Intrusive Effects of Task-Irrelevant Information on Visual Selective Attention: Semantics and Size

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Abstract: Attentional selection is a mechanism by which incoming sensory information is prioritized for further, detailed and more effective, processing. Given that attended information is privileged by the sensory system, understanding and predicting what information is granted prioritization becomes an important endeavor. It has been argued that salient events as well as information that is related to the current goal of the organism (i.e., task-relevant) receive such priority. Here, we propose that attentional prioritization is not limited to task-relevance, and discuss evidence showing that task-irrelevant, non-salient, high-level properties of unattended objects, namely object meaning and size, influence attentional allocation. Such intrusion of non-salient task-irrelevant high-level information points to the need to re-conceptualize and formally modify current models of attentional guidance.

Keywords: attentional allocation, semantic guidance, object size, spatial attention

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Highlights:

- Semantic knowledge of objects influences attentional allocation despite task-irrelevance
- Knowledge of objects' real-world size, not the actual retinal size, influences attention despite task-irrelevance
- High-level knowledge of objects (semantics and size) influences spatial allocation of attention by modulating early stages of sensory processing.

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Main body: 2421 words
Figures: 2

Factors that influence attentional selection

Our visual system sorts through massive amounts of sensory input, which it samples almost continuously, to construct a coherent representation of a scene. The process of searching through an environment for information is a fundamental function of sensory processing and reflects the perceptual system's remarkable ability to dynamically select behaviorally relevant information. Such perceptual selectivity, referred to as attentional selection, is central to cognition.

Several decades of behavioral, physiological, and neuroimaging research provided strong evidence that the distribution of attention is controlled by both the intentions of the observer as well as by the salience of the physical stimulus. Evidence for salient and task-relevant guidance of attention has been reviewed extensively elsewhere [1-3], as well as in several entries in this very issue. While salience is important for attentional orienting, this review focuses exclusively on guidance of attention by non-salient information.

It has long been known that non-salient low-level, physical factors such as spatial location [e.g., 4], objects [5, 6] or features [7, 8], either in isolation or in combination [9], guide attentional selection. These discoveries have both elucidated our knowledge of the human visual system and constrained models of visual attention [e.g., 10, 11, 12]. While investigating the contribution of non-salient, low-level perceptual properties to attentional guidance is important, higher-level properties, such as meaning of objects (what they are, how large or small, what they are used for, what they are related to, etc.) also constrain attentional selection.

Viewed environments readily elicit high-level, context-specific activation [13, 14] that is available from as little as ~100ms viewing duration [15-18]. Furthermore, semantic information is ubiquitous in our daily lives: every item has high-level meaning extending beyond apparent low-level properties. For example, your smartphone is not just a black rectangle but a device of a particular size (e.g., bigger than a credit card but smaller than a plate) that is used to check email, browse the web, and check weather and news.

Focus on task-relevance

When searching for a target, predictive low- and high-level properties of the scene influence attentional allocation. For example, manipulating a target's spatial [19, 20], feature [21], or reward [22, 23] probability biases attentional selection. Likewise, a target object's semantic information can bias attention to highly probable scene regions [e.g., a stop sign will be located at an intersection, 24, 25-28] or to frequently co-occurring objects that might be near the target [e.g., playing cards and poker chips, 29, 30-33].

While the mechanistic understanding of attentional guidance by task-relevance is important, it should not go unnoticed that most information in our immediate environment is in fact task-irrelevant. Consider a task of walking on the sidewalk with the goal of reaching the end of the block and turning right where you can hop on the metro and head home (**Fig. 1a**). What is task relevant is the path in front of you, the people on the path, possible irregularities of the pavement underneath your feet, maybe a food cart or anything else that is taking space on the sidewalk. However, the task-relevant aspect of the scene is only a small fraction of the visual information that makes up your environment. The road, the parked cars, the buildings, etc., all reflect light that is being collected by the retinae, thus gaining access to perceptual processing. As such, at any given moment in time, there is more task-irrelevant information than task-relevant. Even task-relevant items may consist of task-irrelevant, non-defining properties that bias attentional allocation (Scarince & Hout, 2018). This underscores the need to understand how this minimally researched aspect of the sensory environment impinges on attentional selection.

Here, we review recent findings showing that high-level properties of task-irrelevant objects, specifically knowledge of semantic relatedness between objects as well as knowledge of their real-world size, influence spatial attentional allocation. This approach of elucidating the influence of task-irrelevant information on attentional prioritization is novel. The gap in knowledge could be attributed to several important reasons: (i) many factors contribute to attentional allocation (e.g., spatial locations, objects, features, local contingencies), thus it was important to first elucidate the contribution of these low-level features before moving on to more complex factors; (ii) investigating semantic contribution would necessitate reliance on more complex, more naturalistic scenes, thus certain level of control would have to be abandoned; and (iii) the contribution from task-relevant semantic information is larger in magnitude, so it was important to elucidate the underlying processes of this information first, before moving on to more subtle task-irrelevant situations. However, recent advances made in our understanding of basic attentional mechanisms, at the behavioral and neural levels [3, 34], provide fertile ground for probing various ways in which irrelevant high-level properties of the scene (e.g., semantics, reward) constrain attentional allocation.

Shifting focus to task-irrelevance: semantic relationships

A growing number of studies suggest that semantic/category information is rapidly processed [15, 16, 35-43] in a manner that minimally engages attentional selection [see for a controversy 38, 44, 45, 46]. There are also a number of influential studies demonstrating that when target identity is critical to the task, its semantic properties influence attentional allocation. For instance, a search target (e.g., a chimney) stored in visual working memory (VWM) facilitates the directing of attention toward likely positions in a scene (a roof) with the very first eye movement [24-26, 47]. Similarly, an object stored in VWM (e.g., a motorcycle) increases the likelihood that a viewer will attend to semantically related objects (a motorcycle helmet) [29-32], or that semantically related distractors will capture attention [48-50].

However, as noted above, there is a wealth of task-irrelevant, high-level semantic information available in any given moment which may impinge upon ongoing cognitive processes. For example, Greene et al. [38] demonstrated in a Stroop-style paradigm that entry-level categorization of visible objects and scenes extends beyond, and can even interfere with, a viewer's ongoing task (here, word categorization). Cornelissen et al. [51] extended this finding to gaze behavior, demonstrating that out-of-place objects within scenes (e.g., a toothbrush on a desk) were dwelled upon for longer than control items, despite object meaning having no bearing on the task (here, search for a target letter embedded in the scene). These studies provide converging evidence that semantic information from task-irrelevant objects/scenes is automatically processed, affecting ongoing routines. This then raises the question as to whether task-irrelevant, semantic information not only interferes with an ongoing task, but can also bias it. Malcolm et al. [52], investigated this with a focus on task-irrelevant information biasing the spatial allocation of attention. Participants were shown three objects, with one at the center of a screen (e.g., make-up brush) and one on either side, one of which was semantically related to the center object (e.g., lipstick) while the other was not (e.g., pepper grinder) **(Fig 1b)**. A target (a T or L) and two distractors then appeared on the objects. Despite the semantic relationship between the objects never predicting target location, participants were both more accurate and faster at discriminating the target when it appeared on the semantically-related object than on the non-related object (**Fig 1c)**. This effect was transient, peaking at 750ms SOA, suggesting there was a necessary initial processing time followed by a re-adjustment. This semantic biasing of spatial attention occurred later than studies in which semantic information was relevant to the search task (e.g., de Groot, Huettig [53]), suggesting an expected processing delay of the semantic influence since the information was not relevant to the task. Similar results have since been found during scene viewing, with localized meaning ratings providing a greater predictor of gaze than low-level saliency [54]. These results in combination strongly demonstrate that semantic properties of objects influence visual attention allocation, even when the information is not task-relevant, suggesting that semantic information is processed in an obligatory manner and influences attentional allocation.

Having established that semantic relationships of task-irrelevant objects influences attentional allocation raises the question of how this semantic influence is instantiated neurally. Capitalizing on the behavioral findings of Malcolm et al. [51], we recently pursued a set of neuroimaging studies probing the underlying neural substrate of semantic influence of task-irrelevant object properties [55]. We reasoned that semantic influence of task-irrelevant objects on attentional allocation could proceed along two different neural routes, either through influencing spatial attention (i.e., the spatial location occupied by the object), or by modulating object representations (i.e., enhancing object representation itself). The distinction is an important one as it probes the neural mechanism of semantic facilitation. If semantic relatedness affects spatial attention, then spatial locations occupied by semantically related objects will receive attentional priority. This mechanism would be instantiated by engaging attentional selection network within the frontal and parietal cortices. Alternatively, semantic relatedness might result in perceptual benefit by enhancing fidelity of object representations. This mechanism would be instantiated by more precise neural coding within object selective cortex (i.e., ventral visual stream). More specifically, we hypothesized that task-irrelevant semantic information modulates neural activity in the early visual cortex (EVC) through either the facilitation of object representations in object-selective lateral occipital complex (LOC) or spatial representations of objects in spatially-selective intraparietal sulcus (IPS) (**Fig 1d**). First, we replicated the behavioral finding showing that despite the task-irrelevant nature of the object semantic relationships, with faster target discrimination/matching performance when both objects were semantically related. Second, we showed that semantic relatedness of task-irrelevant objects influenced overall activation within the IPS and in the EVC (but not LOC), with increased activation when an irrelevant semantically-related object appeared. Lastly, using multivoxel pattern analysis (MVPA) trained to decode object identity, we demonstrated that the neural pattern of objects (accuracy to decode object identity) is enhanced when both are semantically-related. We reasoned that this increase in identity classification was driven by an increased attentional benefit shared between semantically related objects. Combined, these results demonstrate that task-irrelevant semantic relationships between objects modulate early visual cortical activity by influencing attentional priority maps in IPS with subsequent increase in the strength of object representations in the early sensory regions (EVC). Thus, attention is guided towards the spatial location in which a semantically, yet task-irrelevant, object is located and the increased attentional benefit results in an overall boost in the overall representation of the object.

Shifting focus to task-irrelevance: inferred size of objects

Size is an intrinsic attribute of all objects in the physical world, and its computation is inherently present given the retinotopic nature of visual processing in the ventral visual system (i.e., size of the retinal image and observer's distance) [56, 57]. The impact of object size on visual perception has been well-demonstrated, from classic mental imagery experiments [58, 59], to recent studies of object representations reporting topographic organization of object size in occipito-temporal cortex [60, 61]. Additionally, the influence of size has been the focus of substantial psychophysical research on motor movement. A well-known psychophysical principle, Fitts' Law, proposes that the size of an object influences motor movements: when the distance between two objects is identical, faster but less precise movements are executed toward a wider as compared to narrower object [62].

As in the prior section, it is important to shift focus from examining the influence of object size on attentional allocation when task relevant, to when object size is not essential for the task. For example, in an influential study, Castiello and Umiltà [63] demonstrated that attentional focus is directly modulated by the size of the object. Participants were asked to detect a presence of a target that was either embedded within a small or a large square. It was observed that when targets were embedded within a large object, response times were longer than when the same target was embedded within a small square, providing evidence that attentional focus is more concentrated when targets are embedded in smaller objects. Thus, the results suggest that the efficiency of attentional processing is an inverse function of the size of attentional focus. Importantly, the square within which targets were embedded was completely task-irrelevant. Most recently, work from our lab extended these findings to show that attentional shifts within and between objects is also modulated by differences in physical size of objects [64].

While the role of real-world physical size in modulating attentional allocation has been investigated, the effect of inferred size on attentional selection is ill-defined. Appearance of object size depends on how close or far it is from you, thus introducing an inconsistency between the actual and the retinal size. For example, imagine you are looking at a car parked in the driveway through your kitchen window, and on the window sill there stands a mason jar. Given how far you are from the window and how far the car is, a mason jar will be perceptually larger (in terms of retinal image) than the car (**Fig. 2a)**. However, you know that mason jars are smaller than cars and thus you are not fooled into thinking that there is a giant mason jar in your house and a tiny car outside of it. But, does this perceptual adjustment of objects by mechanisms of size constancy extend to influencing attentional allocation? And by extension, and more germane to this review, does knowledge about real-world size of task-irrelevant objects influence attentional allocation?

In a recent study, we investigated whether inferred real-world object size, rather than retinal size, influences attentional allocation [65]. Across five experiments, attentional allocation was measured in objects of equal retinal size, but varied in inferred real-world size (e.g., domino, bulldozer). Adopting a cuing paradigm, targets were presented either in the cued or non-cued location of the object (**Fig. 2b)**. Importantly, the participants' task was to identify target letters, rendering objects and their real-world size entirely task-irrelevant.

Following each experiment, participants rated the real-world size of each object. We hypothesized that if inferred real-world size influences attention, selection in retinal size-matched objects should be less efficient in larger objects (following the logic of Castiello and Umiltà and Fitt's law). Furthermore, if this size effect influences attentional allocation, then the magnitude of this effect should increase with greater attentional demand. Predictions were supported by faster identified targets in objects inferred to be small than large (**Fig. 2c)**, with costlier attentional shifting in large than small objects when attentional demand was high. Critically, there was a direct correlation between the rated size of individual objects and response times (and shifting costs) (**Fig. 2d)**. Finally, systematic degradation of size inference proportionally reduced object size effect. It is concluded that, along with retinal size, inferred real-world object size of task-irrelevant objects parametrically modulates attention. These findings have several important implications for models of attentional control; invite sensitivity to object size for future studies that use real world images in psychological research; and most germane for this review, strongly show the influence of task-irrelevant object processing to attentional allocation.

Conclusion

Most previous studies used paradigms in which high-level properties of objects are relevant to the task at hand. If high-level properties of objects were to affect attention *only* when task-relevant, it would mean that, despite the ubiquitous nature of high-level information, it is either: (i) strategically processed and utilized only during task-related situations; or else is (ii) continually processed but then actively suppressed by the visual system unless relevant to an ongoing task. Both scenarios seem unlikely, given that perceived objects readily elicit context-specific activation [13, 14, 38] hinting that the high-level properties of perceived objects are indeed processed even in task-irrelevant situations. Here, we provide a subset of growing evidence indicating that high-level properties of task-irrelevant objects, such as semantic relatedness and size (both physical and inferred), affect perception and attentional guidance. However, given the novelty of focus on the influence of task-irrelevant object properties on attentional allocation, the full extent of this task-irrelevant intrusion remains elusive. Such intrusion of non-salient task-irrelevant high-level information points to the need to re-conceptualize and formally modify current models of attentional guidance.

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Figure 1

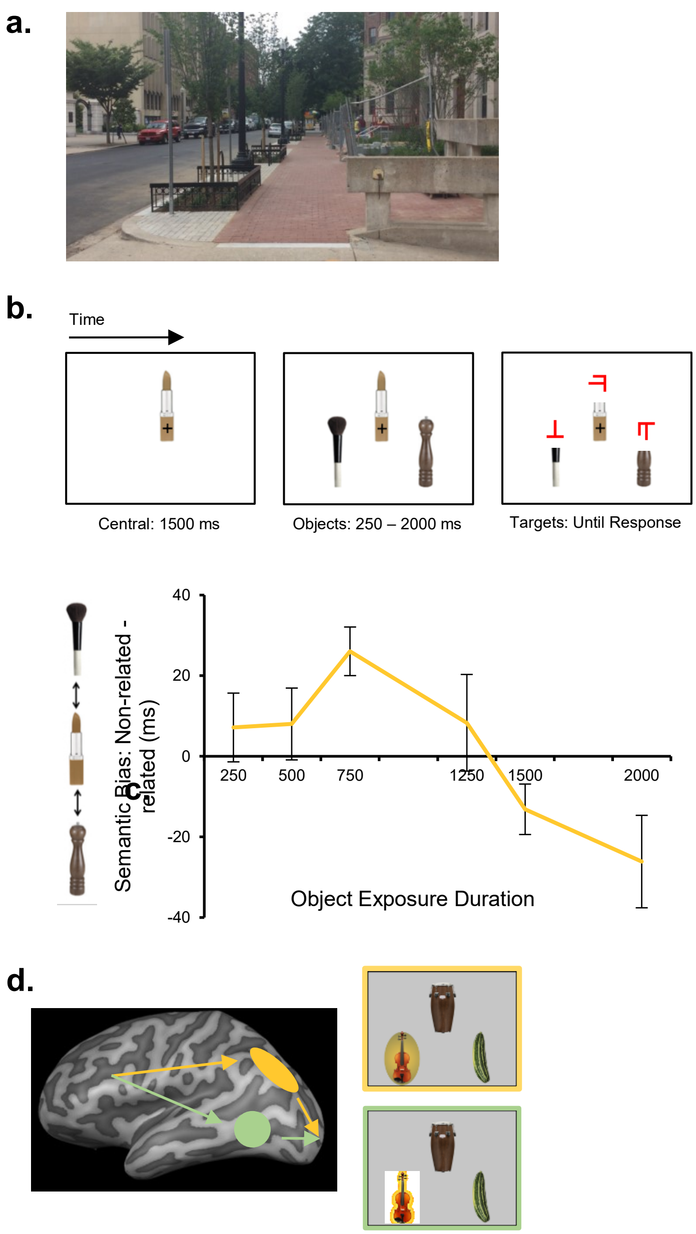
a.
b.
Time
Central: 1500 ms
Objects: 250 – 2000 ms
Targets: Until Response
c.
Semantic Bias: Non-related - related (ms)
40
20
0
-20
-40
250
500
750
1250
1500
2000
Object Exposure Duration
d.

Figure 2

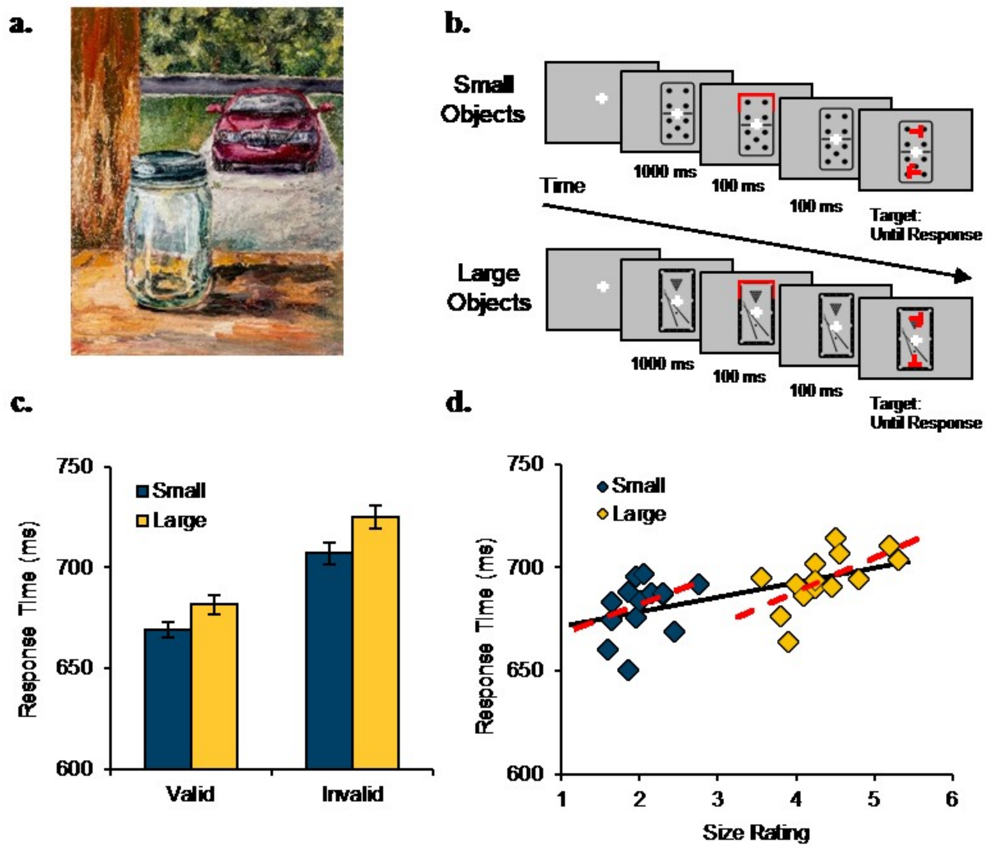
a.
b.
Small Objects
1000 ms
100 ms
100 ms
Target: Until Response
Time
Large Objects
1000 ms
100 ms
100 ms
Target: Until Response
c.
Small
Large
Response Time (ms)
750
700
650
600
Valid
Invalid
d.
Small
Large
Response Time (ms)
750
700
650
600
1
2
3
4
5
6
Size Rating

Figure Captions

Figure 1. (a) When rushing down a street towards the metro, more information is actually task-irrelevant (e.g., parked cars, food trucks, trees, buildings) than is task-relevant (e.g., path, pedestrians). (b) Experimental paradigm of Malcolm, Rattinger, & Shomstein (2016). Participants were presented with a center reference object followed by two objects presented to the left and right of fixation. One of these objects was always semantically-related (SR) to the reference object while the other was not related (NR). Participants performed a target discrimination task that was orthogonal to the objects' semantic relationship, rendering object identity task-irrelevant. (c) Semantic bias (RT of when target appears on NR object minus the RT of when target appears on SR object) peaked at a 750 ms SOA demonstrating that once an object's information has been processed, that information can influence attention even when irrelevant to the task. (d) Two possible neural mechanisms of the influence of task-irrelevant semantic information on attentional allocation. Facilitation can occur in object representations in object-selective lateral occipital complex (LOC; green) and/or in spatial representations of objects in spatially-selective intraparietal sulcus (IPS; yellow).

Figure 2. a) Despite the same retinal size, prior knowledge informs the observer of the size discrepancy between a mason jar (small) and parked car (large). b) Trial sequence of Collegio et al. (in press). Participants were presented with either small (e.g., domino) or large (e.g., pool table) object of equal retinal size. One end of the object was cued and targets appeared in either the cued or non-cued object locations. Crucially, objects (and their real-world size) were completely task-irrelevant. c) Target identification was significantly faster in objects with a small inferred real-world size than in objects with large inferred size, demonstrating the influence of task-irrelevant real-world object size on attentional allocation. d) The amount of attentional facilitation (y-axis) was directly predicted by individual ratings of inferred size of individual objects. Blue and yellow colors represent a median split analysis performed on individual ratings of objects.