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Association knowledge guides conjunctive predictions in novel situations

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Abstract

The mind readily learns cue-outcome associations where an object predicts a specific outcome. Previous work suggested that when multiple objects associated with different outcomes were jointly presented, the mind made conjunctive predictions that represented the common property of the associated outcomes. Using attentional tracking measures, we provided more evidence for the weighted summation framework when the conjunctive predictions involved spatial locations (Experiment 1) or conceptual categories (Experiment 2). Then, we examined the reverse of conjunction, where participants were presented with a single object, which is a part of an object pair that was previously associated with an outcome (Experiment 3). Rather than making predictions based on mental operations such as subtraction, we found that participants' predictions were purely based on previous associations. These results together demonstrated the robust tendency to make conjunctive predictions based on knowledge of cue-outcome associations.

Keywords: associative learning, conjunctive prediction, visual search, attention, cursor-tracking

Introduction

It is an important ability to accurately predict the outcome based on a preceding cue. For example, we automatically step on the gas pedal after traffic lights turn green, and we brake immediately after traffic lights go red. The mind readily learns these cue-outcome associations via mechanisms such as conditioning (Fanselow & Poulos, 2005; Mackintosh, 1974), associative learning (Le Pelley, 2004), and statistical learning (Saffran et al., 1996).

An often overlooked question is how the mind makes predictions in a new situation where the two cues presented were previously associated with different outcomes. Recent results suggested that people made conjunctive predictions rather than disjunctive ones when encountering two cues for the first time (Yu & Zhao, 2020). Specifically, in a visual search paradigm, participants first viewed a cue (e.g., a blue dot) and then searched for a target in an array. Each cue predicted a specific outcome (e.g., the blue dot meant that the target would always appear in the top half of the array, and the red dot meant that the target would always appear in the left half of the array). After being exposed to the cue-outcome associations, participants completed a prediction phase where the two cues were now presented simultaneously, and participants searched for the target which could appear anywhere in the array. In other words, the two cues were no longer predictive of the target location, but the attentional prioritization of a conjunctive or disjunctive region in the array would indicate an expectation of the target to appear there, thus indicating the nature of predictions made by the participants. There were three types of locations: conjunctive, disjunctive, and impossible. The conjunctive location contained one quadrant and was associated with both of the presented cues; the disjunctive location contained two quadrants and was associated with one of the two presented cues, and the impossible location contained one quadrant and was associated with neither of the presented cues. Through three experiments, it was found that search time for the conjunctive location was reliably faster than that for the disjunctive and impossible locations.

Such results provided support for the weighted summation framework (Yu & Zhao, 2020) where participants would select the overlap of outcomes and thus make conjunctive predictions when encountering the joint presentation of two different cues.

An alternative explanation for the faster search time in the conjunctive location was that when encountering the joint presentation of two cues (e.g., red and blue dots), participants processed the two encountered cues one at a time. In this account, participants were perfectly faithful to the previous knowledge and made no predictions beyond what they had previously learned. Specifically, participants would process one cue first and search for the target based on that cue. When doing so, they would either first check the conjunctive quadrant for the target, or one of the disjunctive quadrants that was associated with this color. If the target was not found in these two quadrants, participants would then search for the target in the other disjunctive quadrant that was associated with the second cue. Based on this strategy, participants would check the conjunctive location either first or second, but they would check one of the disjunctive locations third. Therefore, on average, search time in the conjunctive location would be faster. Based on the same rationale, if participants consistently failed to attend to both color cues, and based their search strategy on only one color, search time in the conjunctive location would also be faster. This explanation that participants processed the two cues one at a time could explain the faster search time in the conjunctive location without any conjunctive predictions.

One possible method to rule out this alternative explanation is to track participants' eye movement and analyze the first quadrant their eye gaze entered. This is because the first entry into a quadrant would clearly indicate participants' predictions about where the target should appear. For a hypothetical pair of cues such as the blue and red dots, the blue dot predicted that the target would appear in the top half of the array, and the red dot predicted the left half of the array. For trials where participants based their search strategy on processing the blue dot first, they would on average first enter the top-right quadrant half of the time to search for the target, and the top-left quadrant half of the time. Likewise, if they based search strategy on the red dot first, they would first enter the top-left quadrant half of the time, and the bottom-left quadrant half of the time. Overall, if participants processed one color at a time during search, they would first enter the top-left quadrant (conjunctive location) exactly 50% of the time. The summed frequency of first entry into the bottom-left and top-right quadrants (disjunctive locations) would also be 50% of the time. On the other hand, if participants predicted that the target would appear in the conjunctive location (the top-left quadrant), they would first enter that quadrant more often than their combined first entry into the disjunctive quadrants.

Using this tracking paradigm, the current study first replicated the findings in Yu and Zhao (2020) to rule out the discussed alternative explanations of the original findings (Experiment1). Additionally, two more important questions about participants' predictions can be answered with the tracking paradigm.

First, in the previously discussed spatial search paradigm, the conjunction of outcomes (e.g., target in the top-left quadrant) was already presented to the participants during exposure. Conjunctive predictions can be generated simply by selecting from the encountered exemplars that were associated with the cues. Therefore, Experiment 2 examined whether conjunctive predictions can be made for conceptual categories (e.g., a cue predicting large objects, another cue predicting animate objects), where the abstract conceptual conjunction (new exemplars of large animate objects) was never previously seen being associated with the cues.

Second, if predictions are based on selecting the outcome with the highest probability after weighted summation, then predictions can also be based on the most probable outcome after a weighted subtraction. Experiment 3 examined the possibility of a weighted subtraction.

Due to the pandemic, the tracking measure described in all experiments here would employ an online BubbleView technique. The idea for online tracking came from (Kim et al., 2017, https://bubbleview.namwkim.org/), but we have coded the tracking paradigm ourselves to fit the requirements of the current experiments. Specifically, participants viewed a blurred display of shapes where the location of each shape was discernible, but the specific identity of each shape was not. Participants had to first move their cursor to the center of the screen to activate a red probe circle. They could then move the probe circle around, and the shapes within the circle will be fully revealed. The size of the circle was designed so that the shapes can only be revealed one at a time.

Experiment 1

This experiment aimed to replicate the results of Yu and Zhao (2020) using a bubble view tracking paradigm.

Participants

Replicating the original paradigm (Yu & Zhao, 2020), a total of 60 students (38 female, mean age=21.5 years, SD=2.8) participated for course credit. All subsequent experiments followed this sample size.

Stimuli

[1]For each trial in the experiment, participants saw one colored dot first, followed by a search array (Fig. 1). The color dot could appear in one of four colors (R/G/B): red (255/0/0), yellow (255/255/0), blue (0/0/255), or grey (192/192/192). Each dot subtended 2.2° of visual angle. For each search array following the dot, 16 objects were presented in an invisible 8-by-8 grid. Each cell in the grid subtended 1.7° of visual angle. The 8-by-8 grid was divided into four 4-by-4 quadrants, where each quadrant was separated from the adjacent two quadrants by 2.2° of visual angle. Each quadrant contained four objects, where no row or column in the quadrant could be empty.

Out of the 16 objects in each array, 15 were distractors in "L" shapes, randomly pointing to the left or right. There was only one target in each array, which was a rotated "T", randomly pointing to the left or right. Participants were asked to find the target "T" and indicate which direction the "T" was pointing (left or right) by pressing a key on the keyboard, as quickly and accurately as possible.

For each trial, the color dot was presented on the screen for 1000ms. Followed by a 1000ms blank screen, the search array appeared on the screen until response. There was a 1000ms blank screen interval between trials.

Procedure

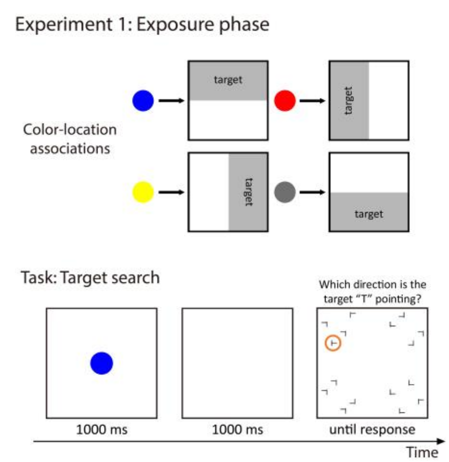

Fig. 1. Experiment 1 exposure phase. Each color dot predicted the location of the target in the subsequent search array. In the visual search task, participants saw the color dot first, and then searched for a target (the rotated "T") and judged the direction of target as quickly and accurately as possible.

Participants first completed the exposure phase (Fig. 1). During exposure, one color dot appeared on the screen at a time followed by a visual search array. The task employed

[1] As data were collected online, participants used their own personal computers to view stimuli. The program detects whether a mobile device or a computer was used. We only took data when viewing from a computer. The stimuli dimensions given below assumed that the presentation screen is a standard 24-inch LED monitor with the viewer seated 50cm away.

the bubble view technique described in the introduction. Each of the four colors was presented for 6 times during exposure, resulting in a total of 24 trials (the order of the trials was random). Each color predicted that the target “T” in the search array always appeared in a unique half of the array (the top, left, bottom, or right half). For example, after the blue dot, the target always appeared in the top half of the array. After the red dot, the target always appeared in the left half of the array. The target location within each half of the array was counter-balanced between the two quadrants (e.g., counterbalanced between top-left and top-right quadrants for the top half), and the target location within each quadrant was randomly determined. The color-location associations were randomly determined for each participant but remained fixed throughout the experiment for the participant.

Since the procedures were administered online, the color-location associations were made explicit to ensure an adequate level of association knowledge. Before exposure, participants were explicitly told about these specific associations in the instructions. Then, they were tested on these associations in a multiple-choice format. The test was administered continuously until perfect accuracy was reached. Next, the program would start the exposure phase. Following the exposure, the same test procedures were administered again to ensure participants’ knowledge of the color-location associations going into the next phase. This test procedure was used for all the subsequent experiments.

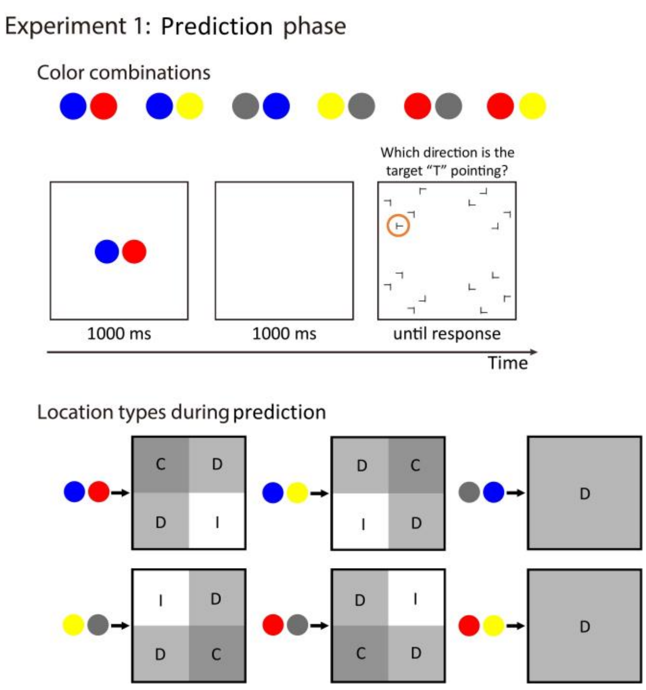

Fig. 2. Experiment 1 prediction phase. The four colors were combined into six color pairs. The pairs were presented first, followed by a search array. The target appeared in all four quadrants with equal frequency following each pair. Based on the color-location associations during exposure, there were four types of target location following each color pair. These include the locations consistent with a conjunctive prediction (C), locations consistent with a disjunctive prediction (D), and the impossible locations (I).

After exposure, participants completed the prediction phase (Fig. 2). During this phase, two color dots were presented at the same time in each trial, followed by a search array. There were six unique color pairs. Each color pair and the following search array were presented four times in the prediction phase in a random order, resulting in 24 trials in total. Following each pair, the target appeared in the four quadrants with equal frequency (the top-left, top-right, bottom-left, and bottom right quadrant). The location of the target within the quadrant was randomly determined.

Since the target now appeared in the four quadrants with equal frequency, faster response time in target search in a given quadrant and first entry into a quadrant to search for the target would both indicate that the participant prioritized that quadrant for target search. This would mean that the participant expected that the target would appear in that quadrant, suggesting a prediction of where the target would appear after seeing the two color dots.

Based on the color-location associations during exposure, there were four types of target location following each pair: locations consistent with a conjunctive prediction (C), locations consistent with a disjunctive prediction (D), and the impossible locations where the target would never appear based on the prior color-location associations (I). Participants were only told that they would now see two color dots appearing simultaneously on the screen before each search array, after which they would search for the target.

Results and Discussion

We first analyzed the responses time (RT) of correct trials in the prediction phase. We grouped the trials in the prediction phase into three types: conjunction, disjunction, and impossible. For the blue and red pair, the blue dot previously predicted that the target would appear in the top half of the array and the red dot previously predicted that the target would appear in the left half of the array. This means that the top left quadrant was the conjunctive quadrant, the top right and the bottom left quadrants were the disjunctive quadrants, and the bottom right quadrant was the impossible quadrant. Faster RT in the conjunctive quadrant would indicate that participants expected the target to appear in that quadrant, suggesting a conjunctive prediction. We plotted the RT in each location in the prediction phase (Fig. 3).

Since data were collected online, we performed additional measures to clean up the data. If overall search accuracy in the prediction phase was below 60%, the data from that participant would be taken out. The same practice was used for all subsequent experiments. Using this threshold, we collected data from 67 participants, and data from 7 of the participants were taken out. For the remaining participants, the average accuracy was 96%.

A one-way repeated-measures (location types: conjunction, disjunction, and impossible) ANOVA revealed a significant main effect [$F(2,118)=4.94$, $p<.01$, $\eta_p^2=0.09$]. This suggests that participants attended to the four quadrants differently during the prediction phase. Post-hoc Tukey HSD tests showed that RT in the impossible trials was reliably slower than that in the conjunction trials [p=.03].

Importantly, we analyzed the tracking data of correct trials and computed the location that participants first entered. Again, using the blue and red pair as an example, if participants in a trial first entered the top-left quadrant to search for the target, this would indicate that they made a conjunctive prediction about the target location. Trials where the two colors were associated with two non-overlapping halves (top half and bottom half) were excluded in this analysis. This is because participants could only enter a disjunctive quadrant in these trials. As described in the introduction, this tracking measure was aimed to test the alternative account where participants might base their search strategy on processing one color at a time. Also, since some participants might not base their search strategy on the exposure color-location associations, especially if they realized that colors no longer predicted target locations in the prediction phase. Therefore, the critical comparison to see whether participants made conjunctive predictions would be between the frequency of first entry into the conjunctive quadrant, and the summed frequency of first entry into the two disjunctive quadrants.

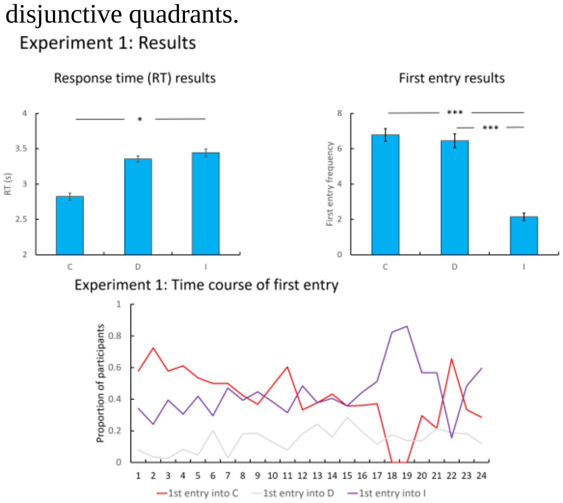

Fig. 3: Experiment 1 results. The response time (RT) for each type of trials was graphed on the top-left and the average frequency of first entry into the different types of locations was graphed on the top-right. Note that the frequency in the disjunctive location (D) is the sum of frequencies for the two disjunctive quadrants. (Error bar reflect ± 1 SE; *p<.05, ***p<.001). On the bottom is a trial-by-trial analysis of the first entry into different types of locations. In a given trial, the proportion of participants who first entered the conjunction location was plotted in red, the proportion for the disjunction location in grey, and the proportion for the impossible location in purple.

A one-way repeated-measures (location types: conjunction, disjunction, and impossible) ANOVA of first entry frequencies revealed a significant main effect [$F(2,118)=43.46$, $p<.001$, $\eta_p^2=0.42$]. However, Post-hoc Tukey HSD tests showed that first entry into the conjunction location was not reliably more frequent than that for the disjunction locations [p=.87], while first entry frequency into the impossible location was reliably lower [p's<.001].

Nevertheless, there were 24 trials during the prediction phase, where the colors no longer predicted the target location. As a result, participants might start searching for the target randomly as the phase progressed. Therefore, we plotted the time-course of participants' first entry into different types of locations (Fig. 3). Using a McNemar's test, we found that in the first 6 trials (out of 24), the proportion of participants who first entered the conjunction location was higher than those who first entered the disjunction location (p's<.05). As time progressed, this proportion lowered. These time course results suggested that participants initially made conjunctive predictions, but as they might have realized that the colors no longer predicted target locations, they started searching for the target randomly. It should be noted that the time-course analysis was exploratory, and more thorough interpretations of these results would be elaborated in General Discussion.

Overall, these results demonstrated that participants more frequently searched for the target in the conjunctive location, ruling out the alternative explanation where participants might process the two cues one at a time after the joint presentation of the two cues. This suggested that participants made conjunctive predictions upon seeing both color cues.

Experiment 2

In Experiment 1, the color cues were associated with the spatial location of the search target. In Experiment 2, we aimed to replicate the findings in Experiment 1 using conceptual combinations. Specifically, the color cues in Experiment 2 now predicted different categories of images, and the conjunction of two categories would be represented by set of new images that were conceptually consistent.

Participants

A new group of 60 students (45 female, mean age=21.3 years, SD=1.5) participated for course credit.

Stimuli and Procedure

The paradigm of Experiment 2 substantially differed from that of Experiment 1 in the following ways.

First, in the search array following each colored dot, only four shapes appeared on the screen. Three of the shapes were rotated "L"s, and one of them was a rotated target "T". (Fig. 4). These shapes were blurred, and participants had to move the cursor to reveal them one at a time. Each shape appeared on a grayscale image of a certain object. There were four types of objects: large animate objects, small animate objects, large inanimate objects, and small inanimate objects. The images of objects were not blurred, and were of the same physical size and modified from the image set from Long, Yu, and Konkle (2018).

Second, during exposure, the color of the preceding dot predicted the category of images on which the target could appear. The color was no longer directly associated with the location of the target. For example, after blue, the target always appeared on animate objects, which would include both large and small animate objects (Fig. 4); after yellow, the target always appeared on large objects, which would include both large animate and large inanimate objects. The knowledge of these color-category associations was again explicit. The locations of the four types of object images were randomized for each trial, and the specific color-category associations were randomized across participants.

Lastly, in the prediction phase that followed the exposure, participants again saw the joint presentation of two dots on the screen, followed by the search array (Fig. 4). The color of the dots no longer predicted on which category of images the target would appear. For each image pair, there were three image types (conjunction, disjunction, and impossible) following their joint presentation (Fig. 4). New images for each category were used. Participants' response time and cursor movements were again recorded for analysis. We did not present image pairs that did not overlap in their associated outcome. For example, blue-red pair was not presented, because blue and red were associated with animate and inanimate objects, respectively, and these two categories had no overlap. This resulted in 4 color pairs, and the target appeared once on each of the four image types after each color pair, resulting in 16 trials in the prediction phase.

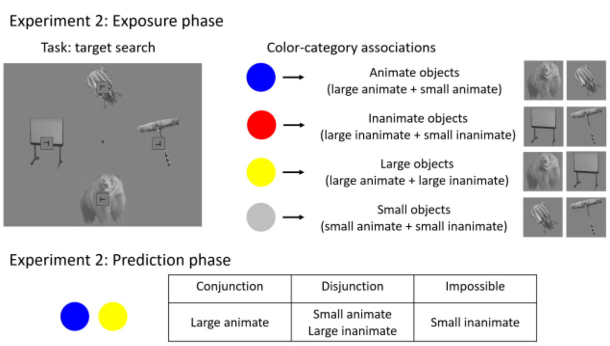

Fig. 4: Experiment 2 paradigm. During exposure, participants viewed search arrays following each colored dot. Four shapes (3 "L"s and a target "T") appeared on four different types of object images. These shapes were blurred and participants had to move the cursor to reveal them. Each color predicted on which category of object images the target would appear. During the prediction phase, participants again saw the joint presentation of two colored dots before each search array. The target appeared on all images with equal frequency. Following each pair of colors, there were three types of images: conjunction (C), disjunction (D), and impossible (I). Illustrated here are only examples of possible color-category associations.

Results and Discussion

Data from 12 participants were taken out due to low accuracy. The accuracy of the remaining participants was 99%.

We first analyzed the responses time (RT) of correct trials in the prediction phase (Fig. 5). A one-way repeated-measures (image types: conjunction, disjunction, and impossible) ANOVA revealed a significant main effect [$F(2,118)=9.20$, $p<.001$, $\eta_p^2=0.13$]. Post-hoc Tukey HSD tests showed that RT in the conjunction trials was reliably faster than that in the disjunction and impossible trials [p's<.01].

Then, we analyzed the tracking data of correct trials and computed the images participants first checked for the target. Again, for the blue and yellow pair, if participants first checked the large animate image to search for the target, this would indicate that they made a conjunctive prediction about the target appearance. A one-way repeated-measures ANOVA of first entry frequencies revealed a significant main effect of image types [$F(2,118)=25.08$, $p<.001$, $\eta_p^2=0.30$]. However, Post-hoc Tukey HSD tests showed that first entry for conjunction images was not reliably more frequent than that for disjunction images [$p=.76$] (Fig. 5).

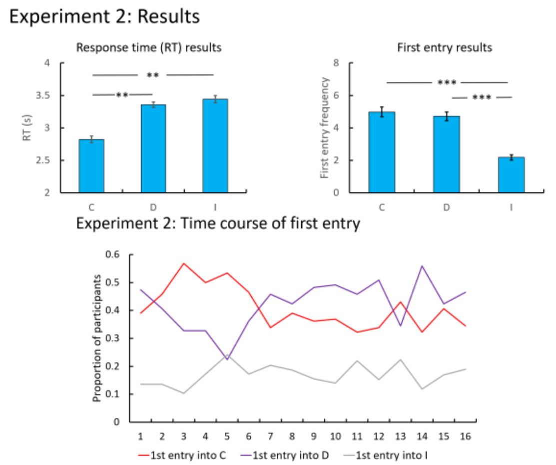

Fig. 5: Experiment 2 results. The response time (RT) for each type of trials was graphed on the top-left and the average frequency of first entry into the different types of images was graphed on the top-right (Error bar reflect ± 1 SE; $^{**}p<.01$, $^{***}p<.001$). On the bottom is a trial-by-trial (x-axis) analysis of the first entry into different types of images.

We again plotted the time-course of participants' first entry into different types of images (Fig. 5). We found that in trials 2-6 (out of 16), the proportion of participants who first entered the conjunction image was higher than those who first entered disjunction images, and this difference was reliable for trials 3-5 (p's<.05). As time progressed, this difference dissipated. These time course results again suggested that participants initially made conjunctive predictions, but as they might have realized that the colors no longer predicted target images, they started searching for the target randomly.

Overall, these results demonstrated that participants were more likely to search for the target on the conjunctive images. This suggested that conjunctive predictions can be made not only for spatial combinations, but also for conceptual combinations of overlapping categories.

Experiment 3

The previous two experiments employed RT measures as well as attention tracking analyses. Consistent with Yu and Zhao (2020), the results showed that participants made conjunctive predictions that represented the overlap of the outcomes associated with the two joint cues. Experiment 3 examined the reverse of such conjunction. That is, after learning that two joint cues were associated with an outcome, what do people predict when seeing one of the cues alone?

Participants

60 students (38 female, mean age=20.2 years, SD=2.5) participated for course credit.

Stimuli and Procedure

The stimuli and procedure in the experiment were mostly the same as those in Experiment 1, except for two important differences.

First, during the exposure, participants saw paired colored dots presented jointly on the screen. The same four colors were used, and grouped into two pairs. The target search task was the same following each pair. The two color pairs predicted that the target would appear in two non-overlapping halves of the screen (e.g., if the blue-red pair predicted the top half, then the yellow-grey pair predicted the bottom half). During exposure, there were trials with single dots as well. A single dot was randomly selected from each pair, and it predicted that the target would appear in a quadrant that was a subset of its color pair's association. For example, after blue and red, the target always appeared on the top of the array; so after blue, the target would always appear in the top-left/top-right quadrant of the array. Each color pair and single dot was presented 10 times, resulting in 40 trials. The knowledge of the color-location associations was again explicit. The order of the color pair and single dot trials was randomized.

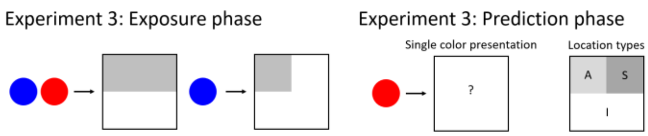

Fig. 6. Experiment 3 paradigm. During exposure, a color pair predicted that the target would appear in one half of the array (e.g., blue-red predicted the top half). There were two pairs in total, and the other pair predicted a non-overlapping half (e.g., the bottom half). A single colored dot from each color pair predicted that the target would appear in a quadrant, which is a subset of its pair's associated location (e.g., blue predicted the top-left quadrant). During the prediction phase, the other single color from each pair (e.g., red) was presented alone, and the target appeared in all four quadrants with equal frequency following the single color. For red, it was not associated with the bottom half during exposure, making the bottom half the impossible location (I). The top-left quadrant was associated with red through the blue-red pair, making it the associated location (A). The top-right was also associated with the blue-red pair, but not blue alone. So if blue's associated outcome was subtracted from blue-red pair's associated outcome, participants would predict the target to appear in the top-right quadrant, making the top-right the subtracted location (S).

Next, during the prediction phase, the other single colored dot from each pair was presented on the screen. These were the single dots that were never presented alone during exposure. Again, following each single dot, the target appeared in all four quadrants once, resulting in 8 trials in total. There were three types of locations (Fig. 6). Take the red color, the bottom half was never associated with the blue-red pair, so it would be the impossible location (I). Both the top-left and top-right quadrants were associated the blue-red pair during exposure, but blue alone was associated with the top-left quadrant. So if participants subtracted blue's associated outcome from the pair's associated outcome, they would predict that the target should appear in the top-right quadrant. Therefore, the top-left quadrant would be the subtracted location (S). The remaining top-left quadrant was the associated location (A), since it was associated with both the red-blue pair and blue alone during exposure.

Results and Discussion

Data from 6 participants were taken out due to low overall accuracy. The resulting accuracy was 98%.

As before, we analyzed RT of correct trials in the prediction phase (Fig. 7). Take the red dot for example, if RT was faster in the top-right quadrant (location S) than the other quadrants, it would indicate that participants made a prediction based subtracting blue's associated outcome from the blue-red pair's associated outcome. If RT was not different in the top-right (location S) and top-left (location A) quadrants, this would suggest that participants made predictions based all outcomes that were previously associated with the blue-red pair. A one-way repeated-measures ANOVA revealed a main effect of location type [$F(2,118)=9.17$, $p<.001$, $\eta_p^2=0.13$]. Post-hoc Tukey HSD tests showed that the only difference in RT was that RT in the impossible location was reliably slower than that in the subtracted location (S) or the associated location (A) [p's<.01].

Then, we analyzed the tracking data of correct trials and computed the locations participants first searched for the target. There were two impossible quadrants (I), and for each participant, we took the mean frequency of first entry into the two quadrants rather than the sum. Then, this frequency was averaged across participants. This differed from how we computed frequency for the disjunction location in Experiment 1, because the impossible locations were never associated with any color. A one-way repeated-measures ANOVA of first entry frequencies revealed a significant main effect of location types [$F(2,118)=11.17$, $p<.001$, $\eta_p^2=0.17$]. Again, post-hoc Tukey HSD tests showed that the only difference was that frequency in the impossible location was reliably lower than that in the subtracted location (S) or the associated location (A) [p's<.01].

Overall, these results suggested that participants' predictions were based on associations learned during exposure, but their predictions were not based on subtracting single color's associated outcome from the corresponding color pair's associated outcome.

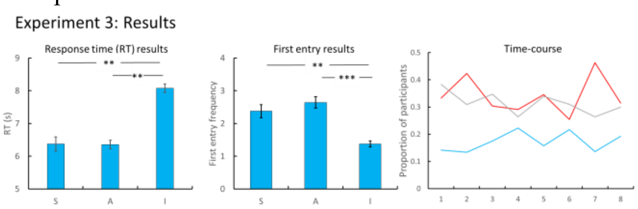

Fig. 7: Experiment 3 results. The RT for each type of trial was graphed on the left, the frequency of entry into the three types of locations was graphed at the center, and on the right is a trial-by-trial analysis of the first entry into different types of location. (Error bar reflect ± 1 SE; $^{**}p<.01$, $^{***}p<.001$).

General Discussion

In this study, we examined how predictions were made in the presence of two objects that were associated with two different outcomes. Using a visual search paradigm, unique colors or color pairs predicted a specific location of the target in the search array (Experiments 1 and 3) or they predicted target appearance on a specific category of images (Experiment 2) in the exposure phase. In the prediction phase, we examined where the target was expected to appear when two colored dots (Experiments 1 and 2) or a single dot (Experiment 3) were presented to participants for the first time. Importantly in the prediction phase, the target appeared in any location or on any image with equal frequency.

Based on the speed of visual search (RT), as well tracking participants' cursor movement to see where they first searched for the target, we found that participants were more likely to search for the target in the conjunctive location/image than the disjunction locations/images or the impossible location/image. These results suggested that participants made conjunctive predictions that represented the overlap of the outcomes associated with the two cues. This was not strictly a rational prediction upon seeing the two joint cues because there was no prior trials or instructions indicating that conjunctive predictions should be made. This meant that the prioritization of the conjunctive location over the disjunctive locations in the search task occurred without prior experience or instructions.

It should be noted that in the experiments reported here, participants received explicit instructions about the color-location associations. Therefore, when encountering the joint presentation of color cues, participants' search strategy may have been more affected by explicit knowledge. Nevertheless, this possibility does not alter the way the current results should be interpreted. This is because if participants were faithfully basing their judgement on the knowledge of color-location associations during exposure, the summed frequency of first entry into the disjunctive location should be the same as the frequency of first entry into the conjunctive location. This possibility was discussed in the introduction. Instead, we found that participants searched for the target in the conjunctive location more frequently. This meant that participants' search strategy deviated from the color-location associations during exposure and suggested that they made conjunctive predictions. Such conjunctive predictions were incidental, since participants were never told to make any predictions beyond exposure-phase knowledge, nor were there any previous examples of target appearance in the conjunctive location. Exploring such incidental predictions was the focus of the current research, rather than finding out whether or not such predictions were based on the explicit knowledge of cue-outcome associations.

The reverse of this conjunctive prediction was a subtractive prediction. Whether participants would make subtractive predictions was directly examined in Experiment 3. Specifically, during exposure, a color pair (e.g., AB) predicted an outcome, and a single color (e.g., A) from that pair predicted a subset of that outcome. Then in the prediction phase, we found that when seeing the other color presented alone (e.g., B), participants did not subtract the single-color (A) outcome from the outcome of the AB pair. Rather, participants predicted the outcome of B to be anything that was previously associated with AB. This suggested that when encountering the novel occurrence of predictive cues (e.g., seeing B alone), participants' predictions were likely non-deliberate and only based on previous associations.

It should be noted that conclusions for Experiments 1 and 2 were drawn from the prediction phase time-course data. This was because the colors no longer predicted target location in the prediction phase, and knowledge from exposure would go through extinction as time progressed. But the timeline of extinction was not directly measured, so the time-course analyses were exploratory. A better way to examine conjunctive predictions is to reduce the effect of extinction. This could be done by reducing the color-location associations to a percentage significantly lower than 100%. Indeed, recent results show that when the association strength was lowered to reduce extinction in prediction phase, first entry into the conjunctive location was reliably more frequent than that in the disjunctive location (Yu & Zhao, in prep).

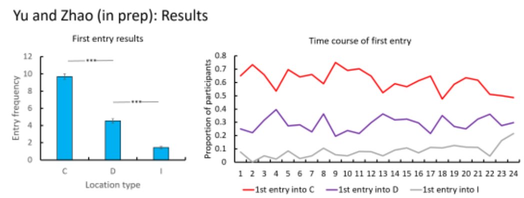

Fig. 7: First entry results for Yu and Zhao (in prep). The frequency of first entry into the three types of locations was graphed on the left, and on the right is a trial-by-trial (x-axis) analysis of the first entry into different types of location. (Error bar reflect ± 1 SE; ***p<.001).

In conclusion, the current results suggested that in the presence of multiple predictors, knowledge of cue-outcome associations guides predictions about the outcomes in a conjunctive fashion.

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