*Power (Faul et al., 2007) for the power analysis. Based on a previous paradigm that used similar emotional faces as stimuli (Picardo, Baron, Anderson, & Todd, 2016), the effect size was 0.45 in the ratings of different congruent emotional faces in Study 2. Given this effect and a paired-samples design in the current experiment, a minimum of 65 participants were required to achieve 95% power. Therefore, we recruited 65 undergraduate students (48 female, mean age = 20.0 years, SD = 2.4) from UBC in this experiment.

5.2. Stimuli and procedure

The stimuli consisted of 12 unique faces. The 12 faces were randomly selected from the "Yale Face Database" (Georghiades, Belhumeur, & Kriegman, 1997). Consistent with Experiment 1, eight faces were randomly selected for each participant to be grouped into four 'face pairs'. The remaining four faces were random. The exposure phase was the same as Experiment 1 where participants completed the cover one-back task over a continuous stream of faces all in neutral expressions. There was one difference from Experiment 1: each face was presented for only five times during exposure (Fig. 3A).

After exposure, participants completed an expression rating task similar to the size recall task in Experiment 1 (Fig. 3B&C), except for the following critical differences: (1) the first face in each pair was presented for 2000 ms on the screen in a sad expression; (2) after the first face, the screen remained blank for 3000 ms, and a paired second face or a random face was presented for 500 ms in a neutral expression; and (3) participants were asked to rate the expression of the second face or the random face, regardless of the first faces, on a scale from −100 to 100 (−100 means that the face is extremely sad, and 100 means that the face is extremely happy).[1] Participants then completed a test phase identical to that in Experiment 1.

5.3. Results

During the test phase, face pairs were chosen over foils as more familiar for 51% (SD = 14.8%) of the time, which was not different from chance [$t(64) = 0.63$, $p = .53$, $d = 0.08$]. Thus, participants were at chance at choosing the face pairs as more familiar. We think that the chance performance in the test phase could be a result of the short exposure in the experiment. Despite the chance performance at the test phase, the second face in the pair was rated as reliably sadder than random faces [$t(64) = 2.09$, $p = .04$, $d = 0.24$] (Fig. 3E). This result suggests even in the absence of robust familiarity with the face pairs, changes in facial expressions can be automatically and implicitly transferred to the temporally associated face.

6. Experiment 5

To replicate Experiment 2, the second face in the pair changed expressions in this experiment, and participants rated the expression of the first face or a random face that never preceded the second face.

[1] We conducted three pilot studies to justify the use of sad faces but not happy faces in Experiments 4 and 5. In the first pilot (N = 42), we assessed the priming efficacy of happy faces. Participants rated neutral faces after seeing a happy face on a scale from -100 to 100. The average rating was −1.2 (SD = 15.3). To assess whether this rating was due to a lack of priming effect or a possible contrast effect, we conducted a second pilot where participants rated neutral faces, sad faces, or happy faces without any prime (N = 145 for each of the three groups). The average rating for neutral faces was 24.3 (SD = 23.3), which was closer to the ratings of sad faces (M = −4.1, SD = 27.9) than to happy faces (M = 70.1, SD = 16.6). Moreover, neutral faces were rated as sadder after happy faces than presented alone [$p = .001$], suggesting a contrast effect rather than a priming effect. Since neutral faces were rated as closer to sad faces than to happy faces, we believe that sad faces were better primes for neutral faces than happy faces, because of affective congruency priming (Fazio et al., 1986; Hermans et al., 1994; Wentura, 1999). For these reasons, we used only sad faces in Experiments 4 and 5. In the third pilot study (N = 20), we manipulated the length of exposure to the face pairs and assessed participants' awareness of the statistical regularities. With the same amount of exposure as in Experiments 1 and 2, more than half of the participant became explicitly aware of the face pairs. Thus, the amount of exposure was reduced in Experiments 4 and 5.

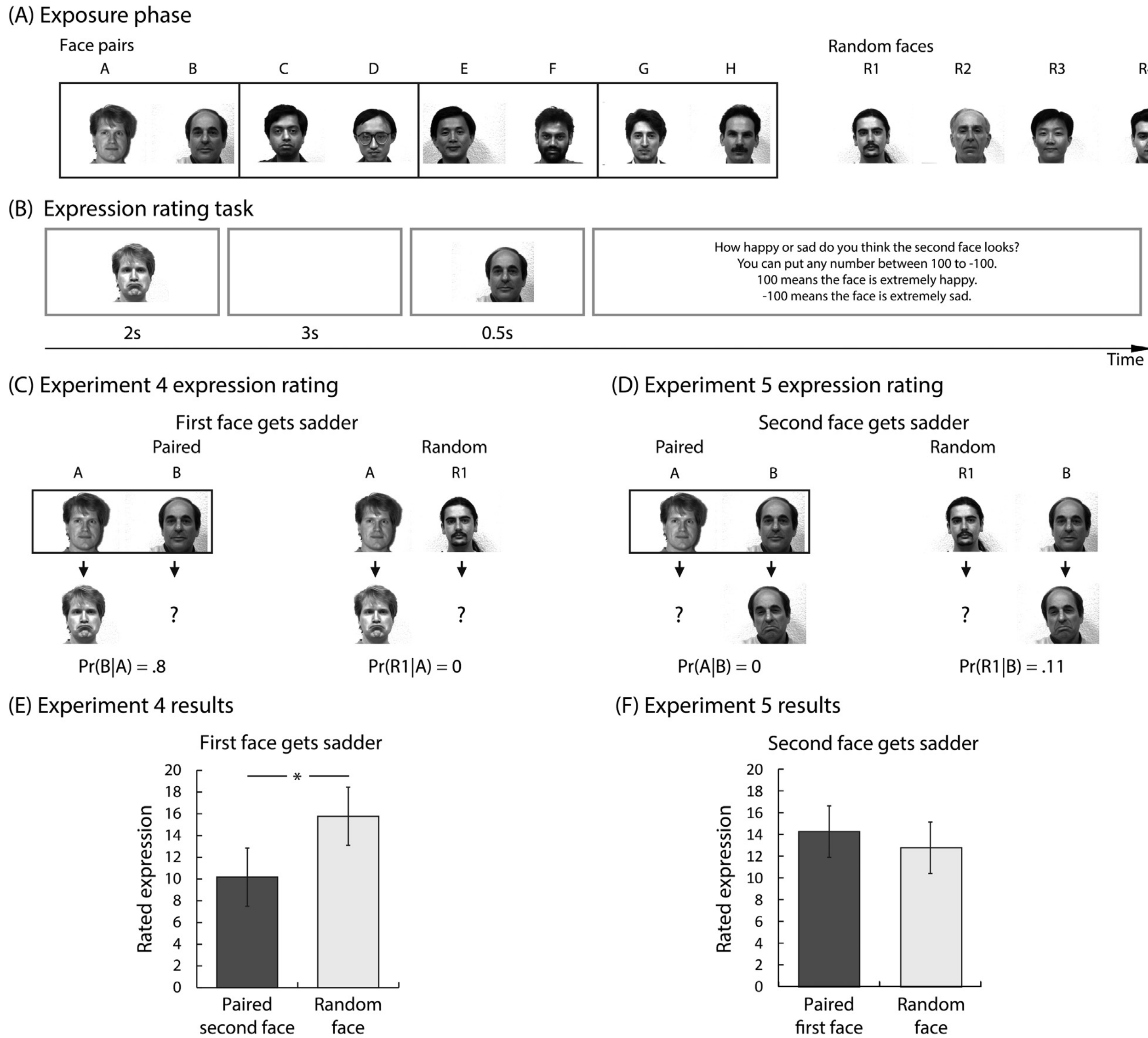

Fig. 3. *(A) Exposure phase.* Observers viewed a sequence of faces consisting of four face pairs and four random faces in neutral expressions. *(B) Expression rating task.* After exposure, observers completed an expression rating task, where they viewed a face in each pair with a sad expression. After the sad face, a blank screen appeared for 3 s. Then observers briefly viewed the other member of the pair in a neutral expression, or a random face that never appeared after the first face in a neutral expression. Participants were asked to rate the expression of the paired face or the random face, regardless of the expressions of the face presented in a sad expression. *(C) Experiment 4.* The first face of each pair was presented in a sad expression. *(D) Experiment 5.* The second face of each pair was presented in a sad expression. *(E) Experiment 4 results.* When the first face was sad, the reported expression of the second face in the pair was reliably sadder than that of the random face. *(F) Experiment 5 results.* When the second face in the pair was sad, there was no difference in the rated expression of the first circle in the pair and that of the random circle. (Error bars represent within-subjects SE, $*p < 0.05$).

6.1. Participants

As in Experiment 4, 65 new undergraduates (41 female, mean age = 20.2 years, SD = 2.7) from UBC participated for course credit.

6.2. Stimuli and procedure

The faces were the same as Experiment 4. The procedure was also the same as that in Experiment 4, except for one critical difference: in the expression rating task, participants saw the second face in each pair in a sad expression, and were asked to rate the expression of the first face in the pair or a random face (Fig. 3D).

6.3. Results

During test, face pairs were chosen as more familiar than foils for 55% (SD = 14.5%) of the time, which was reliably above chance [$t(64) = 2.68$, $p < .01$, $d = 0.08$], showing learning of the face pairs. During debriefing, no participant was able to correctly identify any face pairs. The first face in the pair was not rated as sadder than random faces [$t(64) = 0.62$, $p = .53$, $d = 0.03$] (Fig. 3F). This suggests that changes in facial expressions in the second face are not successfully transferred to the first face, despite the fact that participants expressed robust learning of the face pair at test. Moreover, across Experiments 4 &5, there was a reliable 2 (Experiment 4 vs. Experiment 5) × 2 (paired faces vs. random faces) interaction [$F(1,82) = 3.93$, $p = .0496$, $\eta_p^2 = 0.07$]. The results suggest that expression changes in the first face can be transferred to the second face in the pair, but not vice versa. In other words, expression changes in one face are automatically transferred to the face that reliably follows.

7. General discussion

The goal of the current study was to examine how the cognitive system updates the representations of objects upon changes to an associated object. We found that the second circle in the pair was recalled to be larger or smaller when the first circle increased or decreased in size, respectively (Experiment 1). However, when the second circle in the pair changed in size, the recalled size of the first circle was not influenced (Experiment 2). We found that the strength of updating seemed to depend on the conditional probability between the two objects (Experiment 3). We replicated the same findings in Experiments 4 and 5 with more complex face stimuli that changed facial expressions. Importantly, most participants were not explicitly aware of the color or face pairs. These results suggest that changes in one object are automatically and implicitly transferred to its partner that reliably follows, updating the representation of the partner.

It is important to point out that the updating effect observed here can be interpreted as a learning-induced priming or anchoring effect. This is because in the size recall task (Experiments 1–3) or the expression rating task (Experiments 4–5) the probe immediately followed the updated object. This means that the recall or the judgment of the probe is primed by the previous object. However, the priming effect here is learning-induced because we found a stronger bias for the second object in the pair than for a non-paired object.

Such updating is surprising for several reasons. First, the change in the first object was completely irrelevant to the size recall or expression rating of the second object, and yet changes in the first object were automatically transferred to the second object. Second, no new information about the second object was presented since the exposure phase, and the size recall or expression rating of the second object must be based purely on the memory of the second object. Given that the second object never changed, there should be no updating, and yet participants still updated the representation of the second object upon seeing the changes in the first. In other words, changes in the first object automatically distorted the representation of the second object.

Third, the first object was absent during the recall or the rating of the second object, which means that the bias in the second object was driven by the changed representation of the first object held in working memory. Past research has demonstrated that context plays an important role for the representation of individual objects in the environment (Bar, 2004; Maloney & Wandell, 1986). In the current experiments, the first object may have served as a context for the second object, biasing the retrieved representation of the second object. We should note that the bias observed in the recall or the rating of the second object cannot be solely explained by an anchoring effect. Specifically, in Experiment 1 the critical comparison was between the second circle in the pair and the random circle, both of which were presented immediately after the first circle. If the results were due to anchoring, then both circles would be overestimated or underestimated given the previous larger or smaller first circle, respectively. Yet, the second circle in the pair was overestimated or underestimated more strongly compared to the random circle.

Fourth, the knowledge about the pairs was implicit, in that only one participant out of five experiments demonstrated explicit awareness of the pairs. Even though participants chose the pair as more familiar than the foil at the test phase, most of them indicated during debriefing that they felt like guessing which one looked more familiar. Nonetheless, the implicit knowledge about the pairs enabled the transfer of changes from the first to the second object.

Finally, the effect of automatic updating can be dependent on the conditional probability between the two objects. In the current study, objects were associated with different conditional probabilities. As summarized in Table 1, the two objects in a pair appeared one after another 80% of the time (strongly paired). The second object of a pair preceded a random object, or two random objects appeared one after another 11.4% of the time (weakly paired). The first object in a pair was never followed by a random object, the first object never followed the second object in a pair, and the first object in a pair was never followed by a second object in a different pair (never paired). We found that the changes in one object were more readily transferred to a strongly paired object than to a never paired object. In other words, the more likely the second object followed the first one, the more likely that changes in the first object were to be transferred to the second one. Future studies should quantify this relationship to reveal the minimum conditional probability needed for successful transfer.

Rationally, the transfer results are not to be expected, as participants were explicitly told to ignore the first circle and to accurately recall the size of the following circles as they appeared in the exposure phase. Why would participants automatically and implicitly update the representations of the second object in the pair? We provide two accounts that may explain this automatic updating.

First, the strong association between the two objects in a pair could raise an implicit interpretation that a latent cause that induced changes in the first object can also induce changes in the second object. Second, when participants learned the color pairs, the circles always appeared in the same size, and the faces were always in the same neutral expression during the exposure phase. Therefore, the representation of the pair may include the relational information that the circles were always in the same size and the faces were always in the same expression. To maintain this representation, when an object in the pair changed, the other object would need to change to match its partner.

The current findings also support the unitization hypothesis. As shown previously, co-occurring objects are perceived to be less numerous and more similar to each other, leading to a unitized representation of the individual objects (Yu & Zhao, 2018; Zhao & Yu, 2016). If the co-occurring objects are represented as one unit, then changes in one object can be transferred to the second object within the unit. This can be efficient because the co-occurring objects do not need to be directly observed for their representations to be updated.

One caveat about the test phase in the current study is that the familiarity choice between the pair and the foil may not accurately reflect the degree of learning the pairs. In the size recall task or the rating task, the two paired objects appeared one after another for multiple times, whereas the two objects in the foil in the test phase never appeared together. This additional exposure to the pair may have boosted learning, leading participants to choose the pair as more familiar than the foil in the test phase.

The current study is significant in several ways. First, the results demonstrate that statistical learning supports the automatic updating of object representations, based on changes in associated objects. Second, the study shows that the changes can only be transferred through specific temporal relationships, not just through mere associations between objects. Third, the current study highlights the efficiency of the cognitive system in that it can update the representations of objects that are not directly observable, given new information about other related objects. Finally, the current study reveals a novel cognitive consequence of statistical learning on object representation, and that objects are not always faithfully represented given changes to other associated objects.

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Appendix A. Supplementary material

The raw data of each participant's average recalled size for each condition in Experiments 1-3 and average expression rating for each condition in Experiments 4-5 can be found in the supplementary materials. Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.cognition.2018.08.015.

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