Intrusive Effects of Semantic Information on Visual Selective Attention

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Abstract

Every object contains semantic information in extension to its low-level properties. It is well documented that such information biases attention when it is necessary for an ongoing task. However, whether semantic relationships influence attentional selection when they are irrelevant to the ongoing task remains an open question. The ubiquitous nature of semantic information suggests that it could bias attention even when these properties are irrelevant. In the present study, three objects appeared on screen, two of which were semantically related. After a varying time interval, a target or distractor appeared on top of each object. The objects' semantic relationships never predicted target location. Despite this, a semantic bias on attentional allocation was observed with an initial, transient bias to semantically related objects. Further experiments demonstrated that this effect was contingent on the objects being attended: if an object never contained the target, it no longer exerted a semantic influence. In a final set of experiments, we demonstrate that semantic bias is robust and appears even in the presence of more predictive cues (spatial probability). The results suggest that as long as an object is attended, its semantic properties bias attention, even if it is irrelevant to an ongoing task and there are more predictive factors available.

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Introduction

Our environment contains more visual information than we can process in a given moment due to capacity limitations within the retina and cerebral cortex. The visual system has evolved to deal with this limitation by selecting, or attending to, a subset of available stimulation considered to be important (Castelhano, Mack, & Henderson, 2009; Yarbus, 1967). Selective attention devotes limited processing capacity to task-relevant or salient information, facilitating the viewer's current goals. A fundamental objective in the study of human behavior, therefore, is to understand the properties that constrain attentional selection.

Decades of research has demonstrated that the attentional system takes advantage of a range of properties within the environment for the purposes of selection. For instance, low-level, physical factors such as spatial location can bias attention (Posner, Snyder, & Davidson, 1980), as can object boundaries (Egly, Driver, & Rafal, 1994; Malcolm & Shomstein, 2015; Pajak & Nuthmann, 2013; Shomstein & Behrmann, 2008) and features (Treisman & Gelade, 1980; Wolfe, 1994). In addition, high-level properties in our surroundings, such as meaning, can also bias attentional selection. For example, a scene's gist biases attention when looking for a target (Eckstein, Drescher, & Shimozaki, 2006; Malcolm & Henderson, 2010; Neider & Zelinsky, 2006; Spotorno, Malcolm, & Tatler, 2014; 2015; but see Castelhano & Heaven, 2011), even with very short presentation durations (Castelhano & Henderson, 2007; Hillstrom, Scholey, Liversedge, & Benson, 2012; Võ & Henderson, 2010). Similarly, an object's high-level meaning can bias attentional allocation to semantically related distractors. For instance, you are more likely to fixate a ceramic mug when looking for a coffee machine than if you had been looking for a notebook (Belke, Humphreys, Watson, Meyer, & Telling, 2008; de Groot, Huettig, &

Olivers, 2016; Hwang, Wang, & Pomplun, 2011; Mack & Eckstein, 2011; Moores, Laiti, & Chelazzi, 2003).

An important aspect of the previous studies showing object semantics influencing attentional allocation is that these experiments tended to use real-world objects as search targets and distractors. As such, the high-level meaning of the target is always task-relevant, making semantics central to the successful completion of the task. There is also direct evidence that task-relevant objects readily elicit context-specific activation (Auckland, Cave, & Donnelly, 2007; Bar & Aminoff, 2003; Bar, Aminoff, & Schacter, 2008; Çukur, Nishimoto, Huth, & Gallant, 2013; Davenport & Potter, 2004), and influence early stages of vision such as parallel processing (Belke et al., 2008) and figure-ground separation (Cacciamani, Mojica, Sanguinetti, & Peterson, 2014). Such observations, pointing to regular extraction and fast influence of high-level properties on vision, raises the question whether object semantic properties influence attention even when it is irrelevant to an ongoing task. Importantly, whether semantic information influences attentional allocation independent of its relevance to an ongoing task has not been investigated and thus remains an open question. Would merely attending to a real-world object – when its meaning is irrelevant – similarly activate semantic knowledge and bias attention to a semantically related object in the scene?

Here, we hypothesize that semantic relationships among objects serve to constrain attentional selection independent of task relevance. To foreshadow, Experiments 1-5 show that semantic properties of viewed objects bias attention even when they are task-irrelevant. We also hypothesized that if task-irrelevant semantic biasing is robust, it must do so regardless of other predictive information that may be present in the scene (Experiments 6-8). To test semantic influence on attentional allocation, participants were presented with displays consisting of three real-world objects: one central and, after a variable delay, two peripheral objects. Critically, one of the two peripheral objects was semantically related (SR) to the central object while the other was non-related (NR). A target and two distractors were then presented, superimposed on the objects. Importantly, the target occurred equally on the SR and NR objects, making their respective semantic relationships irrelevant to predicting target location. If semantic information biases attentional allocation, independent of task-relevance, then the time to locate the target should be affected by the objects' semantic relation to the central object. In order to test the second prediction that semantic information biases attentional allocation even when alternative predictive factors are available, we introduced an independent spatial probability bias (Experiment 6-8).

Since task-irrelevant semantic biasing of attentional allocation has not been extensively studied, our aim was threefold: i) demonstrate that non-predictive semantic information influences attentional allocation and that it does so robustly; ii) map out the temporal profile of semantic influence by varying the time that objects were visible on the screen prior to target onset; and iii) probe whether semantic influence is robust and automatic.

Experiment 1

The aim of the first experiment is to demonstrate that task-irrelevant semantic relationships shared between two objects biases attentional selection. A central object appears on the screen and remains there for 1.5 seconds after which two objects (one semantically related to the central object) appear, arranged equidistantly from the central reference object. Targets appeared on the central object on 50% of the trials, with the remaining targets distributed equally between the two remaining objects. The logic is as follows: once the central object is presented it is attentionally selected and prioritized given that half of the targets will appear in that spatial location. Following selection of the central object, if semantics guides attentional selection, targets that appear on the object that is semantically related to the central object should be processed faster and accurately.

Additionally, the temporal profile of semantic influence was examined by focusing on two time intervals. The intervals were chosen by following results observed by de Groot and colleagues (2016). The authors demonstrated that when semantics is relevant to the task, its influence on attention was observed around 300-400ms mark. Given that in the de Groot et al. (2016) study semantics was relevant to the task, and in our experiment semantics is irrelevant, we expected that a semantic contribution would be delayed. Therefore, two intervals probed in this experiment were restricted to 750 and 1250ms.

Methods

Participants. Twenty-three participants took part in Experiment 1 (13 female, mean age 20.0). All were from The George Washington University, gave informed consent, and were naïve to the purpose of the experiment. Experimental procedures were approved by the GWU Institutional Review Board.

Stimuli and Design. Forty upright objects (Google Images or in-house photos) were selected and scaled to 2.7˚in height, with widths varying between 0.4-2.1˚(Figure 1). Objects were partially desaturated in Photoshop (Photoshop CS, Adobe, California) in order to reduce potential low-level attentional biasing and to make the red target and distractors more visible. Objects were arranged in triads: one centrally located object with a fixation cross at the bottom of it and two peripheral objects centered 1.8˚to either side of the fixation cross. Objects were organized into ten groups, defined by a peripheral object pair (e.g., a make-up brush and pepper grinder) occurring equally on either side of the screen, and two central objects (e.g., the lipstick and saltshaker), only one of which appeared in a given trial. The central object was semantically related to one of the two peripheral objects (e.g., the lipstick was related to the make-up brush, and the saltshaker to the pepper-grinder, see Figure 1, top-left).

A target (a red T or L) and two distractors (red T/L hybrids) appeared on every trial on top of the objects in any cardinal orientation. All target/distractor items were equidistant from the fixation cross. Targets appeared 50% of the time on the central object and 25% of the time on either peripheral object.

Procedure.

The experimental paradigm was controlled by E-Prime (Sharpsburg, PA). A central object was presented in isolation for 1500ms, followed by an onset of peripheral object pair. The three objects then remained on the screen either for 750 or 1250ms, after which time target/distractors items were presented. Participants were instructed to keep their eyes fixated on the central fixation cross and perform a T/L discrimination task (Figure 2). Trials were separated by a 500ms inter-trial interval, during which, if responses were incorrect, the word "incorrect" was flashed in the center.

Participants were given 15 practice trials, followed by 4 blocks of 160 trials. In each block, stimuli appeared in random order and object exposure timings were selected randomly from the pair with a reset after two trials. At the end of each block participants were informed of their current accuracy and mean response times (RTs). The experiment lasted approximately 45-

50 minutes.

Results and Discussion

Participants' median RTs and accuracies were collected. Two participants were removed for having overall median RTs exceeding 2.5 standard deviations of grand mean. See Table 1 for RTs.

Probability Manipulation Check. Targets occurred on the central object on 50% of trials, making it behaviorally relevant. In order to verify that participants were prioritizing attention to the central object at each exposure duration, median RTs and accuracy were analyzed in a 2x2 repeated measures ANOVA with target location (central object and the average of SR and NR peripheral objects) and exposure duration (750 and 1250ms) as factors.

There was a main effect of target location on RT ($F(1, 20)=74.15$, $p<.001$, $\eta_p^2=.788$) with faster responses for targets on the central than the peripheral objects (739 and 874ms, respectively). There was also a main effect of exposure duration ($F(1, 20)=5.94$, $p=.024$, $\eta_p^2=.229$) with shorter times in the 1250ms condition (816 and 796ms, for 750 and 1250ms object exposure, respectively), but no interaction between factors ($F<1$). Accuracy similarly showed a main effect of target location ($F(1, 20)=10.53$, $p=.004$, $\eta_p^2=.345$) with more accurate responses for identifying targets appearing on the central object (96.2% and 93.7%). There was no main effect of exposure duration on accuracy ($F(1,20)=1.69$, $p=.209$, $\eta_p^2=.078$; 95.2% and 94.7%, respectively), nor an interaction between target location and exposure duration ($F<1$). The combined results indicate that the intended central object probability bias was effective across both exposure durations.

Semantic Bias. The probability analysis above suggests that attention is initially biased to the central object, and then to the peripheral objects. If the semantic relationship between the central object and the peripheral objects biases attention, then we should find a difference between the SR and NR RTs.

A two-way, repeated measures ANOVA was run with semantic relation (SR and NR) and the two exposure durations (750 and 1250ms) as within-subject factors. There was a main effect of semantic relation on RT ($F(1, 20)=5.26$, $p=.033$, $\eta_p^2=.208$) with targets responded to faster on SR objects (865ms) than NR objects (882ms), and a strong trend for a main effect of exposure duration, with participants finding the target faster after 1250ms ($F(1, 20)=4.14$, $p=.055$, $\eta_p^2=.171$; 886 and 862ms for 750 and 1250ms, respectively), but no interaction between the two ($F(1,20)=2.31$, $p=.144$, $\eta_p^2=.103$). Accuracy did not show any main effect of semantic relation ($F<1$) or exposure duration ($F(1, 20)=1.52$, $p=.232$, $\eta_p^2=.071$), nor any interaction ($F<1$).

As predicted, there was an attentional bias toward the SR object despite the fact that the semantic relationship between the peripheral objects and the central object was not predictive of target location (Figure 3). The results thus suggest that semantic information is incorporated into the attentional allocation processes even when it is irrelevant to the ongoing task, and biases attention to semantically related items.

While this experiment definitively demonstrates semantic biasing of attention at 750 and 1250ms following presentation of semantically related and non-related objects, it leaves open the question of whether semantic bias occurs prior to 750ms and whether it persists following the 1250ms. Indeed, when semantic information is task-relevant, as in de Groot et al. (2016), semantically related distractors are first fixated around the 300-400ms mark, suggesting that there may be an earlier semantic bias not probed in Experiment 1. Additionally, we cannot determine if the found SR bias is transient or fixed: that is, are participants attending to the SR object for a finite epoch, or do they linger on the SR object until target onset.

Experiment 2

In order to test both earlier and later time points of the semantic bias, in Experiment 2 we probed two new exposure durations: 500ms and 2000ms. This manipulation will examine whether the semantic effect found at 750ms and 1250ms is stable or transient. If the semantic effect is stable, we should still see a bias to the SR object at 2000ms; if the effect is transient, the effect should disappear or inverse.

Methods

Participants. Thirty-two participants took part in Experiment 2 (26 female, mean age 19.8). All were from The George Washington University, gave informed consent, and were naïve to the purpose of the experiment. Experimental procedures were approved by the GWU Institutional Review Board.

Stimuli, Design and Procedure. The stimuli and design were the same as in Experiment 1, with the only exception being that the exposure durations were now 500 and 2000ms.

Results and Discussion

Median RTs and accuracies were collected. One participant was removed for having overall median RT 2.5 standard deviations longer than the grand mean, and one was removed for having an overall accuracy below 80%. See Table 1 for RTs.

Probability Manipulation Check. There was a main effect of target location on RT (F(1, 29)=82.12, p<.001, η_p^2=.739; with faster responses on the central object than the peripheral objects (726 and 846ms, respectively). However, there was no main effect of exposure duration and no interaction between the factors (Fs<1). Accuracy similarly showed a main effect for target location (F(1, 29)=14.59, p=0.001, η_p^2=.335) with more accurate responses for identifying targets appearing on the central object (95.6% and 93.2%), but there was no main effect of exposure duration, nor an interaction (Fs<1). Just as in Experiment 1, the results indicate that the intended central object probability bias was effective, with faster and more accurate responses to targets on the central object as compared to peripheral objects.

Semantic Bias. A two-way, repeated measures ANOVA was run with semantic relation (SR and NR) and the two exposure durations (500 and 2000ms) as within-subject factors. There was no main effect of semantic relation on RT (F(1, 29)=1.91, p=.177, η_p^2=.062), and no effect of exposure duration (F<1). However, there was an interaction (F(1,20)=4.65, p=.040, η_p^2=.138). Follow-up paired t-tests showed no semantic bias towards the SR object at 500ms (t<1; SR=840 and NR=848ms), but a significant difference towards the NR object at 2000ms (t(29)=2.28, p=.030; SR=861 and NR=835ms). Accuracy showed no main effect of semantic relationship or exposure duration (Fs<1), but a marginal trend for an interaction (F(1,29)=3.53, p=.070, η_p^2=.108) driven by higher accuracy for the SR object at 500ms and the NR object at 2000ms, though neither of these were significantly different..

In summary, we did not find a bias toward the SR object at 500ms which suggests that while task-irrelevant semantic information can bias attention (see Experiment 1), it needs a longer interval of time than if the information were relevant to the task (cf. de Groot et al., 2016). Interestingly, we found that at a later time point (2000ms) there was in fact a bias to the NR object, suggesting that the initial bias to the SR object was transient. In combination with

Experiment 1, the results thus suggest that there is a slow acting utilization of semantic information to bias attention toward SR objects which disappears and even inverses at later epochs.

Experiment 3

While Experiment 2 demonstrated that semantic bias is not present at 500ms and only emerges at 750ms (Experiment 1), it could have a cyclical nature. In other words, semantic bias could emerge early, and then cycle through epochs of influence. In this experiment two additional object exposure duration were used, one probing semantic influence at 250ms (the earliest object exposure) and 1500ms.

Methods

Participants. Twenty-two participants took part in Experiment 3 (13 female, mean age 19.2). All were from The George Washington University, gave informed consent, and were naïve to the purpose of the experiment. Experimental procedures were approved by the GWU Institutional Review Board.

Stimuli, Design and Procedure. The stimuli and design were the same as in Experiments 1 and 2, with the only exception being that the exposure durations were now 250 and 1500ms.

Results and Discussion

Median RTs and accuracies were collected. One participant was removed for having overall median RT 2.5 standard deviations longer than the grand mean, and one was removed for having an overall accuracy below 80%. See Table 1 for RTs.

Probability Manipulation Check. There was a main effect of target location on RT (*F*(1, 19)=49.00, *p*<.001, η_p^2=.721; with faster responses on the central object than the peripheral objects (722 and 836ms, respectively). However, there was no main effect of exposure duration and no interaction (*F*s<1). There was a main effect of target location on accuracy (*F*(1, 19)=6.63, *p*=.019, η_p^2=.259) with more accurate responses for identifying targets appearing on the central object (95.6% and 94.4%), but there was no main effect of exposure duration (*F*<1). There was, however, an interaction between target location and exposure duration on accuracy (*F*(1,19)=6.87, *p*=.017, η_p^2=0.265). Paired t-test showed that this was due to responses to targets on the central object being significantly more accurate than responses to the peripheral object at 250ms (*t*(19)=3.26, *p*=.004; 95.8% and 93.9%), and responses being non-significantly higher for the central object at 1500ms (*t*(19)=1.03, p=.315; 95.4% and 94.9%). The results show, as in Experiments 1 and 2, that the central object probability bias was effective.

Semantic Bias. A two-way, repeated measures ANOVA was run with semantic relation (SR and NR) and the two exposure durations (250 and 1500ms) as within-subject factors. There were no main effects of semantic relation or exposure duration on RT (*F*s <1). However, there was an interaction (*F*(1,19)=4.44, *p*=.049, η_p^2=.189). Follow-up paired t-tests showed non-significant bias towards the SR object at 250ms (*t*<1; 835 and 842ms), but a significant bias towards the NR object at 1500ms (*t*(19)=2.10, *p*=.049; 839 and 826ms, respectively). Accuracy showed no main effect of semantic relationship (*F*(1,19)=1.28, *p*=.273, η_p^2=.063; 93.9% and 94.9%, respectively) nor exposure duration (*F*(1,19)=1.60, *p*=.222, η_p^2=.077; 94.0% and 94.7%, respectively), and no interaction (*F*<1).

Taken together, Experiments 1-3 suggest that task-irrelevant semantic information has a relatively slow acting effect on attention, not onsetting until ~750ms (see Figure 3b for summary). Importantly, this contribution is much later compared to studies that render semantic relationships task-relevant. Here, the objects themselves did little more than act as place holders for the target/distracter items. Nonetheless, semantic relationships between the objects influenced attentional allocation. This suggests that there is a steady accrual of semantic information, even when it is irrelevant to the task, which then biases attention.

In addition, the initial semantic bias appears to be transient (Figure 3a, and summary in Figure 3b), and that later in the time course SR objects are inhibited (i.e., slower RTs to targets that appear on the semantically related object). This biasing toward SR followed by a bias away from that same location at later epochs, strongly resembles the microgenesis of spatial allocation of attention. Namely, summoning attention to a spatial location with a peripheral cue speeds up processing at the cued location at short intervals following the cue (i.e., 300ms or less), while slowing processing at the cued location following longer intervals. The slowing at the cued location is reminiscent of inhibition of return (IOR: Klein, 2000; Posner & Cohen, 1984; Tipper, Jordan, & Weaver, 1999), characterized by attention being repelled away from the cued location (marked by attention as having been visited) in favor of other locations. Our results are consistent with this pattern, suggesting that semantic properties of an object serve to constrain spatial allocation of attention (i.e., at shorter object exposures spatial locations bounded by a semantically related object enjoy an attentional benefit, while at longer object exposures those same spatial locations exhibit an inhibition similar to IOR).

<u>**Experiment 4**</u>

Experiments 1-3 demonstrate that semantic bias emerges around 750ms and then persists either in the form of biasing attention to the semantically related object (750 and 1250ms), or towards the semantically non-related objects at late object exposure durations (1500 and 2000ms). In this Experiment the aim was to guard against two alternative interpretations that can be put forth in explaining the observed pattern of results. First, the observed semantic biases could have been a by-product of the particular duration pairings. Notably the gap between durations in each group varied (i.e., 1250-750=500ms, 1500-250=1250ms; 2000-500=1500ms). While this should not affect attentional biasing at the first time point in each pair (250, 500 and 750ms), it may have had an effect on the later pairings (1250, 1500 and 2000ms). As a control, in the next two experiments the object exposure time before onsets of target/distractors was decoupled. In Experiment 4, object exposure duration (750 and 1500ms) was split between subjects. If the initial SR bias is robust, it should be replicated. If the later NR bias is robust, it should be replicated.

A second alternative possibility is that because targets were more likely to appear on the central object (50%), this probability bias somehow tipped the scale toward the semantically related object. In order to control for this, in Experiment 4 the target occurred on all three objects equally reducing the relevance of the central object and, by extension, the SR object. Additionally, participants completed a post-test questionnaire where they indicated if there were any factors they believed predicted target location.

This Experiment, therefore, serves three purposes: (i) it provides an internal replication of the observed findings; (ii) decouples possible contributing effects of object exposure pairings, and (iii) removes potential biases associated with unequal probability of target presentations.

Methods

Participants. Participants were assigned into one of two groups with a 750ms (31 participants, 19 female, mean age 20.0) or 1500ms (32 participants, 22 female, mean age 19.1) exposure duration. All were from The George Washington University, gave informed consent, and were naïve to the purpose of the experiment. Experimental procedures were approved by the GWU Institutional Review Board.

Stimuli and Design. The stimuli and design were the same as in Experiment 1-3, with the following exceptions. Targets were equally likely to appear on any of the three objects. Exposure durations were either 750 or 1500ms, varied between participants.

Procedure: The experimental paradigm was the same as Experiment 1, except participants were given 15 practice trials, followed by 8 blocks of 80 trials. RT and accuracy feedback was given at the end of each block. The experiment lasted approximately 45-50 minutes.

Results and Discussion

In each experiment, one participant was removed for poor accuracy and one for having an overall median RT over 2.5 standard deviations from the grand mean (four removed, cumulatively). Response times are shown in Table 1. Unlike Experiments 1-3, there was no probability manipulation, thus a 3 x 2 mixed-design ANOVA was conducted with target location as the within factors subject (central, SR and NR) and exposure duration as the between-subject factor (750 and 1500ms). There was a main effect of target location ($F(2, 114)=6.64$, $p=.002$, $\eta_p^2=.104$) with faster responses on the central object and slowest on the NR object (736, 758 and 764ms for central, SR and NR, respectively), but no effect of exposure duration ($F(1, 57)=1.11$, *p*=.296, η_p^2=.019), and no interaction (*F*(2, 114)=1.21, *p*=.302, η_p^2=.021). Paired t-tests showed that the central object still led to faster RTs than either the SR or NR objects (*t*s>2.26, *p*s<.028). Critically, RTs on SR objects were significantly faster than on NR objects (*t*(58)=2.52, *p*=.015). Accuracy analysis yielded no main effect of target location (*F*(2,114)=1.67, *p*=.193, η_p^2=.028), and no main effect for exposure duration, nor an interaction (*F*s<1).

The results corroborate Experiment 1 with a significant bias toward the semantically related object. Thus, semantic bias observed in Experiment 1, at 750msec, was indeed replicated. Interestingly, however, the 1500ms bias toward semantically non-related object was not replicated. This suggests that the previous NR bias is either a weak effect or could have resulted from a particular pairing of object exposure.

Questionnaire. The post-experiment questionnaire asked participants, in order: 1) Did you notice anything about the relationship between objects? If so, what do you think it was? 2) Did you notice anything about the frequency of where the target appeared? If so, what do you think it was? 3) If you were told that there was an imbalance in where the target appeared, what do you think it would be? Questions 1 and 2 were designed to motivate the participants to think about the objects they just saw. The final question was the one we used to gauge how many participants falsely assumed that targets appeared more often on semantically related objects.

Only one participant in each experiment wrongly assumed that semantic information predicted target location, and both guessed that the target occurred more often on the NR object (which did not bear out in their results). The fact that participants did not guess that semantic relationship predicted target location strongly suggests that semantic relationships were treated as task-irrelevant.

To summarize, we replicated Experiment 1's results with an attentional benefit for the semantically related object following 750ms object exposure duration. Given the central object was less relevant in Experiment 4 (target 33% of the time) than Experiment 1 (target 50% of the time), the reduced difference between the central and SR and NR objects is to be expected. In addition to providing internal replication of the main finding, Experiment 4 eliminated two alternative interpretations: i) that the semantic bias observed in the original experiment was simply due to the 50% probability bias on the central object, and ii) participants were intentionally using semantic information to bias attentional allocation. The results support the hypothesis that objects' semantic information bias spatial allocation of attention, even when it is not predictive. Interestingly, the NR bias was not replicated, perhaps suggesting that either the findings is weak in nature of the effect, or a result of the exposure duration pairs. As this effect was not germane to the current investigation, we did not conduct any further follow-up studies.

Experiment 5

The results of Experiments 1-4 suggest that there is an initial, transient bias to a semantically related object, even when semantic information is not predictive. However, we continued to find shorter RTs to the central object even when it did not have a probability bias. This suggests that participants are still attending to the central object first, and that the semantic properties of this object then influence attentional allocation. This raises the question as to whether an object needs to be attended for it to semantically influence attention. In Experiment 5, targets never occurred on the central object and occurred on the SR and NR objects 50% of the time, each. The central object was therefore always visible, but would draw minimal attention since the target would never occur there. If a visible object semantically biases attention even when minimally attended, we should still find a semantic bias. Conversely, if an object needs to be attended to exert an semantic-based attentional bias, then we should fail to see a semantic bias when the central object never contains the target.

Participants. Thirty-two participants took part (24 female, mean age 19.0) exposure duration. One participant was removed for having accuracy below 80%, and one for having an overall median RT that was 2.5 standard deviations greater than the grand mean. All were from The George Washington University, gave informed consent, and were naïve to the purpose of the experiment. Experimental procedures were approved by the GWU Institutional Review Board.

Stimuli and Design and Procedure. The stimuli and design were the same as in Experiment 1-4, with the following exceptions. Targets never appeared on the central object, and appeared equally often (50%) on either the semantically related or non-related object. The only exposure duration was 750ms.

Results and Discussion

Two participants were removed, one for poor accuracy and one for having an overall median RT over 2.5 standard deviations from the grand mean. This left 30 participants' data to analyze. A paired t-test with semantic relation (SR and NR) as the factor found no difference in median RTs ($t<1$), nor for accuracy ($t(29)=1.43$, $p=.164$). This result suggests that in order for the object's semantics to influence attentional allocation, that object (here, the central object) has to be attentionally selected first. The mere presence of an object is insufficient to produce semantic bias on attentional allocation.

Taken together, Experiments 1-5 demonstrated that task-irrelevant semantic information biases attentional allocation. This is a relatively slow acting, transient process, and requires that an object is spatially attended.

Experiment 6, 7, and 8

The next set of experiments examines the robustness of the semantic biasing effect. In all of the previous experiments, the semantic relationship did not predict the target location nor did any other factor (apart from the central object probability bias in the first four experiments). The resulting semantic bias could therefore have been a result of the visual system 'defaulting' to using semantic information as a guiding factor in the absence of other predictive factors. In real-world situations, there will inevitably be some factor that can be relied upon to help find a target (e.g., if looking for the how much an item in a supermarket is, we would be primed to look at the shelf underneath for the price tag). If semantic biasing robustly influences attentional allocation, then it should persist even when a predictive factor is present.

Previous research has shown that semantic biasing of attention can co-exist with other factors. de Groot et al. (2016) found in their search task that visual and semantic factors independently bias attention. Similarly, Belke et al. (2008) found that perceptual load did not affect semantic biasing of attention, and that while cognitive load did affect semantically related objects, it did so only after an object had been selected. In neither case did these factors predict target location. Experiments 6-8 probed the robustness of the semantic bias by including a predictive factor: a spatial probability bias. Instead of targets being equally distributed among SR and NR objects, targets were now more likely (37.5%) to appear on one side of the screen than the other (12.5%) (e.g., left object would receive more targets than the right independent of whether it was or was not semantically related). Given this design, the high probability location would half of the time coincide with the SR object and half of the time with the NR object, again making semantic relatedness completely task-irrelevant. The peripheral side of the screen with the increased spatial probability was counterbalanced across participants. If semantic properties influence attentional allocation independently of other predictive factors, then we will continue to see an SR attentional bias. Conversely, if a strongly predictive factor (spatial probability) makes semantic information no longer necessary, then it will stop influencing attentional allocation. Participants were assigned to 750-1250ms, 500-2000ms, or 250-1500ms exposure duration groups, allowing for a direct comparison with results obtained from Experiment 1-3.

Methods

Participants. Twenty-eight participants took part (24 female, mean age 19.9) in Experiment 6; thirty participants (22 female, mean age 19.4) in Experiment 7; and 26 participants (20 female, mean age 19.5) in Experiment 8. All were from The George Washington University, gave informed consent, and were naïve to the purpose of the experiment. Experimental procedures were approved by the GWU Institutional Review Board.

Stimuli and Design. Experiment 6 mirrored design of Experiment 1 with targets appearing 750 or 1250ms after peripheral object onset, while Experiment 7 had targets appearing 500 or 2000ms after exposure durations mirroring Experiment 2, and Experiment 8 had exposure durations of 250 or 1500ms, mirroring Experiment 3. Importantly, in all three experiments, targets appeared on the central object 50% of the time, and on the high- and low-probability sides of the screen 37.5% and 12.5% of the time, respectively. The high-probability side of the screen was counterbalanced across participants.

Procedure. In all three experiments, the experiment began with 15 practice trials, followed by 8 blocks of 80 trials. RT and accuracy feedback was given at the end of each block. Exposure durations were randomized. The experiment lasted approximately 45-50 minutes.

Experiment 6 results: The data were analyzed similarly to Experiments 1-5, except now the first block of experimental trials were removed ensuring that we only analyzed trials after the spatial probability bias was learnt. Two participants were removed for having accuracy less than 80%. Response times are shown in Table 1.

We concentrated our analyses on the peripheral objects. A within-subjects 2 x 2 x 2 ANOVA was conducted, with semantic relationship (SR and NR), target location (peripheral high probability and peripheral low probability), and exposure duration (750 and 1250ms) as the factors. There was a main effect target location with faster responses on the peripheral high probability object ($F(1,25)=19.61$, $p<.001$, $\eta_p^2=.440$; peripheral high probability =799, peripheral low probability =875ms) and an interaction between semantic relationship and exposure duration ($F(1,25)=6.25$, $p=.019$, $\eta_p^2=.200$). The interaction was driven by an absence of a difference between SR and NR RTs at 750ms ($t<1$), and the presence of a significant bias towards the SR object at 1250ms ($t(25)=3.12$, $p=.005$; 825 and 845ms, for SR and NR, respectively). None of the other effects were significant (Fs<1.78, ps>.195) in RT, and accuracy analysis did not yield any significant main effects or interactions (Fs<1.40, ps>.248).

Experiment 7 results: The data were analyzed similarly to Experiment 6. One participant was removed for having an accuracy less than 80% and one for having an overall median RTs over 2.5 standard deviations over the grand mean. Response times are shown in Table 1.

A 2 x 2 x 2 repeated measure ANOVA on median RTs and accuracy was conducted, with semantic relationship (SR and NR), target location (peripheral high probability and peripheral low probability), and exposure duration (500 and 2000ms) as the factors. There was a main effect of target location with shorter RTs on the peripheral high location ($F(1,27)=32.28$, $p<.001$, $\eta_p^2=.544$; 777 and 841ms, respectively), but no other analyses were significant (*F*s<2.89, *p*s>.100). There was a strong trend for a main effect of target location on accuracy ($F(1,27)=3.97$, $p=.056$, , $\eta_p^2=.128$) with higher accuracy on the peripheral high probability condition (SR=94.6%, NR=93.2%), but no other main effect or accuracy was significant interactions for accuracy (*F*s<2.74, *p*s>.110).

Experiment 8 results: The data were analyzed similarly to Experiments 6 and 7. One participant was removed for having an overall median RTs over 2.5 standard deviations over the grand mean. The removal criteria left an extra participant in the right spatially-biased group, so the last participant in this particular manipulation was therefore removed in order to leave an equal number of participants biased to the left and right. There were 24 participants remaining for analysis. Response times are shown in Table 1.

A 2 x 2 x 2, repeated measure ANOVA was run on median RTs and accuracy, with semantic relationship (SR and NR), target location (peripheral high probability and peripheral low probability), and exposure duration (250 and 1500ms) as the factors. There was a main effect of target location, with shorter RTs on the peripheral high probability location

(F(1,23)=45.26, p<.001, η_p^2=.663; 785 and 856ms, respectively), and a very weak trend for an interaction between semantic relation and exposure duration (F(1,23)=3.08, p=.092, η_p^2=.118). No other analyses were significant (Fs<2.69, ps>.115). When analyzing accuracy, there was a main effect of target location, with higher accuracy on the peripheral high probability location (F(1,23)=13.82, p=.001, η_p^2=.375; 93.9% and 91.0%, respectively), but no other main effect or interaction was significant (Fs<2.31, ps>.143).

Questionnaire. None of the participants in Experiment 6-8 indicated that they believed semantic relationships predicted target location, indicating that high-level information was explicitly treated as task-irrelevant.

Experiments 6-8: Discussion

Experiments 6-8 were designed to test the robustness of the semantic bias when a more predictive factor was available. Despite participants indicating that they did not believe that semantic information was relevant, and the clear effect that the spatial probability bias had, object semantic information continued to bias attention. The results suggest that the visual system continually, in an on-line manner, processes semantic information of attended objects and uses it to bias attention, rather than only ‘defaulting’ to semantic information when no other guiding factor is available.

This finding goes beyond other studies that find continual influence of semantic relationships by demonstrating that this influence is independent of other factors, such as visual similarities (de Groot et al., 2016) or perceptual load (Belke et al., 2008). However, in the current case, the other factor, a spatial probability bias, predicted where the target would occur.

This may explain why, while the previous studies found minimal changes to semantic biasing of attention, we found a delayed onset, not peaking until 1250ms.

In order to verify whether this delayed onset of the semantic bias was statistically significant, we compared Experiment 1 and Experiment 6. Both experiments used exposure durations of 750 and 1250ms, and both showed a semantic bias of attention. However, in Experiment 1 this effect was stronger at 750 while in Experiment 6 this effect was only significant at 1250ms. We ran a 2 x 2 x 2, mixed design ANOVA with Experiment (balanced and spatial bias) as the between-subject factor, and semantic relation (SR and NR) and exposure duration (750 and 1250ms) as the within subjects factors.

There was a main effect of semantic relationship ($F(1,45)=7.46$, p=.009, $\eta_p^2=.142$) with a bias to the SR object (849 and 861ms, respectively) and a trend for faster RTs in the 1250ms condition ($F(1, 45)=3.64$, p=.069, $\eta_p^2=.071$; 862 and 848ms, respectively). Critically, there was a three-way interaction with experiment, semantic relation and exposure duration ($F(1, 45)=7.88$, $p=.007$, $\eta_p^2=.149$). Paired t-tests showed that there was a semantic bias toward the SR object at 750ms in the balanced experiment ($t(20)=4.32$, p<.001), but not at the 1250ms ($t<1$); conversely, in the spatially biased experiment, there was no effect at 750ms ($t<1$), but a bias toward the SR object at 1250ms ($t(25)=3.12$, $p=.005$). No other main effect or interaction was significant (Fs<1.75, ps>.196). The results therefore suggest that the presence of a predictive cue delays, but does not extinguish, semantic biasing of attention.

Image Analysis: Color and Size

Even though the earliest time point for observing semantic influences was rather late (750ms) to be driven by low-level factors (i.e., color and size), we set out to formally rule out this possibility. To do so, we compared the differences in feature space between the central objects and their respective SR objects with the differences between central objects and their respective NR objects. Individual objects were cut out and converted into LAB color space which breaks down pixel information into a Luminance channel, and Red-Green and Blue-Yellow color channels. Histograms were made for each channel of each object and bin-to-bin comparisons were run, summing the difference between the central object and its respective SR or NR object. The smaller the difference between objects, the greater the similarity in that channel. If the results were due to low-level similarities we should find significantly smaller differences in one or more channels between the Central and SR objects, than the Central and NR objects. Paired t-tests found that none of the three channels had significant differences (ts<1). Object sizes were then determined by a pixel count, and a similar comparison between the central object and the SR and NR objects were again made, with smaller differences suggesting similar sizes. A paired t-test failed to find a significant effect ($t(19)=1.02$, $p=0.322$). The results suggest that the observed semantic bias was not a result of systematic low-level feature similarities.

General Discussion

When viewing real-world environments humans prefer attending to objects over empty backgrounds (Einhäuser, Rutishauser, & Koch, 2008; Hwang et al., 2011; Land, Mennie, & Rusted, 1999; Mack & Eckstein, 2011; Nuthmann & Henderson, 2010; Pajak & Nuthmann, 2013; Yarbus, 1967), making object properties an integral part of attentional biasing. While the effect of low-level object properties on attention, such as boundaries and colors, has been well documented (e.g., Egly et al., 1994; Theeuwes, 1994; Treisman & Gelade, 1980; Wolfe, 1994), the effect of semantic information – a property inherently available in any recognizable object – is less well understood. Previous research has focused on situations when semantic information is relevant to an ongoing task (e.g., store an item in visual working memory, Belke et al., 2008; de Groot, Huettig, & Olivers, 2015; Hwang et al., 2011; Mack & Eckstein, 2011; Moores et al., 2003; Telling, Meyer, & Humphreys, 2010). However, objects' contextual relations are readily processed (Bar & Aminoff, 2003; Bar et al., 2008) and readily available, suggesting that semantic information could continually bias attentional allocation even when it is task-irrelevant.

Over eight experiments we demonstrate that non-predictive semantic information biases attentional allocation. Experiments 1-3 show an initial bias to the SR object, beginning around 750ms after onset. This time is markedly later than de Groot et al (2016) found, but while they made semantic information a critical component to the task (the meaning of the target is what separated it from distractors), here the semantic information was irrelevant, thus pushing the effect to occur later in time. This semantic bias was also found to be transient, and in fact inversed toward the NR object at later time points (1500 and 2000ms). Experiment 4 showed that this effect was not due to a target location bias on the central object, as it still occurred even when targets were split evenly between the three objects. However, Experiment 5 showed that the central object has to at least be attended to: simply seeing the object was not enough to trigger a semantic bias on attention. These results strongly suggest that the visual system is sensitive to the semantic properties of attended objects – even when they do not predict the target location – and bias surrounding attention to semantically similar items. Experiment 6-8 tested whether this semantic bias only constrains attentional allocation in the absence of other, more predictive cues. We found that attention was again biased to the SR object, although the onset of this effect was delayed from 750 to 1250ms, while the late NR bias found at 1500 and 200ms in

Experiments 2 and 3 were not replicated in Experiments 7 and 8. This could either be due to the NR effect being weak or else being delayed like the SR bias and occurring at longer time than we probed for. The delayed bias to the SR object contrasts with other studies showing semantic biasing of attention was independent of other factors (visual similarity, perceptual load, etc.); however in the present case, the other factor was predictive of target location. A potential explanation for the current results might be that in the presence of an apparent attentional strategy (as probability is in this case) the influence of task-irrelevant semantic information is integrated into attentional guidance only if enough time has passed after the objects appear and before targets are presented. Further research will have to be conducted to understand this effect. In summary, results of Experiments 6-8 suggest that semantic information's bias on attention is ongoing and robust.

Results reported here support the hypothesis that semantic biasing is not exclusive to task-relevant situations, but is an ongoing factor that continually affects attentional allocation. The combined results suggest that high-level semantic information complements low-level sensory properties in forming a bi-directional approach to allocating attention. It also opens the question as to the mechanism by which these high-level factors affect attentional distribution. Previous research suggests that object's contextual associations are derived in parahippocampal (PHC) and retrosplenial (RSC) cortices (Bar & Aminoff, 2003; Livne & Bar, 2016). These representations could potentially affect the spatially-organized attentional priority map in inferior parietal sulcus (IPS, Sheremata & Silver, 2015) directly, or indirectly through object recognition processing regions in the inferior temporal cortex (Bar, 2004), before influencing activity in IPS.

Conclusion

The visual representation of the world biases our attention in consistent ways, independent of the viewer's task. For example, the effect of low-level object properties (edges, color, etc.) on the spatial allocation of attention is well-established. However, the current results demonstrate that even higher-level properties such as semantic information affect attentional bias. High-level semantic properties therefore play an integral role in the ongoing attentional biases within the visual system. If we are to develop a predictive and generalizable visual attention model in real-world settings, relative semantic properties of objects will have to be incorporated.

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	Condition	250	500	750	1250	1500	2000
Exps. 1-3	Valid	726	726	747	731	719	725
	sem	26	24	25	25	24	25
	SR	835	840	872	858	839	861
	sem	33	30	31	21	29	36
	NR	842	848	899	866	826	835
	sem	32	29	30	26	28	29
Exp. 4	Valid			722		749	
	sem			22		31	
	SR			733		783	
	sem			25		33	
	NR			740		788	
	sem			26		32	
Exp. 5	Valid						
	sem						
	SR			677			
	sem			17			
	NR			680			
	sem			17			
Exps. 6-8	*Valid*	680	699	703	690	696	706
	sem	21	16	26	27	24	17
	SR, High %	794	774	804	786	788	786
	sem	25	24	26	26	23	22
	NR, High %	775	779	809	797	785	771
	sem	24	22	26	26	23	24
	SR, Low %	852	840	882	864	852	859
	sem	25	29	34	35	32	29
	NR, Low %	843	824	862	893	878	839
	sem	26	29	35	39	31	28

Table 1. Response Times (in milliseconds) and standard error of the mean (sem).

Figure 1. Complete set of stimuli used. There were ten base pairs of peripheral objects, as seen in the ten boxes outlined by the black lines. Peripheral objects were shown on each side of the screen, equally. Each base pair also had two central objects associated with it, one of which appeared during a trial. The central objects were selected to be semantically relevant to one of the two peripheral objects. For example, on the top-left box, the salt shaker was related to the pepper grinder, while the lipstick was related to the make-up brush.

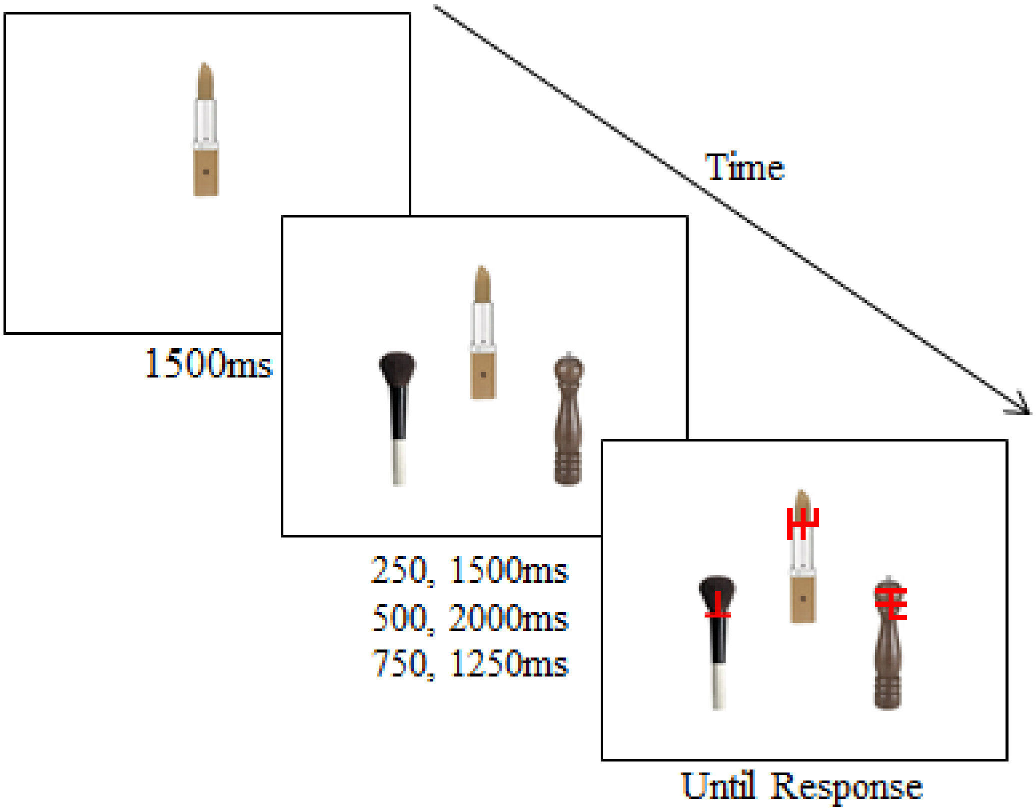

Figure 2. A single trial consisted of a central object appearing on the screen for 1500ms. Participants were asked to fixate the central fixation cross throughout the trial. Two peripheral objects then appeared for either 250 or 1500ms, 500 or 2000ms, or 750 or 1250ms. The target and distractor items then appeared and participants had to respond as quickly and accurately as possible whether the target was a T or an L.

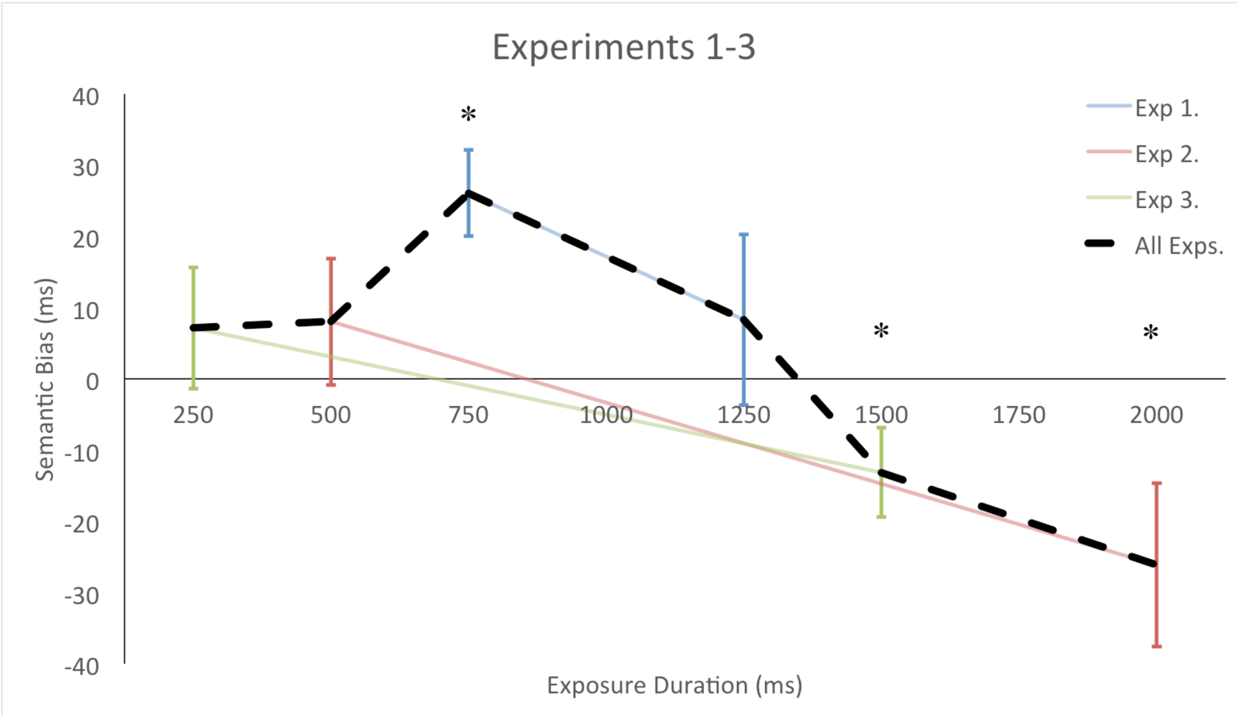

Figure 3. Experiments 1 through 3. Semantic bias (the difference in RTs between the NR-SR condition) over the six exposure durations. Positive numbers represent a bias toward the SR object; negative numbers toward the NR object. Error bars represent one standard error.

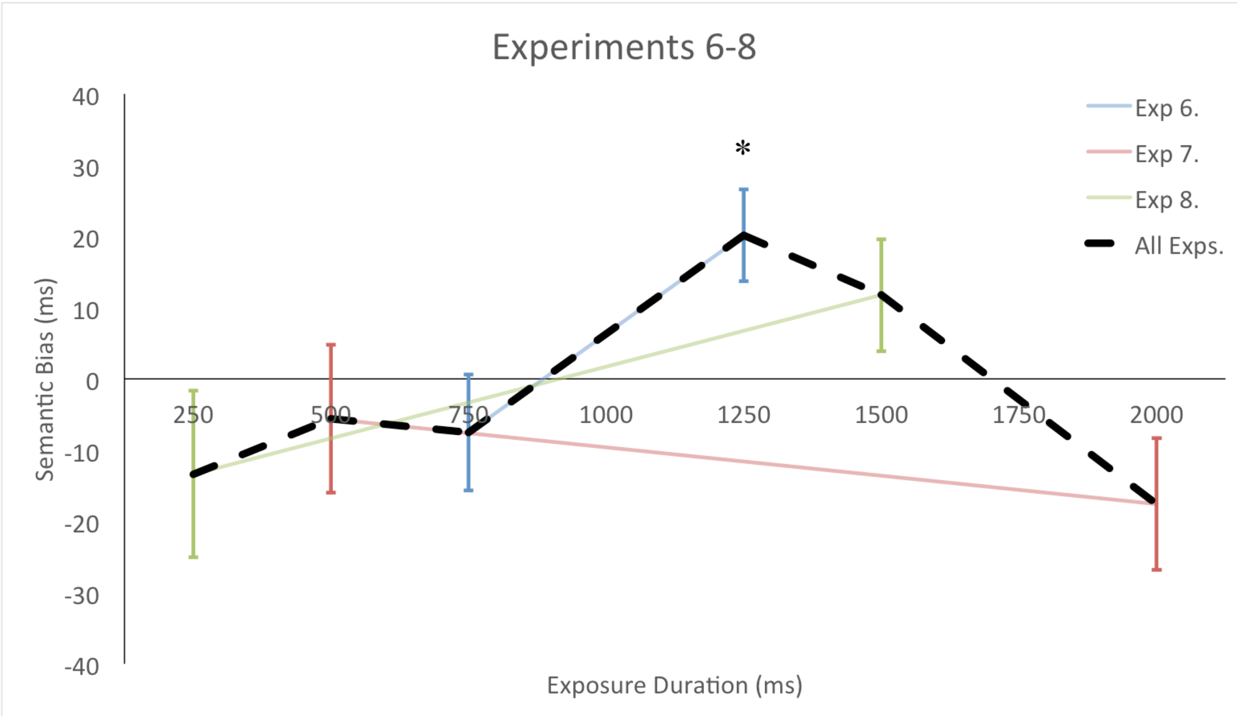

Figure 4. Experiments 6 through 8, which included the spatial probability bias. Semantic bias (the difference in RTs between the NR-SR condition) over the six exposure durations. Positive numbers represent a bias toward the SR object; negative numbers toward the NR object. Error bars represent one standard error.

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