Title
Statistical learning creates novel object associations via transitive relations

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Statistical learning creates novel object associations via transitive relations

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Abstract

A remarkable ability of the cognitive system is the creation of new knowledge based on prior experiences. What cognitive mechanisms support such knowledge creation? We propose that statistical learning not only extracts existing relationships between objects, but also generates new associations between objects that have never been directly associated. Participants viewed a continuous color sequence consisting of base pairs (e.g., A-B, B-C), and learned these pairs. Importantly, they also successfully learned a novel pair (A-C) that could only be associated through transitive relations between the base pairs (Exp1). This learning, however, was not successful with three base pairs (e.g., learning A-D from A-B, B-C, C-D), revealing a limit in this transitive process (Exp2). Beyond temporal associations, novel transitive associations can also be formed across categorical hierarchies (Exp3), but with limits (Exp4&5). The current findings suggest that statistical learning provides an efficient scaffold through which new object associations are transitively created.

Keywords: Statistical learning; transitive inference; implicit associations; regularities; categorical hierarchy

Introduction

A remarkable feature of the human cognitive system is that it is able to generate new knowledge based on existing information. For example, upon learning that Starbucks is next to a grocery store which is next to a wine shop, people can automatically infer that Starbucks is close to the wine shop. What cognitive mechanisms support such inference?

One mechanism that detects the relationships among objects in the environment is statistical learning, which involves the extraction of relationships between individual objects in terms of how they co-occur over space or time (Fiser & Aslin, 2001; Saffran, Aslin, & Newport, 1996). Statistical learning 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 to the co-occurring objects (Yu & Zhao, 2015; Zhao, Al-Aidroos, & Turk-Browne, 2013), and facilitates information compression (Brady, Konkle, & Alvarez, 2009; Zhao & Yu, 2016).

The critical distinction between statistical learning and other forms of associative learning is that for statistical learning the two objects are related based only on conditional or conjunctive probability, whereas for associative learning the two objects are associated through explicit cues, such as segmentation, grouping, or proximity. Statistical learning occurs incidentally, without conscious intent or explicit awareness, and the nature of the knowledge is implicit, in that observers are not explicitly aware of the co-occurrences between the objects (Turk Browne, Jungé, & Scholl, 2005; Turk-Browne, Scholl, Chun & Johnson, 2009).

Such implicit knowledge is also stimulus specific. That is, exposure to the co-occurrences between individual objects leads to the knowledge that these objects are associated. Given the ability to implicitly extract the co-occurrences, an unexplored question is whether statistical learning forms new associations of objects that have never co-occurred with each other and can only be associated based on prior knowledge.

Initial support for this question comes from studies on transitive inference. For example, previous work has shown that people can successfully learn the hierarchical order of abstract objects (e.g., if A<B and B<C, then A<C) without awareness using trial-by-trial feedback (Greene, Spellman, Dusek, Eichenbaum, & Levy 2001; Kumaran & Ludwig, 2013). A recent study shows that the hippocampus supports the transfer of values across objects that were previously associated, enabling people to make decisions between options that were never directly rewarded (Wimmer & Shohamy, 2012). Given this possibility of reactivating previous connections between objects, we predict that statistical learning can form novel associations among the objects that were never directly associated in the past.

The goal of our current study was to examine whether statistical learning enables the creation of new associations among objects that have never appeared together. Here, we focused on two basic types of transitive relations and asked: (1) given the pairs A-B and B-C, do people automatically learn a new pair A-C (Experiments 1 and 2)? and (2) given object exemplar pairs at one categorical level (e.g., New York-London), do people automatically learn new pairs at the subordinate level (e.g., Central Park-Hyde Park) and the superordinate level (e.g., USA-UK; Experiments 3, 4, and 5)?

Experiment 1

This experiment examined whether new associations could be formed between objects that had never appeared together.

Participants

Thirty undergraduates (21 female; mean age=19.5 years, SD=1.3) from University of British Columbia (UBC) participated for course credit. Participants in all experiments reported normal or corrected-to-normal vision and provided informed consent. All experiments reported here were approved by the UBC Behavioral Research Ethics Board.

Stimuli

The stimuli consisted of nine circles in nine distinct colors (color name=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; brown=103/29/0; black=0/0/0). Each circle subtended 1.6° of visual angle. The colored circles were randomly assigned into six base pairs for each participant and remained constant throughout the experiment. The six base pairs contained three groups of two base pairs. In each group, the second color in the first pair was the same as the first color in the second pair (e.g., A-B, B-C, Fig.1a). This allowed us to test if people could automatically learn a novel pair (A-C) given the two base pairs (A-B and B-C). There were three novel pairs from the six base pairs. Importantly, the two colors in the novel pair were never directly associated with each other. Each base pair was repeated 50 times to form a single continuous temporal sequence of circles in a pseudorandom order with two constraints: no single base pair could repeat back-to-back and no two overlapping base pairs (e.g., A-B, B-C) could occur consecutively.

Procedure

The experiment contained two phases: exposure phase and test phase. During the exposure phase, one colored circle appeared at the center of the screen for 500ms followed by a 500ms inter-stimulus interval (ISI) in each trial. Participants performed a 1-back task where they judged as quickly and accurately as possible whether the current circle had the same color as the previous circle (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, producing a total of 360 trials. This 1-back task served as a cover task irrelevant to learning, in order to conceal the true purpose of the study, ensuring that learning of the color pairs was incidental. Participants were not told anything about the color pairs.

After exposure, participants completed a surprise two-alternative forced choice (2AFC) test phase to examine whether they had successfully learned the base pairs. In each trial, participants viewed two sequences of circles at fixation. Each circle appeared for 500ms followed by a 500ms ISI, and each sequence was separated by a 1000ms pause. Participants judged whether the first or second sequence looked more familiar based on the exposure phase. If they did not respond during the sequence presentation or ISI, the screen remained blank until response. One sequence was a base pair, and the other was a "foil" (e.g., A-E) composed of one color from a base pair (e.g., A-B), and the other from a different base pair (e.g., D-E) while preserving the temporal positions in the pairs. Each base pair was tested against a foil, which was then repeated, resulting in 12 trials in total. It's important to note that each base pair and foil were presented the same number of times at test. Thus, to discriminate the base pair from the foil, participants needed to know which two particular colors followed each other during exposure. The order of the trials was randomized, and whether the base pair or foil appeared first was counterbalanced across trials.

At the test phase, we also examined whether participants learned the novel pair (e.g., A-C from A-B and B-C). The foil was constructed by selecting two colors from two novel pairs while maintaining the temporal positions in the pairs. Each novel pair was tested against a foil. The two colors in the foil came from two different base pairs that never shared a common color. Each novel pair and foil were presented the same number of times at test. If participants chose the novel pair as more familiar, this would suggest that they had formed a new association between two objects that had never directly followed each other but could only be inferred given the knowledge about the two base pairs.

A debriefing session was conducted after test, where participants were asked if they had noticed any colored circles that appeared one after another. For those who responded yes, we further asked them to specify which colors followed each other.

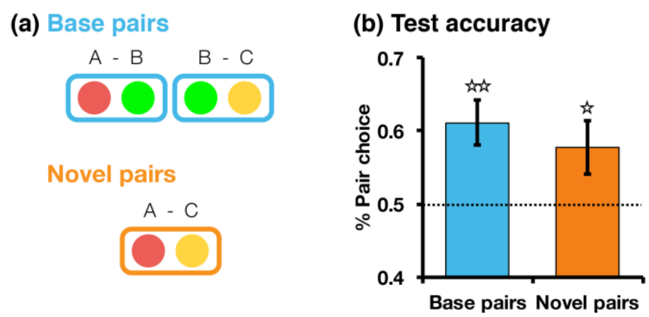

Figure 1: (a) Two example base pairs (A-B, B-C) and a novel pair (A-C). (b) Percent of times the pair was chosen as more familiar than the foil at test (error bars reflect ±1 SEM; *p<.05, **p<.01; dotted line=chance performance of 50%).

Results and Discussion

At the test phase, base pairs were chosen as more familiar than foils for 61.0% (SD=16.9%) of the time, which was reliably above chance (50%) [$t(29)=3.61$, $p=.001$, $d=0.66$] (Fig.1b). This indicates that participants have successfully learned the temporal co-occurrences between the two colors in the base pairs.

Moreover, novel pairs were chosen as more familiar than foils for 58% (SD=19.8%) of the time, which was again reliably above chance (50%) [$t(29)=2.15$, $p=.04$, $d=0.39$] (Fig.1b), suggesting that participants have also successfully learned the novel pairs, although the two colors in the novel pair never directly followed each other during exposure.

During debriefing, only five participants reported noticing color pairs, but none could correctly report which specific colors followed each other. This suggests that participants had no explicit awareness of the base pairs or the novel pairs.

These findings demonstrate that statistical learning automatically forms implicit novel associations between objects that have never appeared together and can only be associated via transitive relations from prior experiences.

Experiment 2

This experiment aimed to examine the limits of transitive associations by increasing the chain of object associations.

Participants

A new group of 30 undergraduates (20 female, mean age=20.5 years, SD=2.7) from UBC participated in the experiment for course credit.

Stimuli and Procedure

The stimuli and the procedure were identical to those in Experiment 1, except that we added one more base pair such that three base pairs formed a novel pair. As before, six base pairs were created for each participant. For every three base pairs, the second color in the first pair was the same as the first color in the second pair, and the second color in the second pair was the same as the first color in the third pair (e.g., A-B, B-C, C-D, Fig.2a). The novel pair (e.g., A-D) consisted of the first color in the first pair and the second color in the third pair. As before, participants performed a cover 1-back task to ensure incidental encoding of the pairs during exposure. Afterwards, participants completed the surprise test phase where they chose whether the pair or the foil looked more familiar.

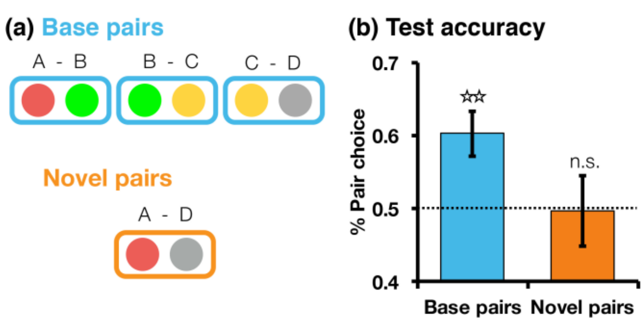

Figure 2: (a) Three example base pairs (A-B, B-C, C-D) and a novel pair (A-D). (b) Percent of times the pair was chosen as more familiar than the foil at test (error bars reflect ±1 SEM; ***p*<.01; dotted line=chance performance of 50%).

Results and Discussion

At test, base pairs were chosen as more familiar than foils for 60.0% (SD=16.8%) of the time, which was reliably above chance (50%) [$t(29)=3.36$, $p=.002$, $d=0.61$] (Fig.2b), suggesting that participants have successfully learned the co-occurrences between the two colors in the base pairs.

However, novel pairs were chosen as more familiar than foils for 49.7% (SD=26.5%) of the time, which was not reliably above chance (50%) [$t(29)=0.06$, $p=.95$, $d=0.01$] (Fig.2b). This suggests that learning of the novel pairs was not successfully expressed at test.

During debriefing, only one participant reported noticing color pairs, but the participant could not correctly report which specific colors temporally followed each other. This again suggests that participants had no explicit awareness of the base pairs or the novel pairs.

The findings demonstrate that while participants have learned the three base pairs, they could not form the novel association between objects in the first and the third pairs. This reveals a limit in the associations that can be formed transitively. This limit may reflect processing constraints as the number of objects or pairs increases.

Experiment 3

As shown in Experiments 1 and 2, novel associations can be formed transitively between objects that have never co-occurred before, and learning of the transitive association may depend on the length of associations. Here, we aimed to generalize the findings by examining another type of transitivity across the categorical hierarchy. Specifically, given the association between two exemplars at one categorical level, can people automatically learn the same association at the subordinate and the superordinate levels?

Participants

A new group of 80 undergraduates (58 female; mean age =20.6 years, SD=3.2) from UBC participated in the experiment for course credit.

Stimuli

The stimuli consisted of eight city names (New York, London, Vancouver, Paris, Tokyo, Beijing, Barcelona, and Bangkok), the eight corresponding park names (Central Park, Hyde Park, Stanley Park, Champ de Mars Park, Yoyogi Park, Bei Hai Park, Güell Park, and Lumpini Park), and the eight corresponding country names (USA, UK, Canada, France, Japan, China, Spain, and Thailand). The eight cities were randomly grouped into four base pairs for each participant (e.g., New York-London, Fig.3a). The city base pairs produced four park pairs at the subordinate level (e.g., Central Park-Hyde Park), and four country pairs at the superordinate level (e.g., USA-UK). The park pairs and the country pairs served as novel pairs to be tested at the test phase, and were never presented in the exposure phase. Each city base pair was repeated 50 times to form a single continuous sequence of cities in a pseudorandom order with the constraint that no city pair could repeat back-to-back.

Procedure

Since participants may not know which park is in which city, they were first trained on a separate task to associate each park with a given city. In this task, participants viewed a park and selected which city contained the park (by pressing a key from “1” to “8”), and received feedback on each trial. They had to achieve 100% accuracy on this task before starting the experiment. We did not test city-country association, since we assumed that most participants should know which city is in which country. There was no mention of any country names, city or park pairs, before starting the experiment.

The experiment consisted of an exposure phase and a test phase, as in Experiment 1. During the exposure phase, one city name was presented at fixation for 500ms followed by a 500ms ISI in each trial. As before, participants performed a 1-back task where they judged whether the current city name was the same as the previous name. For the 1-back task, each city name had a 20% chance of repeating the previous name, producing a total of 360 trials. This 1-back task served as a cover task to conceal the true purpose of the study, ensuring that learning of the city pairs was incidental.

After exposure, participants completed the surprise test phase, as in Experiment 1, to see if they had learned the city pairs, and more importantly, to see if they had learned the corresponding park pairs or country pairs which were never presented during exposure. In each trial, participants judged whether the pair or the foil looked more familiar based on what they saw in the exposure phase. There were three blocks of trials. In the first block, each city pair was tested against a foil where two cities never followed each other during exposure. In the second block, each park pair corresponding to its city pair was tested against a foil that contained the two parks corresponding to the two cities in the foil in the first block. Likewise, in the third block, each country pair and the foil corresponded to the city pair and the foil in the first block. The order of the last two blocks was randomized.

A debriefing session was conducted after the test phase, where participants were asked if they had noticed any cities that appeared one after another. For those who responded yes, we further asked them to specify which cities followed each other.

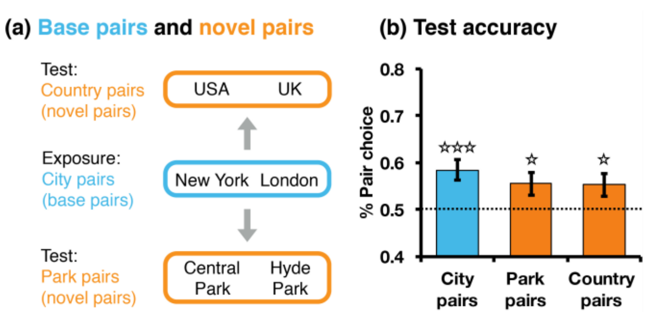

Figure 3: (a) City pairs served as base pairs at one categorical level, and park pairs and country pairs served as novel pairs at the subordinate and the superordinate levels, respectively. (b) Percent of times the pair was chosen as more familiar at test (error bars reflect ±1 SEM; *p<.05, ***p<.001; dotted line=chance performance of 50%).

Results and Discussion

At the test phase, the city base pairs were chosen as more familiar than foils for 58% (SD=19.5%) of the time, which was reliably above chance (50%) [$t(79)=3.82$, $p<.001$, $d=0.43$] (Fig.3b). This indicates that participants have successfully learned the temporal co-occurrences between the two cities in a base pair during exposure.

Moreover, park pairs were chosen as more familiar than foils for 55% (SD=19.6%) of the time, which was again reliably above chance (50%) [$t(79)=2.49$, $p=.01$, $d=0.28$] (Fig.3b), suggesting that participants have successfully learned the park pairs, although no parks were ever presented during exposure. Likewise, country pairs were also chosen as more familiar than foils for 55% (SD=22.3%) of the time, which was again reliably above chance (50%) [$t(79)=2.09$, $p=.04$, $d=0.23$] (Fig.3b), suggesting that participants have also successfully learned the country pairs, although no countries were presented during exposure.

During debriefing, seven participants reported noticing city pairs, but none correctly reported which specific cities followed each other. This suggests that participants had no explicit awareness of the city base pairs.

These results suggest that participants spontaneously formed new associations at both the subordinate and the superordinate levels, based on the regularities extracted at one categorical level. This finding provides further evidence that statistical learning automatically forms implicit novel associations between objects at different levels along the categorical hierarchy, even if these objects are never directly experienced or associated with each other.

Experiment 4

The goal of this experiment was to examine whether the findings in Experiment 3 were specific to city pairs, and whether there were limits in forming the novel transitive associations across the categorical hierarchy.

Participants

A new group of 45 undergraduates (31 female; mean age=20.7 years, SD=2.5) from UBC participated in the experiment for course credit.

Stimuli and Procedure

The stimuli and the procedure were identical to those in Experiment 3, except that park pairs served as base pairs during exposure, and city pairs and country pairs served as novel pairs at test (Fig.4a).

Results and Discussion

At test, the park base pairs were chosen as more familiar than foils for 68% (SD=10.0%) of the time, which was reliably above chance (50%) [$t(44)=12.43$, $p<.001$, $d=1.85$] (Fig.4b), indicating that participants have successfully learned the temporal co-occurrences between the two parks in a base pair during exposure.

Moreover, city pairs were chosen as more familiar than foils for 54.1% (SD=16.3%) of the time, which was again reliably above chance (50%) [*t*(44)=1.71, *p*=.05, *d*=0.26], suggesting that participants have successfully learned the city pairs, even though no cities were ever presented during exposure. However, country pairs were chosen as more familiar than foils for 51.2% (SD=20.4%) of the time, which was not reliably above chance (50%) [*t*(44)=0.41, *p*=.34, *d*=0.06] (Fig.4b).

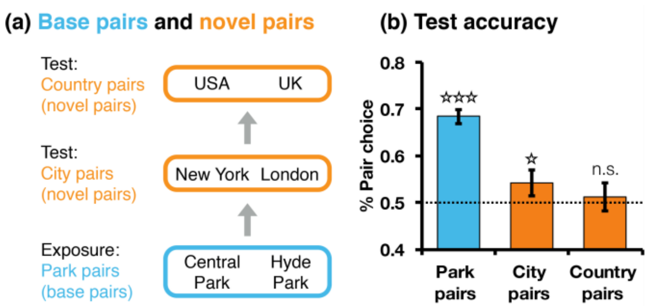

Figure 4: (a) Park pairs were base pairs. City and country pairs were novel pairs. (b) Percent of times the pair was chosen as more familiar (error bars reflect ±1 SEM; **p*<.05, ****p*<.001; dotted line=chance performance of 50%).

During debriefing, three participants reported noticing park pairs, but none correctly reported which specific parks followed each other. This suggests that participants had no explicit awareness of the park base pairs.

These results suggest that participants could successfully form new associations at one superordinate level above the original subordinate level where regularities were learned, but not at two superordinate levels above. This reveals a limit in how far new associations can be formed beyond the categorical level where objects were originally associated.

Experiment 5

The final experiment aimed to replicate the results from Experiment 4 by exposing regularities at the superordinate level and testing whether new associations can be formed at all subordinate levels.

Participants

A new group of 80 undergraduates (61 female; mean age =20.8 years, SD=5.2) from UBC participated in the experiment for course credit.

Stimuli and Procedure

The stimuli and the procedure were identical to those in Experiment 3, except that country pairs served as base pairs during exposure, and city pairs and park pairs served as novel pairs at test (Fig.5a).

Results and Discussion

At test, the country base pairs were chosen as more familiar than foils for 61% (SD=22.0%) of the time, which was reliably above chance (50%) [*t*(79)=4.52, *p*<.001, *d*=0.51] (Fig.5b), indicating that participants have successfully learned the temporal co-occurrences between the two countries in a base pair during exposure.

Moreover, city pairs were chosen as more familiar than foils for 56% (SD=21.0%) of the time, which was again reliably above chance (50%) [*t*(79)=2.46, *p*=.02, *d*=0.27], suggesting that participants have successfully learned the city pairs, even though no cities were ever presented during exposure. However, park pairs were chosen as more familiar than foils for 54% (SD=20.8%) of the time, which was not reliably above chance (50%) [*t*(79)=1.75, *p*=.08, *d*=0.20].

During debriefing, eight participants reported noticing country pairs, but none correctly reported which specific countries followed each other, suggesting that participants had no explicit awareness of the country base pairs.

These results replicated those in Experiment 4, showing that participants successfully formed new associations at one subordinate level below the original superordinate level where regularities were learned, but not at two subordinate levels below. This again reveals a limit in how far new associations can be formed beyond the categorical level where objects were originally associated.

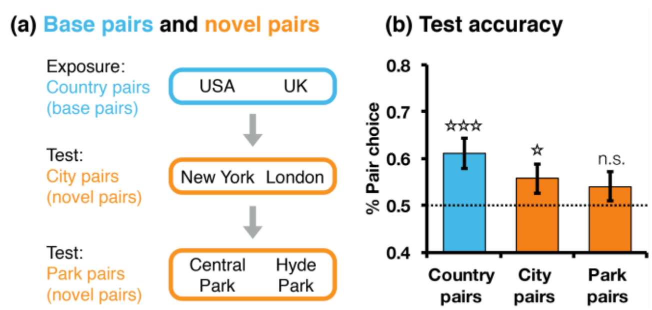

Figure 5: (a) Country pairs were base pairs. City and park pairs were novel pairs. (b) Percent of times the pair was chosen as more familiar (error bars reflect ±1 SEM; **p*<.05, ****p*<.001; dotted line=chance performance of 50%).

General Discussion

The goal of the current study was to examine whether statistical learning enables novel associations among objects that have never been directly associated before. We found that after experiencing that A predicted B and B predicted C, participants automatically and implicitly inferred that A predicted C, although C never directly followed A (Experiment 1). However, this inference was not successful when there were three pairs (e.g., A-B, B-C, C-D) presented during exposure, revealing a constraint in the extent of the transitive inference (Experiment 2). Extending beyond temporal transitivity, we examined if novel associations could be formed across the categorical hierarchy. We found that after learning a pair of objects at one categorical level (e.g., New York-London), participants automatically and implicitly inferred the same association at the subordinate level (e.g., Central Park-Hyde Park) and superordinate level (e.g., USA-UK), even if the subordinate or superordinate objects were never presented or associated with each other (Experiment 3). However, this transitive inference seemed to be limited to the subordinate or the superordinate level immediately below or above the original level where the regularities were experienced, and did not extend to two levels beyond the original level (Experiments 4 and 5).

The current findings suggest that statistical learning can produce knowledge above and beyond the mere co-occurrences among objects that are directly observed. The base pairs support automatic generalizations across objects and category levels. This implies that our cognitive system can draw upon prior experiences to automatically form new relationships between objects through transitive inference.

Interestingly, both the knowledge about the co-occurring objects, and the knowledge about the new associations were completely implicit, since no participant could report which objects co-occurred in the experiments. This finding is consistent with the previous work showing that people can infer relational information between objects without awareness (Greene et al., 2001; Munnelly & Dymond, 2014).

While statistical learning allows the creation of new knowledge, it is important to understand the constraints in this process. The failure to learn A-D in Experiment 2 despite having successfully learned the base pairs A-B, B-C, and C-D could be explained by either an increase in the number of objects, the number of pairs, or the number of connections. The failure to infer country pairs despite having successfully learned the park pairs and inferred the city pairs in Experiment 4, and the similar failure in Experiment 5, could be explained by the conceptual distance in the categorical hierarchy. These constraints may be due to the capacity limit of visual short-term memory (Alveraz & Cavanagh, 2004; Luck & Vogel, 1997). Future studies are needed to identify the factors underlying these constraints.

The current study also extends beyond past work showing that people can learn categorical regularities from associations among individual exemplars (Brady & Oliva, 2008). We found that the regularities extracted at one categorical level can be transferred to subordinate and superordinate levels. This suggests that statistical learning not only operates at an abstract conceptual level, but also automatically propagates learned object associations across the categorical hierarchy.

The current study is significant in several ways. We found that statistical learning not only produces knowledge about existing relationships between objects, but also generates new associations between objects that are never directly associated or experienced. These new associations are automatically formed via transitive relations, either through temporal co-occurrences or across the categorical hierarchy, even in the absence of explicit awareness. Importantly, there are constraints in forming these transitive associations. Understanding the scope and the limits of this transitive inference can help reveal how the cognitive system creates new knowledge from prior experiences.

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