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Statistically learned associations among objects bias attention

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Abstract

A growing body of research suggests that semantic relationships among objects can influence the control of attention. There is also some evidence that learned associations among objects can bias attention. However, it is unclear whether these findings are due to statistical learning or existing semantic relationships. In the present study, we examined whether statistically learned associations among objects can bias attention in the absence of existing semantic relationships. Participants searched for one of four targets among pairs of novel shapes and identified whether the target was present or absent from the display. In an initial training phase, each target was paired with an associated distractor in a fixed spatial configuration. In a subsequent test phase, each target could be paired with the previously associated distractor or a different distractor. In our first experiment, the previously associated distractor was always presented in the same pair as the target. Participants were faster to respond when this distractor was present on target-present trials. In our second experiment, the previously associated distractor was presented in a different pair than the target in the test phase. In this case, participants were slower to respond when this distractor was present on both target-present and target-absent trials. Together, these findings provide clear evidence that statistically learned associations among objects can bias attention, analogous to the effects of semantic relationships on attention.

Keywords Attention · Visual search · Statistical learning · Semantic relationships · Selection history

Introduction

Visual search is a fundamental attentional task that is involved in a variety of everyday activities. Successfully searching for objects involves selecting task-relevant information while ignoring distracting information. Indeed, both stimulus-driven factors and goal-directed factors have been found to influence the allocation of attention (Corbetta & Shulman, 2002; Theeuwes, 2010). However, visual salience and observers' task goals are not the only factors that influence the control of attention. In many cases, successfully searching for objects also involves remembering the identities and locations of objects. Indeed, a large body of research suggests that the control of attention is supported by multiple memory systems (see Hutchinson & Turk-Browne, 2012, for a review). For example, both implicit forms of memory, such as intertrial priming (Maljkovic & Nakayama, 1994) and statistical learning (Geng & Behrmann, 2005; Jiang et al., 2013; Wang & Theeuwes, 2018a), and explicit forms of memory, such as working memory (Olivers et al., 2006; Soto et al., 2005) and episodic memory (Fan & Turk-Browne, 2016; Nickel et al., 2020), have been found to influence the allocation of attention.

One form of memory that plays an important role in the allocation of attention is observers' semantic knowledge (see Wu, Wick et al., 2014b, for a review). A large body of research suggests that observers' knowledge of the surrounding scene context can influence the control of attention. For example, observers can rapidly extract the context, or *gist,* of a scene and use it to guide their attention toward the likely locations of objects (Neider & Zelinsky, 2006; Torralba et al., 2006). A growing body of research also suggests that semantic relationships among individual objects can influence the control of attention. For example, when observers search for a particular object, their attention is often biased toward semantically related objects in the display (Belke et al., 2008; de Groot et al., 2016; Moores et al., 2003;

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Telling et al., 2010). Similar findings have been observed in real-world scenes (Hwang et al., 2011; Wu, Wang et al., 2014a). Moreover, semantic relationships have been found to bias attention even when they are irrelevant to observers' task (Malcolm et al., 2016). Together, these findings suggest that semantic knowledge plays an important role in the allocation of attention.

In addition to sharing semantic relationships, objects often co-occur with each other in predictable ways. For example, tables and chairs not only share a semantic relationship but also co-occur in specific spatial configurations. A large body of research suggests that observers can implicitly learn these statistical regularities, even in the absence of awareness or explicit grouping cues (Fiser & Aslin, 2001, 2002; Turk-Browne et al., 2005). Moreover, this statistical learning process has been found to influence the allocation of attention. For example, observers are faster to identify targets when they appear in repeated spatial configurations (Chun & Jiang, 1998, 2003) or at high-probability locations (Geng & Behrmann, 2002, 2005; Jiang et al., 2013). Similar findings have been observed for the suppression of salient distractors (Britton & Anderson, 2020; Ferrante et al., 2018; Wang & Theeuwes, 2018a, 2018b, 2018c). Moreover, observers are faster to identify targets when they appear at locations that contain statistical regularities, suggesting that attention is automatically biased toward these regularities (Yu & Zhao, 2015; Zhao et al., 2013). Together, these findings suggest that statistical learning plays an important role in the allocation of attention.

Although semantic knowledge and statistical learning have similar effects on attention, few studies have examined the relationship between these factors. Many theories assume that semantic knowledge and statistical learning are supported by distinct memory systems (e.g., Hutchinson & Turk-Browne, 2012). However, because semantically related objects frequently co-occur in the same scenes, these factors are often confounded with each other. Thus, it is often difficult to disentangle the effects of these factors. Notably, there is some evidence that statistical learning can bias attention similarly to the effects of scene context on attention. For example, as studies of contextual cueing demonstrate, observers are faster to identify targets when they appear in repeated spatial configurations (Chun & Jiang, 1998, 2003). Similar findings have been observed in real-world scenes, suggesting that learned associations between objects and the surrounding scene context can bias attention (Brockmole et al., 2006; Brockmole & Henderson, 2006a, 2006b). However, it is unclear whether statistically learned associations among individual objects can bias attention similarly to the effects of semantic relationships on attention.

Although few studies have directly addressed this question, there is some evidence that learned associations among objects can bias attention. For example, Mack and Eckstein (2011) found that participants were faster to locate targets when they were presented near cue objects that frequently co-occur in the same scenes (e.g., a fork and plate). Participants were also more likely to fixate the cue objects, suggesting that attention was biased toward these objects. Similarly, Boettcher et al. (2018) found that participants were faster to locate targets when they were presented near larger anchor objects that typically predict the location of the target (e.g., a shower and towel). However, because the objects in these studies were always semantically related to the target, it is unclear whether these findings are due to statistical learning or existing semantic relationships. In the present study, we examined whether statistically learned associations among objects can bias attention in the absence of existing semantic relationships. Such an outcome would provide clear evidence that statistically learned associations among objects can bias attention, analogous to the effects of semantic relationships on attention.

Experiment 1

In Experiment 1, we examined whether statistically learned associations among objects can bias attention. Participants searched for one of four targets among pairs of novel shapes and identified whether the target was present or absent from the display. In an initial training phase, each target was paired with an associated distractor in a fixed spatial configuration. Thus, this distractor served as a cue that could be used to predict both the location and presence of the target. In a subsequent test phase, each target could be paired with the previously associated distractor or a different distractor. If statistically learned associations among objects bias attention when they predict the location and presence of the target, participants should be faster to respond when the previously associated distractor is present on target-present trials. Moreover, if these associations bias attention even when they do not predict the location or presence of the target, participants should be slower to respond when this distractor is present on target-absent trials.

Method

Participants

Assuming a small effect size ($f = 0.1$) and a moderate correlation between levels of our within-subjects variables ($\rho = 0.5$), an a priori power analysis conducted using G*Power 3 (Faul et al., 2007) indicated that a sample size of 24 participants would be sufficient to detect at least one simple effect of distractor condition at 80% statistical power. However, to account for the added variability of recruiting and testing participants online, we increased our sample size to 48 participants. As a result, a group of 56 participants from the Texas A&M community were recruited and tested online; however, eight participants were excluded due to low accuracy (65% correct or less; *n* = 4), because they failed to complete one or more blocks of trials (*n* = 3), or because they did not report normal or corrected-to-normal visual acuity (*n* = 2). Participants could be excluded for multiple reasons. The remaining 48 participants (27 females; mean age = 18.9 years, *SD* = 1.6 years) were between the ages of 18 and 35 and reported normal or corrected-to-normal visual acuity and normal color vision. All participants received course credit for participating in the experiment.

Apparatus and stimuli

Stimuli were adapted from Fiser and Aslin (2001) and Turk-Browne et al. (2005), and consisted of 24 novel shapes (see Fig. 1). Four shapes served as targets and four shapes served as critical distractors, while the remaining shapes served as non-critical distractors. Each target could be paired with one of two critical distractors (the *associated distractor* and *unassociated distractor,* respectively; see Fig. 2A–B), while each noncritical distractor could be paired with one of two different noncritical distractors. To select the unassociated distractors, the associated distractors for two different targets were switched, so that the associated distractor for each target served as the unassociated distractor for a different target. This ensured that each critical distractor appeared equally often as the associated or unassociated distractor. The shapes in each pair were presented in a fixed spatial configuration, with each shape always appearing on the same side of a pair. All images subtended 12% of participants' screen height, and were presented in black on a white background. The images were arranged into search displays, which consisted of eight shapes arranged into four pairs. The four pairs were presented 32% of participants' screen height above, below, to the left, and to the right of the center of the screen, and the shapes within each pair were separated by 14% of participants' screen height. The experiment was programmed and run using PsychoPy3 software (Peirce et al., 2019), and participants viewed the images on their own computers.

Training phase

At the beginning of each trial, one of the four targets (the *cued target*) was presented in the center of the screen (see Fig. 2C). After 1,000 ms, a fixation cross (2% of participants' screen height) was presented for 1,000 ms. Afterward, an array of eight shapes appeared on the screen. Participants were instructed to search for the cued target and identify whether it was present or absent from the display. On target-present trials, the cued target was presented in the same pair as its associated distractor. On target-absent trials, one of the uncued targets was presented as a foil target, and was presented in the same pair as its associated distractor, which also served as the unassociated distractor for the cued target. This ensured that the associated distractor always predicted the location and presence of the target on both target-present and target-absent trials. The remaining shapes were randomly selected from the set of noncritical distractor pairs, with the constraint that no two pairs could contain the same shape. Participants pressed the "z" or "/" keys to identify whether the target was present or absent from the display (the mapping of the response keys was counterbalanced

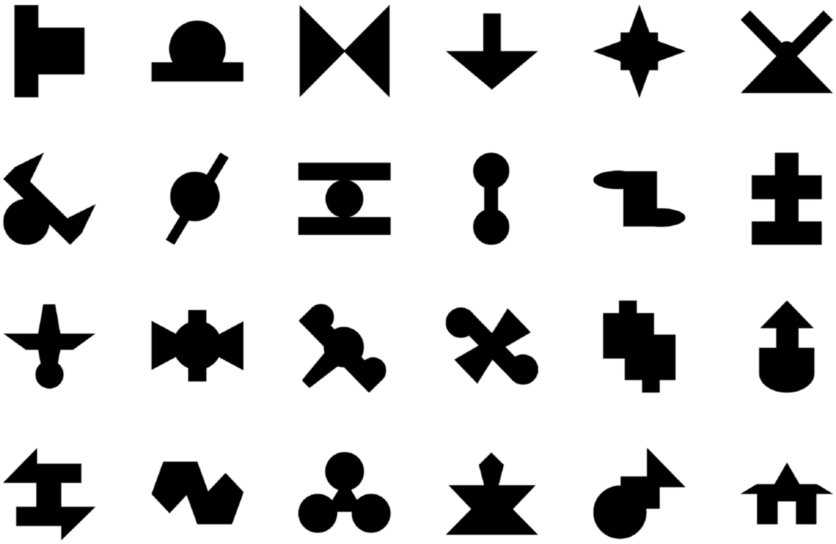

Fig. 1 Novel shapes used in the present study. *Note.* Eight shapes served as targets and critical distractors, while the remaining shapes served as noncritical distractors

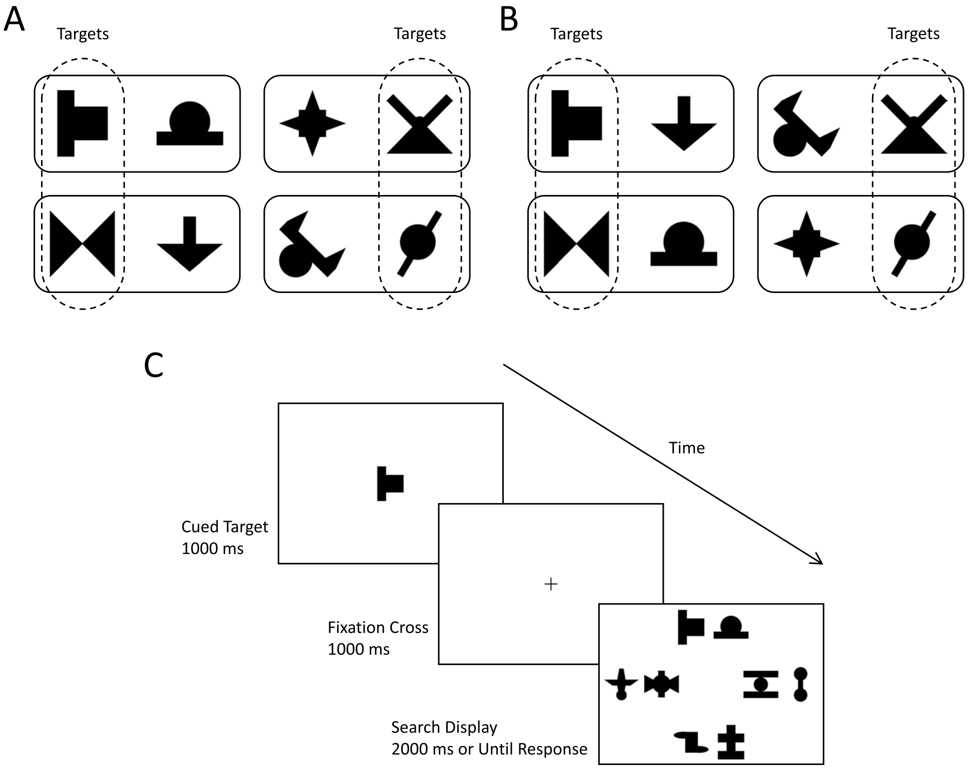

Fig. 2 Example associated and unassociated distractors and trial sequence in the present study. *Note.* **A** Example targets and their associated distractors in the present study. **B** Example targets and their unassociated distractors in the present study. Targets in both panels are indicated by the dashed line. **C** Example trial sequence in the present study

across participants). A trial ended after 2,000 ms or once participants made a response. Participants received an error message if they responded incorrectly or if their response times were less than 100 ms or greater than 2,000 ms.

Participants completed 16 practice trials followed by four blocks of 80 trials, for a total of 320 trials. The four targets were presented randomly and equally often within a block, and appeared equally often on target-present and target-absent trials. As a result, the identity of the cued and foil target were counterbalanced across trials. The cued and foil target also appeared equally often at each of the four locations. Thus, the location of the cued and foil target were also counterbalanced across trials.

Test phase

The task was the same as in the training phase. However, on target-present trials, the cued target was presented in the same pair as either its associated or unassociated distractor. On target-absent trials, the foil target was presented in the same pair as either the associated or unassociated distractor for the cued target. All other details of the experimental procedure were identical to those in the training phase.

Participants completed four blocks of 80 trials, for a total of 320 trials. The four targets and critical distractors were presented randomly and equally often within a block, and appeared equally often on target-present and target-absent trials. As a result, the identity of the cued and foil target and the distractor condition were counterbalanced across trials. The cued and foil target also appeared equally often at each of the four locations. Thus, the location of the cued and foil target were also counterbalanced across trials.

Data analysis

We measured both accuracy and response times. Incorrect responses and response times less than 100 ms and greater than 2,000 ms were excluded from analysis. All dependent variables in the training phase were analyzed using paired-samples *t* tests, and all dependent variables in the test phase were analyzed using 2 (target presence: present, absent) × 2 (distractor condition: associated, unassociated) repeated-measures analyses of variance (ANOVAs). Significant interactions were followed by simple effects tests comparing the associated and unassociated conditions for target-present and target-absent trials. To assess the time course of any statistical learning effects, we also analyzed response times in the test phase using a 2 (target presence: present, absent) × 2 (distractor condition: associated, unassociated) × 4 (block: 1, 2, 3, 4) repeated-measures ANOVA. Significant three-way interactions were followed by simple effects tests comparing two-way interactions between distractor condition and block for target-present and target-absent trials.

Results

Training phase

Participants were significantly less accurate on target-present trials (M = 91.49%, SD = 4.60%) compared with target-absent trials (M = 94.56%, SD = 5.38%), $t(47) = -4.35$, $p < .001$, $\eta_p^2 = .287$, but responded significantly faster on target-present trials (M = 739 ms, SD = 108 ms) compared with target-absent trials (M = 980 ms, SD = 158 ms), $t(47) = -20.63$, $p < .001$, $\eta_p^2 = .901$. Thus, participants were faster but less accurate at detecting the target on target-present trials.

Test phase

To test whether statistically learned associations among objects biased attention, we first analyzed average accuracy. Again, there was a significant main effect of target presence, $F(1, 47) = 4.75$, $p = .034$, $\eta_p^2 = .092$, with participants displaying lower accuracy on target-present trials (M = 90.10%, SD = 5.71%) compared with target-absent trials (M = 91.74%, SD = 7.91%). However, there was neither a significant main effect of distractor condition, $F(1, 47) = 3.11$, $p = .084$, $\eta_p^2 = .062$, nor a significant interaction between target presence and distractor condition, $F(1, 47) = 0.13$, $p = .719$, $\eta_p^2 = .003$. Thus, as in the training phase, participants were less accurate at detecting the target on target-present trials.

To further test whether statistically learned associations among objects biased attention, we next analyzed average response times. Again, there was a significant main effect of target presence, $F(1, 47) = 220.43$, $p < .001$, $\eta_p^2 = .824$, with participants responding faster on target-present trials (M = 697 ms, SD = 107 ms) compared with target-absent trials (M = 879 ms, SD = 160 ms). There was no significant main effect of distractor condition, $F(1, 47) = 1.89$, $p = .176$, $\eta_p^2 = .039$. However, there was a significant interaction between target presence and distractor condition, $F(1, 47) = 6.99$, $p = .011$, $\eta_p^2 = .130$. Simple effects tests revealed a significant main effect of distractor condition on target-present trials, $F(1, 47) = 8.54$, $p = .005$, $\eta_p^2 = .154$, with participants responding faster when the associated distractor was present (M = 690 ms, SD = 106 ms) compared with when it was absent (M = 703 ms, SD = 110 ms). However, there was no significant main effect of distractor condition on target-absent trials, $F(1, 47) = 0.51$, $p = .478$, $\eta_p^2 = .011$. Thus, while statistically learned associations among objects facilitated search for the target, this effect was only observed on target-present trials (see Fig. 3).

Lastly, to assess the time course of these effects, we analyzed average response times as a function of block. Consistent with the previous results, there was a significant main effect of target presence, $F(1, 47) = 217.00$, $p < .001$, $\eta_p^2 = .835$. There was no significant main effect of distractor condition, $F(1, 47) = 1.99$, $p = .165$, $\eta_p^2 = .041$. However, there was a significant two-way interaction between target presence and distractor condition, $F(1, 47) = 6.36$, $p = .015$, $\eta_p^2 = .119$. No effects of block were significant, all $ps \geq .089$. Thus, these effects did not differ as a function of block.

Discussion

In Experiment 1, we found that statistically learned associations among objects biased attention similarly to the effects of semantic relationships on attention. Consistent with previous evidence, participants were faster but less accurate at detecting the target on target-present trials. This speed–accuracy trade-off is a well-known characteristic of many visual search tasks, and likely reflects a higher quitting threshold on target-absent trials (e.g., Chun & Wolfe, 1996). More importantly, participants were faster to respond when the associated distractor was present on target-present trials. However, participants were not slower to respond when the associated distractor was present on target-absent trials. Thus, statistically learned associations among objects facilitated search, but only when they predicted the location and presence of the target. These effects did not differ as a function of block. Together, these findings suggest that statistically learned associations among objects can bias attention, particularly when these associations predict the location and presence of the target.

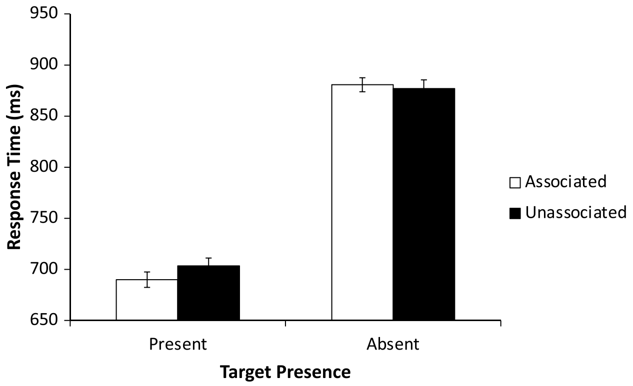

Fig. 3 Average response times in the test phase of Experiment 1. *Note.* Error bars reflect ±1 within-subjects standard error (Cousineau, 2005; Morey, 2008)

Experiment 2

In Experiment 1, statistically learned associations among objects appeared to bias attention. However, because this effect was only observed on target-present trials, it is possible that these associations facilitated target identification or other decision-making processes rather than biasing attention. In Experiment 2, we attempted to provide a more direct test of whether these associations can bias attention. Participants completed the same task as in Experiment 1. However, in the test phase, the previously associated distractor was presented in a different pair than the target so that this distractor never predicted the location of the target. If statistically learned associations among objects bias attention, participants should be slower to respond when the previously associated distractor is present on both target-present and target-absent trials. However, if these associations facilitate target identification or other decision-making processes, participants should not be slower to respond when this distractor is present on either target-present or target-absent trials.

Method

Participants

A new group of 58 participants from the Texas A&M community were recruited and tested online; however, 10 participants were excluded due to low accuracy (65% correct or less; *n* = 10) or because they failed to complete one or more blocks of trials (*n* = 1). Participants could be excluded for multiple reasons. The remaining 48 participants (24 females; mean age = 18.8 years, *SD* = 1.0 years) were between the ages of 18 and 35 and reported normal or corrected-to-normal visual acuity and normal color vision. All participants received course credit for participating in the experiment.

Apparatus and stimuli

The apparatus and stimuli were identical to those in the previous experiment.

Training phase

The training phase was identical to that in the previous experiment.

Test phase

The test phase was similar to that in the previous experiment. However, on each trial, the critical distractor was randomly switched with one of the noncritical distractors in the display, with the constraint that both distractors appeared on the same side of a pair. All other details of the test phase were identical to those in the previous experiment.

Data analysis

The analytical approach was identical to that in the previous experiment.

Results

Training phase

Participants were significantly less accurate on target-present trials (*M* = 89.94%, *SD* = 5.67%) compared with target-absent trials (*M* = 93.48%, *SD* = 5.29%), *t*(47) = −5.27, $p < .001$, $\eta_p^2 = .372$, but responded significantly faster on target-present trials (*M* = 728 ms, *SD* = 102 ms) compared with target-absent trials (*M* = 951 ms, *SD* = 147 ms), *t*(47) = −17.87, $p < .001$, $\eta_p^2 = .872$. Thus, as in the previous experiment, participants were faster but less accurate at detecting the target on target-present trials.

Test phase

To test whether statistically learned associations among objects biased attention, we first analyzed average accuracy. Again, there was a significant main effect of target presence, *F*(1, 47) = 22.43, $p < .001$, $\eta_p^2 = .323$, with participants displaying lower accuracy on target-present trials (*M* = 88.90%, *SD* = 5.90%) compared with target-absent trials (*M* = 92.80%, *SD* = 4.66%). However, there was neither a significant main effect of distractor condition, *F*(1, 47) = 1.79, *p* = .188, $\eta_p^2 = .037$, nor a significant interaction between target presence and distractor condition, *F*(1, 47) = 0.08, *p* = .782, $\eta_p^2 = .002$. Thus, as in the training phase, participants were less accurate at detecting the target on target-present trials.

To further test whether statistically learned associations among objects biased attention, we next analyzed average response times. Again, there was a significant main effect of target presence, *F*(1, 47) = 157.58, $p < .001$, $\eta_p^2 = .770$, with participants responding faster on target-present trials (*M* = 712 ms, *SD* = 129 ms) compared with target-absent trials (*M* = 866 ms, *SD* = 142 ms). There was also a significant main effect of distractor condition, *F* (1, 47) = 4.89, *p* = .032, $\eta_p^2 = .094$, with participants responding slower when the associated distractor was present (*M* = 793 ms, *SD* = 131 ms) compared with when it was absent (*M* = 785 ms, *SD* = 128 ms). However, there was no significant interaction between target presence and distractor condition, *F*(1, 47) = 0.09, *p* = .767, $\eta_p^2 = .002$. Thus, statistically learned

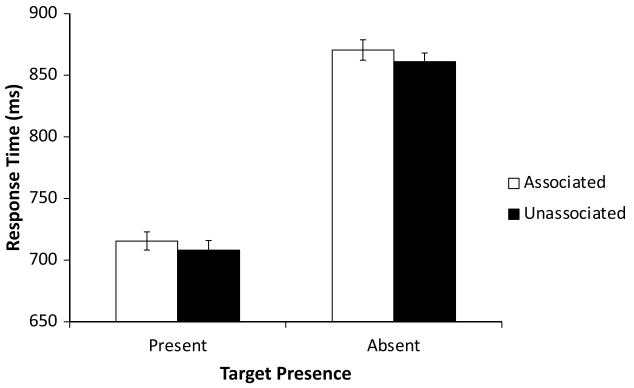

Fig. 4 Average response times in the test phase of Experiment 2. *Note.* Error bars reflect ±1 within-subjects standard error (Cousineau, 2005; Morey, 2008)

associations among objects impaired search for the target on both target-present and target-absent trials (see Fig. 4).

Lastly, to assess the time course of these effects, we analyzed average response times as a function of block. Consistent with the previous results, there was a significant main effect of target presence, $F(1, 47) = 154.93$, $p < .001$, $\eta_p^2 = .767$, and a significant main effect of distractor condition, $F(1, 47) = 5.17$, $p = .028$, $\eta_p^2 = .099$. There was no significant two-way interaction between target presence and distractor condition, $F(1, 47) = 0.08$, $p = .773$, $\eta_p^2 = .002$. However, there was a significant three-way interaction between target presence, distractor condition, and block, $F(3, 141) = 3.66$, $p = .014$, $\eta_p^2 = .072$. Simple effects tests revealed a significant two-way interaction between distractor condition and block on target-absent trials, $F(3, 141) = 2.99$, $p = .033$, $\eta_p^2 = .060$, with the magnitude of the statistical learning effect decreasing as a function of block. However, there was no significant two-way interaction between distractor condition and block on target-present trials, $F(3, 141) = 0.63$, $p = .598$, $\eta_p^2 = .013$. No other effects of block were significant, all *ps* ≥ .387. Thus, while these effects decreased as a function of block on target-absent trials, they did not differ as a function of block on target-present trials.

Discussion

In Experiment 2, we again found that statistically learned associations among objects biased attention similarly to the effects of semantic relationships on attention. As in the previous experiment, participants were faster but less accurate at detecting the target on target-present trials. More importantly, participants were slower to respond when the associated distractor was present. Critically, this effect was observed on both target-present and target-absent trials. Thus, statistically learned associations among objects impaired search when they no longer predicted the location or presence of the target. While these effects decreased as a function of block on target-absent trials, suggesting that the statistical regularities gradually extinguished over the course of the test phase, they did not differ as a function of block on target-present trials. Together, these findings suggest that statistically learned associations among objects biased attention rather than facilitating target identification or other decision-making processes.

General discussion

In the present study, we examined whether statistically learned associations among objects can bias attention. Participants searched for one of four targets among pairs of novel shapes and identified whether the target was present or absent from the display. In an initial training phase, each target was paired with an associated distractor in a fixed spatial configuration. In a subsequent test phase, each target could be paired with the previously associated distractor or a different distractor. In our first experiment, the previously associated distractor was always presented in the same pair as the target. Participants were faster to respond when this distractor was present on target-present trials. Thus, statistically learned associations among objects appeared to bias attention, particularly when these associations predicted the location and presence of the target. In our second experiment, the previously associated distractor was presented in a different pair than the target in the test phase. In this case, participants were slower to respond when this distractor was present on both target-present and target-absent trials. Thus, statistically learned associations among objects appeared to bias attention, even when these associations no longer predicted the location or presence of the target. Together, these findings suggest that statistically learned associations among objects can bias attention in the absence of existing semantic relationships.

Overall, the present findings provide new evidence regarding the effects of statistical learning on attention. Previous evidence suggests that statistical learning plays an important role in the allocation of attention. For example, observers are faster to identify targets when they are presented in repeated spatial configurations (Chun & Jiang, 1998, 2003) or at high-probability locations (Geng & Behrmann, 2002, 2005; Jiang et al., 2013). There is also some evidence that learned associations among objects can bias attention (Boettcher et al., 2018; Mack & Eckstein, 2011). However, it is unclear whether these findings are due to statistical learning or existing semantic relationships. In the present study, we found that learned associations among objects biased attention in the absence of existing semantic relationships. These associations not only facilitated search when they predicted the location and presence of the target, but also impaired search when they no longer predicted the location or presence of the target. Thus, these associations appeared to automatically bias attention (Yu & Zhao, 2015; Zhao et al., 2013). Together, these findings suggest that statistically learned associations among objects can bias attention similarly to the effects of semantic relationships on attention.

More broadly, the present findings provide new evidence regarding the relationship between semantic knowledge and statistical learning. Many theories assume that semantic knowledge and statistical learning are supported by distinct memory systems (e.g., Hutchinson & Turk-Browne, 2012). For example, while semantic knowledge is thought to be an explicit form of memory, statistical learning is thought to be an implicit form of memory. However, these factors have similar effects on attention. It is likely that the effects of semantic knowledge and statistical learning represent distinct influences of prior experience, or *selection history,* and that these factors jointly influence the control of attention (Anderson et al., 2021; Awh et al., 2012). The present findings are largely consistent with this suggestion, and suggest that statistically learned associations among objects can bias attention in the absence of existing semantic relationships. However, this does not mean that these factors do not interact with each other. For example, recent evidence suggests that semantic knowledge can structure the learning of statistical regularities in visual search (Bahle et al., 2021; Kershner & Hollingworth, 2022). Future work should attempt to further examine how these factors interact with each other by manipulating both of these factors in the same study.

Notably, the present findings are consistent with previous evidence regarding the effects of statistical learning on attention. For example, Gozli et al. (2014) had participants identify a target that was preceded by a peripheral cue. Participants were faster to identify the target when it was preceded by a valid cue, suggesting that this cue captured attention. However, these effects were only observed when the cue was presented in a color that was previously associated with the target. Several studies have also found that participants are faster to identify objects when they are presented in a color that was previously associated with those objects (Bahle et al., 2021; Kershner & Hollingworth, 2022). However, while these studies share some similarities with the present study, they differ from the present study in at least one important way. Specifically, the previous studies examined whether statistically learned associations between objects and features can bias attention. In contrast, we found that statistically learned associations among individual objects biased attention. Thus, these effects are not limited to statistically learned associations between objects and features but can also occur for statistically learned associations among individual objects.

The present findings are also consistent with previous evidence regarding other effects of selection history on attention. For example, in a classic study, Shiffrin and Schneider (1977) had participants search for a consistent set of targets in a rapid stream of images. Participants became more accurate at identifying these targets after an extensive training phase, suggesting that attention was biased toward these targets. Moreover, these targets later captured attention when they appeared as distractors in a test phase. Similar findings have been observed using other visual search tasks (Kyllingsbæk et al., 2001, 2014). Again, while these studies share some similarities with the present study, they differ from the present study in at least one important way. Specifically, the previous studies examined attentional biases toward a consistent set of overlearned targets. In contrast, we found that statistically learned associations between targets and distractors can bias attention. Thus, these effects were due to statistically learned associations among objects, not simply an attentional bias toward a consistent set of overlearned stimuli.

While the present findings suggest that statistically learned associations among objects can bias attention, these effects were smaller than the effects of semantic relationships on attention (Belke et al., 2008; de Groot et al., 2016; Moores et al., 2003; Telling et al., 2010). However, while these relationships are learned over a lifetime of experience, the statistical regularities in our study were learned over the course of an hour. Thus, we think these effects are necessarily smaller than the effects of semantic relationships on attention, as the statistical regularities in our study were likely weaker than these relationships. It is also worth noting that the statistical regularities were equated in the test phase, and thus may have been partially extinguished in this phase. Indeed, we observed some evidence that the statistical regularities were gradually extinguished over the course of the test phase in our second experiment. Lastly, there is some evidence that the effects of learned associations on attention are larger when search is more difficult (Zhou & Geng, 2023). Thus, it is possible that these effects may have been larger if we had used a more difficult visual search task. Future work should attempt to clarify the relative size of these effects.

In the present study, we examined whether statistically learned associations among individual objects can bias attention. However, observers can also learn associations between objects and the surrounding scene context. For example, as studies of contextual cueing demonstrate, observers are faster to identify targets when they are presented in repeated spatial configurations (Chun & Jiang, 1998, 2003) or at repeated locations within a scene (Brockmole et al., 2006; Brockmole & Henderson, 2006a, 2006b). There is also some evidence that the effects of learned associations on attention are context-specific. For example, Brockmole and Võ (2010) found that participants were faster to identify targets when they were presented near a cue object that frequently predicted the location of the target (e.g., a pillow). However, these findings were only observed when the cue object was presented in a semantically consistent scene (e.g., a bedroom). In the present study, we found that statistically learned associations among objects biased attention in the absence of a surrounding scene context. However, it is possible that these effects are also context-specific, and can only be observed in the particular context in which they are learned. Future work should attempt to clarify the relationship between the effects of scene context and statistically learned associations on attention.

Lastly, while the present findings suggest that statistically learned associations among objects can bias attention, it is unclear whether participants were aware of these associations. Previous evidence suggests that the effects of statistical learning on attention are often implicit, and can be observed even in the absence of awareness (Chun & Jiang, 1998, 2003; Ferrante et al., 2018; Jiang et al., 2013; Wang & Theeuwes, 2018a). However, there is some evidence that these effects are at least partially driven by awareness (Smyth & Shanks, 2008; Vadillo et al., 2016, 2020). In the present study, we did not directly assess participants' awareness of the statistical regularities, as this would have required us to assess their awareness immediately after the training phase or after these regularities were equated in the test phase. Thus, it is possible that participants were at least somewhat aware of these regularities. Regardless of whether participants were aware of the statistical regularities, the present findings suggest that statistically learned associations among objects can bias attention in the absence of existing semantic relationships. Nonetheless, future work should attempt to clarify the role of awareness in the present findings, as well as the relationship between awareness and selection history in general (Anderson et al., 2021).

In summary, we found that statistically learned associations among objects biased attention in the absence of existing semantic relationships. In our first experiment, participants were faster to respond when the previously associated distractor was present on target-present trials. Thus, statistically learned associations among objects appeared to bias attention, particularly when these associations predicted the location and presence of the target. In our second experiment, participants were slower to respond when the previously associated distractor was present on both target-present and target-absent trials. Thus, statistically learned associations among objects appeared to bias attention, even when these associations no longer predicted the location or presence of the target. Together, these findings provide clear evidence that statistically learned associations among objects can bias attention, analogous to the effects of semantic relationships on attention.

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Open practices statement The materials, analyses, and data from all of our experiments are available on the Open Science Framework (https://osf.io/g5f7t/). None of our experiments were preregistered.

Authors' contributions Andrew Clement: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Writing—Original Draft

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Code availability No code from any our experiments will be made available.

Declarations

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Consent to participate Written informed consent was obtained from all participants.

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