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Content-Specific Expectations Enhance Stimulus Detectability by Increasing Perceptual Sensitivity

Timo Stein and Marius V. Peelen
University of Trento

The detectability of an object in our visual environment is primarily determined by the object's low-level visual salience, resulting from the physical characteristics of the object and its surroundings. In the present study we demonstrate that object detectability is additionally influenced by internally generated expectations about object properties, and that these influences are mediated by changes in perceptual sensitivity. Using continuous flash suppression (CFS) to render objects invisible, we found that providing valid information about the category membership of the object (e.g., "car") before stimulus presentation facilitated awareness of the object, as shown by improved localization performance relative to a noninformative baseline condition and to a condition with invalid prior information. Experiments 2 and 3 showed that the effect of expectation on detection generalized to binocular viewing conditions, with valid category cues facilitating the localization and detection of briefly presented objects. Experiment 4 extended these results to simple stimuli (oriented Gabor patches), for which valid orientation information improved localization performance. Finally, in Experiment 5 we found that the effect of expectation on detection and localization performance partly reflects increased perceptual sensitivity, as evidenced by decreased contrast detection thresholds for validly cued stimuli relative to noncued and invalidly cued stimuli. Together, these findings demonstrate that prior information about specific object properties dynamically enhances the effective signal of visual input matching the expected content, thereby biasing object detection in favor of expected objects.

Keywords: expectation, voluntary attention, detection, localization, masking

In navigating our world, we constantly form expectations about which objects we might encounter and these expectations in turn shape our perception of the world. Thus, rather than passively registering incoming sensory information, perception is a constructive process in which the brain matches sensory input to predictions generated on the basis of prior knowledge and expectations (Helmholtz, 1867). In this process of active inference, expectations related to the specific content and properties of objects in our environment can strongly influence perceptual decision making (Summerfield & de Lange, 2014). For example, many visual "illusions" can be explained as a mismatch between prior expectations and sensory signals (Gregory, 1997). When expectations of visual features or object properties match the visual input, object recognition and identification is improved (e.g., Eger, Henson, Driver, & Dolan, 2007; Esterman & Yantis, 2010; Puri & Wojciulik, 2008).

Although previous work has provided convincing evidence for the powerful effect of expectations on the interpretation, discrimination and identification of visual stimuli, it is unclear whether such content-specific expectations also affect the basic visual awareness of the presence of a stimulus. The detectability of a visual stimulus is primarily determined by its physical characteristics such as its luminance contrast relative to other elements in the visual field, that is, by its bottom-up saliency. However, the visual system's sensitivity to such physical stimulus properties can be dynamically modulated by the state of the observer. Specifically, it is well established that spatial attention can enhance visual perception at multiple processing stages: There is evidence that covert attention directed to a location in space by a central symbolic (e.g., arrow) cue cannot only improve the discrimination and identification of stimulus features but also enhance initial stimulus detection and localization (e.g., Carrasco, Penpeci-Talgar, & Eckstein, 2000; Downing, 1988; Müller & Humphreys, 1991; Theeuwes & Van der Burg, 2007), although other studies found only weak effects, determined important boundary conditions and advanced alternative explanations for such findings (e.g., Chica & Bartolomeo, 2012; Smith, 2000; Smith, Wolfgang, & Sinclair, 2004). In many everyday situations, however, we are lacking precise information about the spatial location of a target object. Rather, we are looking for a content-defined stimulus, such as a stimulus defined through a feature (e.g., something red), a feature dimension (e.g., something colored), or its category membership (e.g., cars). Such content- or feature-based attention is well known

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Timo Stein and Marius V. Peelen, Center for Mind/Brain Sciences, University of Trento.

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Correspondence concerning this article should be addressed to Timo Stein, Center for Mind/Brain Sciences, University of Trento, 38068 Rovereto, Italy. E-mail: timo@timostein.de

to facilitate postselection processes and to improve the discriminability of the attended feature (for reviews, see Carrasco, 2011; Theeuwes, 2010). It remains unclear, however, whether prior knowledge about stimulus content can enhance the initial perception and selection of visual stimuli, as reflected in simple detection and localization responses.

Many studies have demonstrated that content-specific expectations—mainly related to basic stimulus features such as color, orientation, motion, or shape—can improve visual search and perceptual performance. For example, when observers are required to search for a unique target defined by a conjunction of features (e.g., color and orientation) in a visual search array, a word cue providing prior information about the target-defining conjunction (e.g., "red vertical") greatly improves search performance (e.g., Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004). However, because in such paradigms the target identity is ambiguous, feature-specific prior information is directly relevant for discriminating the target from the distractors and may thus act on postselection processes. Another line of research has shown that prior information about a specific stimulus feature (e.g., approximate motion direction) can enhance performance in discriminating this particular feature (e.g., indicating the exact motion direction; Ling, Liu, & Carrasco, 2009), even in tasks tapping early vision, such as orientation discrimination (e.g., Kok, Jehee, & de Lange, 2012). These studies on feature-based attention convincingly demonstrate the impact of content-specific expectations on the discriminability of the precued stimulus content, that is, on those stimulus dimensions that are actually task-relevant. They do not, however, address the question of whether content-specific expectations modulate the simple detectability of a stimulus.

It has long been suggested that even in situations that require only the simple detection or localization of any stimulus present (i.e., without requiring stimulus discrimination or identification), perceptual performance would benefit from additional prior knowledge of stimulus content. For example, in their seminal study Sekuler and Ball (1977) showed that simple stimulus detectability is improved when a task-irrelevant stimulus feature (direction of motion) remains constant over a block of trials, relative to when this task-irrelevant stimulus feature varies between trials. Additionally, visual search performance is dramatically improved in pure blocks in which target properties remain constant compared with mixed blocks in which target properties can change from trial to trial (e.g., Müller, Heller, & Ziegler, 1995; Treisman, 1988; Wolfe, Butcher, Lee, & Hyle, 2003). Furthermore, when target-defining properties alternate randomly within a block, target repetitions lead to improved performance, even in simple feature singleton visual search tasks, a phenomenon called "priming of pop-out" (Maljkovic & Nakayama, 1994). Similarly, showing a visual precue representing a basic feature of the target stimulus that is not directly task-relevant on a trial-by-trial basis (e.g., an oriented line indicating the motion direction of the upcoming target) enhances stimulus detectability (Ball & Sekuler, 1981) and visual search (Theeuwes, Reimann, & Mortier, 2006). Finally, performing a discrimination task on specific basic stimulus properties such as orientation or spatial frequencies improves the simple detection of a stimulus presented elsewhere in the visual field when this stimulus shares these properties (Rossi & Paradiso, 1995).

All of these approaches have in common that they do not necessarily index the effect of voluntary content-specific preparation, but could instead reflect bottom-up priming, either from target properties that repeat across trials, from the symbolic cue depicting target properties in trial-by-trial cueing, or from the stimulus presented simultaneously at another location in the visual field (Theeuwes, 2010, 2013). A series of studies by Theeuwes and colleagues convincingly demonstrated that bottom-up priming could indeed explain many of these effects that had previously been attributed to voluntary top-down preparation (e.g., Pinto, Olivers, & Theeuwes, 2005; Schreij, Theeuwes, & Olivers, 2010; Theeuwes & Van der Burg, 2007, 2011). For example, trial-by-trial cueing effects in simple visual search were found to be restricted to cues that contained a visual representation of target-defining properties and, thus, induced bottom-up priming, whereas word cues did not facilitate search performance (Theeuwes et al., 2006). Thus, it seems that prior information about stimulus content can enhance initial detection and localization only in a bottom-up fashion through visual priming, but not through voluntary top-down preparation.

However, more recent studies indicate that even in the absence of bottom-up visual priming voluntary content-specific preparation can influence simple detection performance. These studies used continuous flash suppression (CFS; Tsuchiya & Koch, 2005), a variant of binocular rivalry in which high-contrast masks flashed into one eye can render a stimulus presented to the other eye invisible for up to several seconds. With this CFS technique, localization latencies for word stimuli can be influenced by semantically related primes (Costello, Jiang, Baartman, McGlennen, & He, 2009) and detection latencies can be modulated by auditory cues labeling a suppressed familiar object or shape (Lupyan & Ward, 2013). It remains unclear, however, whether or not these effects are specific to the technique of CFS, for example because they are mediated by CFS-specific unconscious processes.

To address these questions, in the present study we proceeded in four steps: First, we measured the influence of prior information about the category of a suppressed object on localization performance under CFS (Experiment 1). We used familiar natural object categories to attempt a conceptual replication of the study by Lupyan and Ward (2013) that provided initial evidence for the influence of content-specific expectations using CFS. Second, we tested whether the beneficial influence of such category-specific expectations on simple localization could be similarly found in the absence of interocular suppression. For this, we used standard binocular sandwich masking paradigms instead of CFS (Experiments 2 and 3). Third, we asked whether the effect of top-down preparation on localization performance was restricted to complex, familiar stimuli and high-level advance information, such as object categories, object basic-level labels (Lupyan & Ward, 2013) or word semantics (Costello et al., 2009), or whether similar effects could be obtained with comparably simple stimuli. To do so, we measured whether prior information about the orientation of simple gratings would modulate localization under sandwich masking (Experiment 4). Finally, we directly tested whether such orientation-specific expectations enhance contrast detection sensitivity and measured contrast detection thresholds in the absence of any masking stimuli (Experiment 5). In all experiments, we used word cues to rule out the possibility that visual bottom-up priming could have contributed to the effects. Together, our findings provide comprehensive evidence that content-specific expectations enhance perceptual sensitivity in simple visual detection tasks.

General Method

For all experiments, volunteers were recruited through the University of Trento subject pool. They participated for course credit or payment. All participants reported normal or corrected-to-normal vision and were naïve as to the purposes of the experiments. We aimed for a final sample size of 30 participants for every experiment, except for Experiment 2b for which the final sample size of 70 participants was determined based on a power calculation (see below). When participants had to be excluded from the analyses, additional participants were tested until the final sample size was reached. For the response-time based CFS Experiment 1 participants with very high rates of incorrect responses (more than 2 *SD*s from the sample mean) were excluded. Two participants were excluded from the analysis of Experiment 1a (error rates of 25.9% and 41.9%, respectively) and one participant was excluded from the analysis of Experiment 1b (error rate of 44.4%). For the nonspeeded, accuracy-based Experiments 2a–c, 3, and 4, participants were excluded when they did not show above-chance localization performance across conditions, as determined by binomial tests. This criterion led to the exclusion of one participant from the analyses of Experiment 2c, 14 from Experiment 3, four from Experiment 4a, and seven from Experiment 4b. Note that the exclusion of these participants did not affect the results in a qualitative manner.

Experiment 1

The first experiment was designed to measure the influence of category-specific expectations on localization performance under CFS. For this, we adopted a breaking-CFS (b-CFS) paradigm in which photographs of objects were rendered invisible through interocular suppression at the beginning of each trial. We hypothesized that prior information about the category membership of the suppressed object would reduce the time participants needed to localize the initially invisible object. An auxiliary question addressed in Experiment 1 was whether this beneficial influence of prior information, that is, the cueing effect, would vary as a function of the social and biological significance of the to-be-detected object category. One possibility is that the detection of images from categories with particularly high relevance such as people or animals would disproportionally benefit from category-specific expectations, because observers might particularly well be able to form mental representations of these categories that then could be used to facilitate detection. Alternatively, such top-down preparation to detect stimuli from specific categories may have a smaller effect for these object categories, because the detection of people or animals may be relatively automatic and hard-wired and, therefore, less penetrable by top-down processes (e.g., New, Cosmides, & Tooby, 2007; Tipples, Young, Quinlan, Broks, & Ellis, 2002).

Method

Participants. The final samples included 30 participants in Experiment 1a (22 female, age range 19–39 years, mean 24.4 years), and another set of 30 participants in Experiment 1b (25 female, age range 18–37 years, mean 22.6 years).

Apparatus and stimuli. Observers viewed a 19-in CRT monitor (1,280 × 1,024 pixels resolution, 60 Hz refresh rate) dichoptically through a custom-built mirror stereoscope. Because the exact luminance was not relevant to our research question (i.e., comparing visual detection of identical stimuli depending on prior information), we did not linearize the monitor output. Therefore, we report luminance as the monitor's input values in "percentage black," that is, "50% black" corresponds to a gray value of 128. Visual stimuli were presented with Matlab (The MathWorks, Natick, MA) using the Cogent, 2000 toolbox functions (www.vislab.ucl.ac.uk/cogent.php).

The observer's head was stabilized by a chin-and-head rest at a viewing distance of approximately 50 cm. The mirrors of the stereoscope were adjusted for each observer to promote stable binocular fusion. The screen was black except for the uniform light-gray area (30% black) in which the stimuli were presented. Two red frames (10.4° × 10.4°, enclosing the light-gray area) were displayed side-by-side on the screen such that one frame was shown to each eye (distance between the centers of the two frames 22.4°). To further support binocular fusion, noise contours (width 0.5°) consisting of random pixels were presented within the red frames. During stimulus presentation, a red fixation dot (0.5° × 0.5°) with a black dot (0.2° × 0.2°) in its center was displayed in the center of each frame. Participants were asked to maintain stable fixation throughout the experiment.

Target stimuli were photographs of objects from eight different animate and inanimate basic-level object categories (cars, cats, chairs, cups, guitars, hammers, persons, and shoes). For each category, 20 different exemplars were included, seen from different viewing angles (for example, stimuli, see Figure 1a). These objects were then fit to a rectangle (3.6° × 3.6°, by scaling the longer edge), converted to grayscale, assigned a mean luminance of 50% black and an RMS contrast of 5% (the remainder of the rectangle, i.e., the surround of the object, was assigned a uniform luminance of 30% black, equal to the background of the frames in which the stimuli were presented). To induce interocular suppression, we generated high-contrast, contour-rich CFS masks (9.2° × 9.2°) consisting of randomly arranged white, black, and gray circles (diameter 0.4°–1.8°).

Procedure. A schematic trial sequence is depicted in Figure 1b. Each trial began with a 700-ms presentation of the blank frames only, which was followed by a 1-s *cue period*. In the cue period, a word cue was presented in black uppercase Arial font (height 1.0°) in the center of each frame. In Experiment 1a, the word was either "READY" (noncued condition, 50% of trials) or the Italian word corresponding to the category of the to-be-presented object, for example "MACCHINA" in trials in which a car picture was shown (cued condition, 50% of trials). Participants were informed that category cues always validly predicted the category of the upcoming object, and also that the category of the presented object was always irrelevant to the simple localization task. In Experiment 1b, the word cue again denoted one of the eight object categories, but could now either validly or invalidly predict the category of the presented object. In valid trials (50% of trials), the word corresponded to the category of the presented object, while in invalid trials (50% of trials), the word was randomly selected from the seven nonpresented categories. Partici-

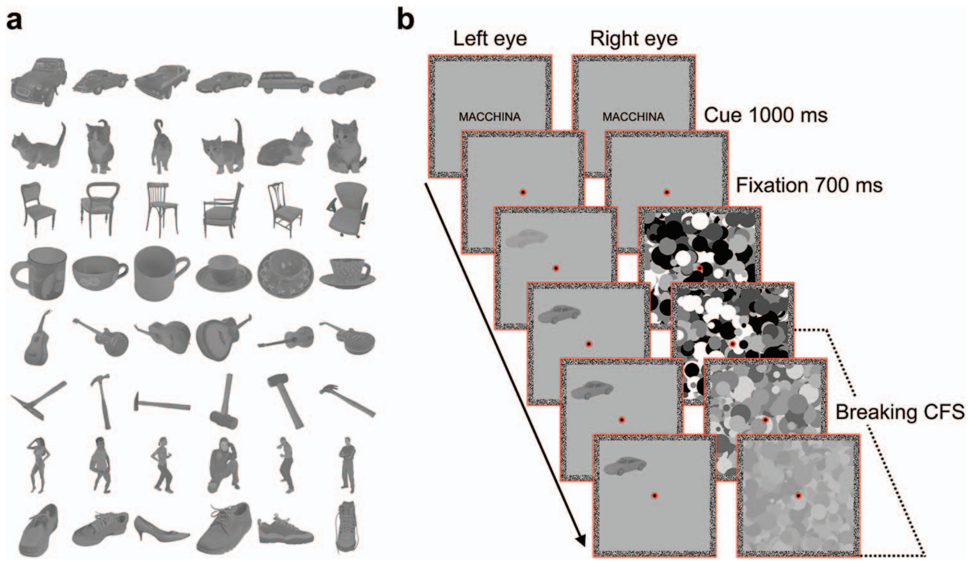

Figure 1. Stimuli and procedure in Experiment 1. (a) Examples of target stimuli from the eight object categories used in Experiments 1, 2, and 3. (b) Schematic of an example trial from Experiment 1. At the beginning of a trial a word provided either no information, valid, or invalid information about the category membership of the object that was subsequently presented under interocular suppression. To induce interocular suppression, CFS masks flashing at 10 Hz were presented to one eye, while an object was gradually introduced to the other eye. In the breaking-CFS (b-CFS) period participants indicated as quickly and accurately as possible in which quadrant an object or any part of an object became visible, irrespective of the object's category. The contrast of the object increased over the first second of a trial, while the contrast of the CFS masks was slowly ramped down over the course of a trial. See the online article for the color version of this figure.

pants were informed that these category cues correctly predicted the category of the presented object in most, but not all trials, and were asked to pay attention to (i.e., to read) the cues.

The cue period was followed by a 700-ms fixation period. In the subsequent *b-CFS period* randomly created CFS masks changing at 10 Hz were presented to one eye and an object was shown to the other eye. To avoid abrupt gradients, objects were gradually faded in over the first second of each trial (by linearly increasing the contrast from 0% to 5% and simultaneously decreasing the luminance from 30% to 50%) and then remained constant until the end of the trial (Figure 1b). Beginning 4 s after trial onset, the contrast of the CFS masks was linearly decreased to zero over 7 s. This contrast ramp was implemented to reduce the number of trials in which the object was not perceived at all. Objects were presented until response or for a maximum trial duration of 12 s in one of the four quadrants (centered at eccentricities of 3.3°). Participants pressed one of four keys ("F," "V," "J," and "N" on a QWERTY keyboard) corresponding to the four quadrants to indicate the location of the object. They were instructed to respond as soon as any part of an object became visible, irrespective of its category, and to be as fast and accurate as possible.

Each experiment contained 320 trials (separated by obligatory breaks after 80, 160, and 240 trials) in which each combination of two cue conditions (Experiment 1a: cued, noncued; Experiment 1b: valid, invalid), eight object categories, and 20 exemplars per category occurred once. For half of the participants in each experiment, target stimuli were shown to the left eye, and for the other half to the right eye. Trial order was randomized and the quadrant in which the target was presented was selected at random for each trial.

Analysis. Response accuracy of all included participants was high (Experiment 1a: M = 96.1%, SD = 4.3%; Experiment 1b: M = 97.7%, SD = 1.8%). Trials with incorrect responses were excluded from the analyses of suppression durations. To measure the influence of prior information on suppression durations for physically strictly identical stimuli, we also excluded correct trials with a given target exemplar from one cueing condition if the response to the same target exemplar in the other cueing condition had been incorrect. The mean proportion of trials included in the calculation of mean suppression durations was 91.6% (SD = 8.0%) in Experiment 1a, and 94.7% (SD = 4.0%) in Experiment 1b. Suppression durations were computed as the time between the start of the target fade-in and the response. Mean suppression durations were analyzed using two-way repeated measures analysis of variances (ANOVAs) with the factors cue (Experiment 1a: cued, noncued; Experiment 1b: valid, invalid) and object category (eight levels). In case Mauchly's test indicated violations of the assumption of sphericity, degrees of freedom and p values are reported as Greenhouse-Geisser corrected.

Results and Discussion

There were large differences in suppression durations between object categories, as reflected in significant main effects of object category in Experiment 1a, $F(3.73, 108.13) = 33.17$, $p < .001$, $\eta_p^2 = .53$, and in Experiment 1b, $F(3.87, 112.12) = 17.61$, $p <$

.001, η_p^2 = .38. This indicates that target stimuli differed in "stimulus strength" (Levelt, 1965), most likely reflecting differences in low-level physical stimulus properties. This is consistent with previous b-CFS studies showing that even when global contrast is matched, various other, partially unknown differences in low-level stimulus properties (e.g., spatial frequency, local contrast differences, and Gestalt factors) can have a strong influence on suppression durations (e.g., Stein, Seymour, Hebart, & Sterzer, 2014; Stein & Sterzer, 2012; Yang, Zald, & Blake, 2007; Yang & Blake, 2012). For the purpose of the present study these overall detection differences did not matter, because we compared the effect of prior information on suppression durations among physically identical stimuli.

More important, the cueing effect was significant in both Experiment 1a, $F(1, 29) = 11.60$, $p = .002$, $\eta_p^2 = .29$ (Figure 2a), and in Experiment 1b, $F(1, 29) = 18.64$, $p < .001$, $\eta_p^2 = .39$ (Figure 2b), reflecting shorter suppression durations for validly cued than for noncued or invalidly cued objects. The two-way interaction between object category and cue was significant in Experiment 1a, $F(7, 203) = 2.24$, $p = .032$, $\eta_p^2 = .07$, indicating that the beneficial effect of prior information differed across object categories, but did not reach statistical significance in Experiment 1b, $F(7, 203) = 1.88$, $p = .075$, $\eta_p^2 = .06$. We explored this interaction further by collapsing the data from the two experiments to have more statistical power for comparing the cueing effect between object categories (see below).

The results from these first two experiments show that prior information about the category of an initially suppressed object can facilitate access to awareness. Whereas the cueing advantage in Experiment 1a (M = 198 ms, SD = 321 ms, 95% CI [78 ms, 318 ms], d = 0.62; see Figure 2a) could have reflected a nonspecific effect of a word cue compared to the "READY" cue, the advantage of valid over invalid cues obtained in Experiment 1b (M = 233 ms, SD = 299 ms, 95% CI [121 ms, 345 ms], d = 0.78; see Figure 2b) shows that localization was facilitated only when the word cue matched the category of the presented object. To rule out that this cueing effect could have been because of bottom-up intertrial priming effects, we excluded all trials in which the presented object category was the same as in the preceding trial (8–16% of all trials). Still, there was a reliable cueing advantage of similar size, both in Experiment 1a (M = 218 ms, SD = 346 ms, 95% CI [88 ms, 347 ms], d = 0.63), and in Experiment 1b (M = 238 ms, SD = 308 ms, 95% CI [123 ms, 353 ms], d = 0.77).

While these analyses demonstrate the beneficial effect of prior category-specific information on object localization, we were also interested in exploring whether advance information would affect the detection of objects from all categories in a similar fashion or whether the cueing effect would vary as a function of the social or biological significance of the category. To have more power for detecting a potential interaction between cue and object category, we combined the data from Experiments 1a and 1b. For this combined data set, there were significant main effects of object category, $F(4.06, 239.67) = 43.38$, $p < .001$, $\eta_p^2 = .42$, and cue, $F(1, 59) = 29.95$, $p < .001$, $\eta_p^2 = .34$, and a significant interaction, $F(7, 413) = 2.14$, $p = .039$, $\eta_p^2 = .04$. The cueing effect was statistically significant for cats, chairs, cups, hammers, and persons (all $p < .05$) but not for cars, guitars, and shoes (all $p > .05$; see Figure 3). However, pairwise comparisons did not reveal statistically significant differences between the cueing effects for different object categories (all Bonferroni-corrected $p > .05$) Thus, Experiment 1 did not provide unequivocal evidence for differences in the beneficial effect of category-specific prior information on access to awareness between the tested object categories.

Experiments 2 and 3

Although the results of Experiment 1 are consistent with previous findings of top-down influences on suppression durations under CFS (Lupyan & Ward, 2013), they leave open the possibility that such content-specific expectations act on unconscious processes that are specific to the method of CFS and that such effects are, therefore, restricted to this highly artificial laboratory technique of interocular suppression. Indeed, the influence of semantic primes on stimulus localization has been found with CFS but not under normal binocular viewing conditions (Costello et al., 2009). Furthermore, because we recorded response times the results of

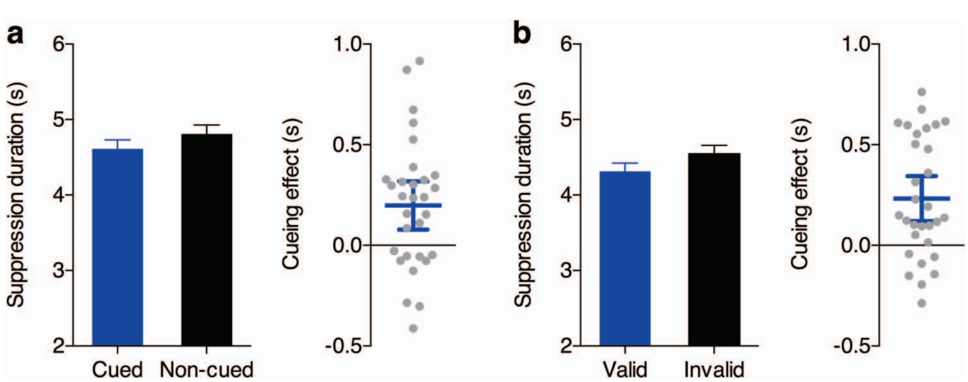

Figure 2. Results from (a) Experiment 1a and from (b) Experiment 1b. The left panels show mean suppression durations in the cued versus noncued condition (Experiment 1a) and in the valid versus invalid condition (Experiment 1b), respectively. Error bars represent the 95% confidence interval (CI) for the comparison between the two conditions. The right panels show the cueing effect (i.e., the difference in suppression durations between noncued/invalid and cued/valid conditions) for individual subjects. The blue horizontal bar denotes the group mean and the blue vertical bar the 95% CI. See the online article for the color version of this figure.

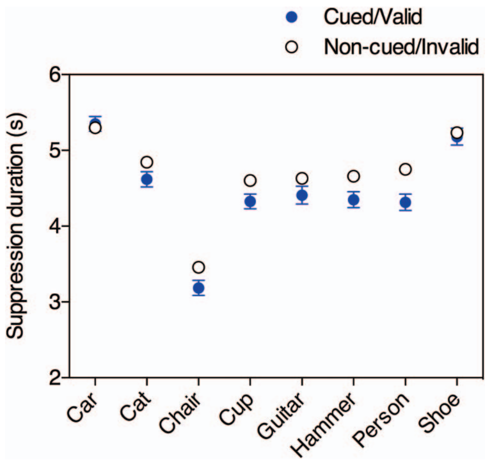

Figure 3. Mean suppression durations across Experiment 1a and 1b, shown as a function of cue and object category. Error bars show the *SE* of the difference between cued/valid and noncued/invalid, separately for each object category. See the online article for the color version of this figure.

Experiment 1 could have at least partly reflected differences in response criteria between the cueing conditions rather than differences in perceptual sensitivity.

To address these issues, in Experiments 2 and 3 we used a standard binocular masking paradigm in which participants had to localize briefly presented images of objects that were sandwiched between forward and backward masks. To rule out that category-specific expectations influenced response criteria rather than perceptual sensitivity, we implemented nonspeeded, criterion-free localization and detection tasks. For Experiments 2 a–c we used spatial four alternative forced-choice localization tasks in which the three nontarget locations were filled with phase-scrambled versions of the target object, such that successful object localization required discriminating the target location with object-like phase information from the three other locations containing identical amplitude and frequency information but random phase information. The critical question was whether this simple task would nevertheless benefit from prior information about the target's category membership. For Experiment 2d this localization task was replaced by a present-absent detection task in which only a single target or nontarget image was presented in each trial. In Experiment 3, we took the approach from the localization Experiments 2a–c one step further and left the three nontarget locations empty, such that successful object localization solely required discriminating the target location from blank alternative locations that differed in amplitude, frequency, and phase information. Note that this task can be solved efficiently by looking for the location with the highest contrast value, based on low-level salience. Does category-specific top-down preparation nevertheless improve performance?

Method

Participants. In Experiment 2a, there were 30 participants (25 female, age range 18–36 years, mean 23.6 years), of whom four had participated in Experiment 3 before. Experiment 2b was an identical replication of Experiment 2a that was conducted to provide a more accurate estimate of the effect size of the cueing effect. A power calculation based on the lower bound of the confidence interval around the effect size obtained in Experiment 2a (95% CI [0.34, 1.15], calculated using Geoff Cumming's ESCI software; Cumming, 2012) yielded a sample size of 70 participants (53 female, age range 18–31 years, mean 22.7 years) for 80% power. The final sample of Experiment 2c included 30 participants (26 female, age range 18–27 years, mean 21.9 years), of whom eight had participated in Experiment 2a before and another three had participated in Experiment 3 before. In Experiment 2d there were 30 participants (25 female, age range 18–32 years, mean 23.4 years), of whom 24 had participated in Experiment 2b in a previous session. The final sample of Experiment 3 also included 30 participants (22 female, age range 18–38 years, mean 23.1 years).

Apparatus and stimuli. The general experimental setup was similar to Experiment 1, but observers now viewed the screen binocularly, without a stereoscope. In the four alternative forced-choice (4AFC) localization Experiments 2a–c and 3 the screen was black except for four light-gray frames (30% black, 3.9° × 3.9°, each enclosed by a thin white border of 0.1° width) in which the target stimuli were presented (see Figure 4). These frames were presented in the quadrants, centered at eccentricities of 4.5°. During stimulus presentation, a white fixation cross (0.5° × 0.5°) was displayed in the center of the four frames. Participants were asked to maintain stable fixation throughout the experiment and they were informed that deliberate or strategic eye movements during stimulus presentation would be detrimental to their performance.

In the present-absent detection Experiment 2d only one light-gray frame (5.9° × 5.9°) with a central black fixation cross (0.5° × 0.5°) was presented centrally on a black screen. No fixation cross was presented while target or nontarget stimuli were presented in this frame.

Target stimuli were the same object photographs as in Experiment 1, with the same luminance and contrast settings (but scaled to rectangles of 3.9° × 3.9° for Experiments 2a–c and Experiment 3, and to 5.9° × 5.9° for Experiment 2d). For Experiment 2, the phases (i.e., the location) of Fourier components in these images were (partially) randomized. For the target image, we applied 50% phase scrambling, while the same images with 100% phase scrambling (i.e., they were no longer recognizable; see Figure 4) served as nontarget images. In Experiments 2a–c three such phase-scrambled nontargets, randomly generated for every trial, were shown in the nontarget quadrants. For Experiment 2d, one such nontarget image was presented in target-absent trials. For Experiment 3, no phase scrambling was applied.

Procedure. A schematic trial sequence from Experiment 2a–c is shown in Figure 4. In Experiments 2a—c and 3 each trial began with a 700-ms presentation of the blank frames only, which was followed by a 1-s *cue period*. In the cue period, a word was presented in white uppercase Arial font (height 1.0°) in the center between the four frames. In Experiment 2d the temporal sequence of the cue period was the same but the cue was shown in black font in the center of the single central frame. In Experiment 2a, 2b, and Experiment 3, we compared performance between a noncued condition (always presenting the word "READY") and a cued condition in which the cues were always valid (as in Experiment 1a). In Experiment 2c and 2d, we compared performance in valid

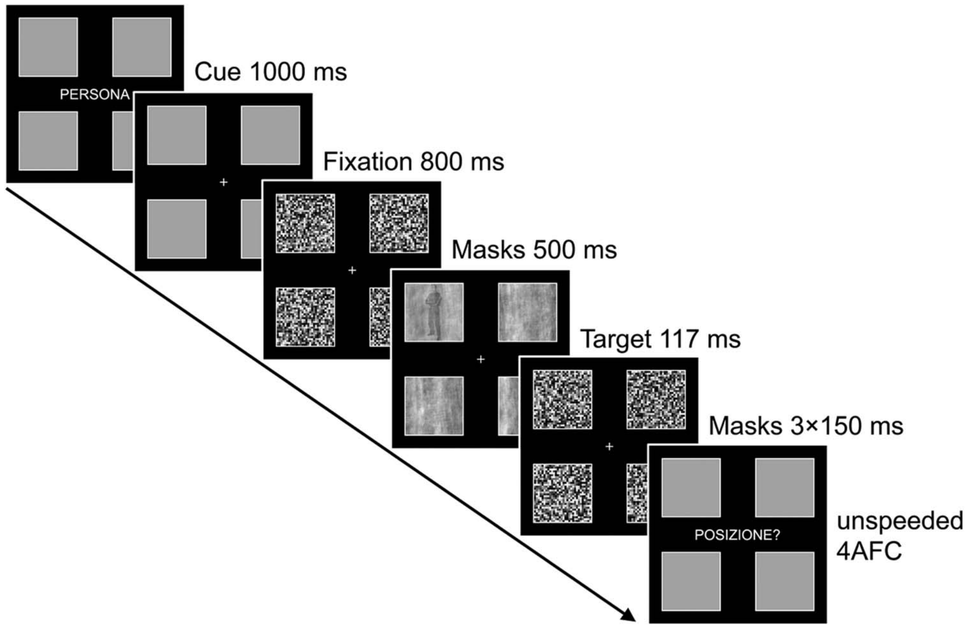

Figure 4. Schematic of an example trial from Experiment 2a–c. At the beginning of a trial a word provided either no information, valid, or invalid information about the category membership of the object that was subsequently presented under sandwich masking. The object target was presented in one of the four quadrants and temporally sandwiched between noise masks. Participants indicated as accurately as possible, without speed pressure, in which quadrant the object was presented. As shown in the figure, in Experiment 2a–c the object was presented with 50% phase scrambling for 117 ms while the other three quadrants were filled with 100% phase scrambled versions of the target image. In Experiment 3 the trial sequence was the same, except that the target display was presented for 33 ms only, and no phase scrambling was applied (analogous to Experiment 4 with Gabor patches, shown in Figure 8).

and invalid trials (as in Experiment 1b[1]). Instructions regarding the word cues were the same as in Experiment 1.

The cue period was followed by an 800-ms fixation period. Subsequently, four noise masks were presented for 500 ms inside the frames. All noise masks were randomly generated for each trial and consisted of small squares (4×4 pixels) with random gray values. Next, target and/or nontarget images were presented for 117 ms (Experiment 2a–c), 83 ms (Experiment 2d), or for 33 ms (Experiment 3). In Experiment 2a–c, the 50% phase scrambled target was shown in one quadrant, whereas 100% phase scrambled versions of the same target were presented in the other quadrants. In Experiment 2d, the 50% phase scrambled target was shown in the central frame in target-present trials, while a 100% phase scrambled image was presented in target-absent trials. In Experiment 3, the target was not phase scrambled (but shown against a blank background, as in Experiment 1) and the other three nontarget quadrants contained only the blank background. Immediately after the presentation of the target, three trailing noise masks were shown inside the frames for 150 ms each. In Experiments 2a–c and 3 participants were asked to indicate as accurately as possible, without speed pressure, the quadrant in which the object was presented (using the same four keys as in Experiment 1). In Experiment 2d participants were required to indicate as accurately as possible, without speed pressure, whether an intact object image was present or absent (using the left and right arrow keys). They were informed that two-thirds of all trials contained an intact object image and practice trials with longer presentation durations preceding the experiment proper were included to familiarize participants with 50% ("present") versus 100% ("absent") phase scrambled object images. After entering their response, participants received feedback (the fixation cross changed to green or red).

Experiment 2a–c and 3 contained 320 trials (separated by obligatory breaks after 80, 160, and 240 trials) in which each combination of two cue conditions (Experiment 2a, 2b, and 3: cued, noncued; Experiment 2c: valid, invalid), eight object categories, and 20 exemplars per category occurred once. Trial order was randomized and the quadrant in which the target was presented was selected at random for each trial. Experiment 2d contained 480 trials (separated by obligatory breaks after 120, 240, and 360

[1] In Experiments 2, 4, and 5 detection performance was compared between trials with valid prior information on the category or features of the target stimulus and trials with either no such prior information (noncued) or invalid prior information (invalid). Note that these two comparisons (cued vs. noncued and valid vs. invalid) were included as exploratory conditions, without proper counterbalancing of participants. Therefore, we did not compare these two manipulations directly. A number of the participants who took part in the accuracy-based localization experiments that compared valid versus invalid cues (i.e., Experiments 2c, 4b, and 5b, see the respective Method sections) had taken part in the corresponding experiments comparing cued versus noncued conditions (i.e., Experiments 2a, 4a, and 5a) before. Therefore, we cannot exclude potential order effects.

trials). In 320 target-present trials each combination of 2 cue conditions (valid, invalid), 8 object categories, and 20 exemplars per category occurred once. In 160 target-absent trials, one randomly selected category cue preceded one randomly selected target image with 100% phase scrambling. Trial order was randomized.

Analysis. For the localization experiments, mean proportions of correct responses were analyzed using two-way repeated measures ANOVAs with the factors cue (Experiment 2a, 2b, and 3: cued, noncued; Experiment 2c: valid, invalid) and object category (eight levels). For the detection Experiment 2d, hit rates were analyzed (because target-absent trials did not differ between cueing or category conditions, false alarm rates did not differ as a function of cueing or category) using a two-way repeated measures ANOVA with the factors cue (valid, invalid) and object category.

In addition, to provide procedure-independent estimates of overall performance and cueing effects, Table 1 shows d' scores. For the criterion-free 4AFC Experiments 2a–c and 4, proportion correct was converted to d' using the Palamedes toolbox (Prins & Kingdom, 2009). For the present-absent Experiment 2d, d' was calculated as the z-transformed hit rates minus the z-transformed false alarm rate (which was identical across cueing and category conditions).

Results and Discussion

The three experiments yielded similar patterns of results. In all experiments, there were overall differences in localization accuracy between object categories, as indicated by significant main effects of object category in Experiment 2a, $F(7, 203) = 15.38$, $p < .001$, $\eta_p^2 = .35$, in Experiment 2b, $F(7, 483) = 59.11$, $p < .001$, $\eta_p^2 = .46$, in Experiment 2c, $F(7, 203) = 24.63$, $p < .001$, $\eta_p^2 = .46$, in Experiment 2d, $F(4.27, 123.67) = 33.86$, $p < .001$, $\eta_p^2 = .54$, and in Experiment 3, $F(7, 203) = 9.51$, $p < .001$, $\eta_p^2 = .25$. More important, there were significant main effects of cueing in Experiment 2a, $F(1, 29) = 16.97$, $p < .001$, $\eta_p^2 = .37$ (Figure 5a), in Experiment 2b, $F(1, 69) = 17.11$, $p < .001$, $\eta_p^2 = .20$ (Figure 5b), in Experiment 2c, $F(1, 29) = 21.90$, $p < .001$, $\eta_p^2 = .43$ (Figure 6a), in Experiment 2d, $F(1, 29) = 17.61$, $p < .001$, $\eta_p^2 = .38$ (Figure 6b), and in Experiment 3, $F(1, 29) = 9.05$, $p = .005$, $\eta_p^2 = .24$ (see Figure 7), with better performance for validly cued than for noncued or invalidly cued object targets. There was no clear evidence for statistically significant category-by-cueing interactions (Experiment 2a: $F < 1$, $\eta_p^2 = .03$; Experiment 2b: $F(5.69, 392.57) = 2.15$, $p = .051$, $\eta_p^2 = .30$; Experiment 2c: $F < 1$, $\eta_p^2 = .03$; Experiment 2d: $F(7, 203) = 1.76$, $p = .097$, $\eta_p^2 = .06$; Experiment 3: $F < 1$, $\eta_p^2 = .03$), indicating that the beneficial effect of prior information did not differ substantially between object categories.

These results replicate and extend the findings of Experiment 1: Also in the absence of interocular suppression and with nonspeeded, criterion-free spatial forced-choice and detection tasks did prior information about the category of an upcoming object improve performance. This beneficial effect of prior information on simple localization and detection was present when participants had to discriminate a 50%-phase scrambled target from its 100%-phase scrambled counterparts, both for the comparison between cued and noncued trials in Experiment 2a ($M = .041$, $SD = .055$, 95% CI [.021, .062], $d = 0.75$; Figure 5a) and Experiment 2b ($M = .026$, $SD = .053$, 95% CI [.013, .039], $d = 0.49$; Figure 5b), as well as for the comparison between valid and invalid trials in Experiment 2c ($M = .057$, $SD = .067$, 95% CI [.032, .082], $d = 0.85$; Figure 6a) and Experiment 2d ($M = .023$, $SD = .030$, 95%

Table 1
Main Results From Experiments 2–4 After Conversion of Proportion Correct to d′ Scores

	Cued/valid	Noncued/invalid	Cueing effect				
	Mean d'	Mean d'	Mean d'	*SD*	95% CI	*p*-value	Cohen's *d*
Experiment 2a							
All trials	1.142	1.001	.141	.181	[.073, .209]	<.001	.778
Rep. excl.	1.130	.986	.144	.203	[.068, .220]	<.001	.707
Experiment 2b							
All trials	1.233	1.145	.088	.181	[.044, .131]	<.001	.484
Rep. excl.	1.231	1.140	.091	.198	[.044, .138]	<.001	.461
Experiment 2c							
All trials	1.281	1.085	.196	.221	[.113, .278]	<.001	.887
Rep. excl.	1.285	1.087	.198	.213	[.118, .278]	<.001	.927
Experiment 2d							
All trials	1.567	1.471	.096	.126	[.049, .143]	<.001	.764
Rep. excl.	1.572	1.475	.097	.141	[.044, .150]	<.001	.686
Experiment 3							
All trials	.555	.479	.076	.137	[.025, .127]	.005	.553
Rep. excl.	.544	.475	.070	.146	[.015, .124]	.014	.475
Experiment 4a							
All trials	.907	.782	.125	.178	[.059, .191]	<.001	.704
Rep. excl.	.898	.761	.137	.217	[.056, .218]	.002	.633
Experiment 4b							
All trials	.859	.698	.161	.186	[.091, .230]	<.001	.862
Rep. excl.	.865	.722	.143	.243	[.052, .233]	.003	.589

Note. "Rep. excl." refers to auxiliary analyses for which trials in which the presented object category was the same as in the preceding trial were excluded.

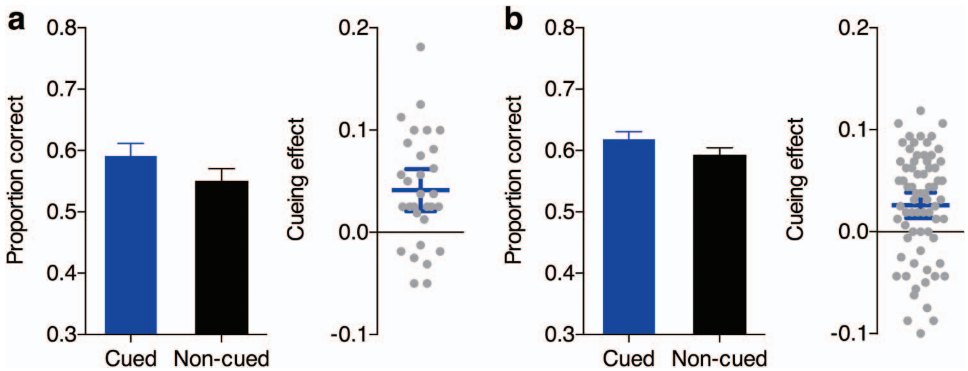

Figure 5. Results from (a) Experiment 2a and from (b) Experiment 2b. The left panels show mean object localization accuracies in the cued versus noncued condition. Error bars represent the 95% confidence interval (CI) for the comparison between the two conditions. The right panels show the cueing effect (i.e., the difference in localization performance between cued and noncued conditions) for individual subjects. The blue horizontal bar denotes the group mean and the blue vertical bar the 95% CI. See the online article for the color version of this figure.

CI [.012, .034], *d* = 0.77; Figure 6b). The larger sample (*N* = 70) included in Experiment 2b also allowed us to estimate the size of the cueing effect with greater precision: In Experiment 2b, the 95% CI for Cohen's *d* ranged from 0.23 to 0.72. Moreover, in Experiment 3 the advantage of cued versus noncued trials (*M* = .022, *SD* = .041, 95% CI [.007, .037], *d* = 0.55; Figure 7) was obtained even when participants simply had to discriminate the location of an object that was darker than the blank background from the three alternative locations containing blank backgrounds only.

Again, additional analyses ruled out that these cueing effects reflected bottom-up intertrial priming effects. When excluding all trials in which the target category was the same as in the preceding trial (9–14% of all trials), there were similar cueing effects, in Experiment 2a (*M* = .042, *SD* = .062, 95% CI [.019, .065], *d* = 0.68), in Experiment 2b (*M* = .027, *SD* = .057, 95% CI [.013, .041], *d* = 0.47), in Experiment 2c (*M* = .057, *SD* = .063, 95% CI [.034, .081], *d* = 0.90), in Experiment 2d (*M* = .024, *SD* = .034, 95% CI [.012, .037], *d* = 0.72), and in Experiment 3 (*M* = .020, *SD* = .043, 95% CI [.004, .037], *d* = 0.47).

Experiment 4

Although the previous experiments clearly demonstrated the beneficial influence of category-specific expectations on simple localization and detection performance, it is possible that this effect of top-down preparation is limited to naturalistic, familiar object stimuli. We therefore next asked whether content-specific top-down preparation represents a general mechanism that can enhance perceptual sensitivity for visual stimuli of different complexity and familiarity that are processed at different levels of visual cortex. To do so, in Experiment 4 we adopted the design of Experiment 3 but replaced images of familiar everyday objects with simple gratings of different orientations. We tested whether prior orientation-specific information would enhance localization

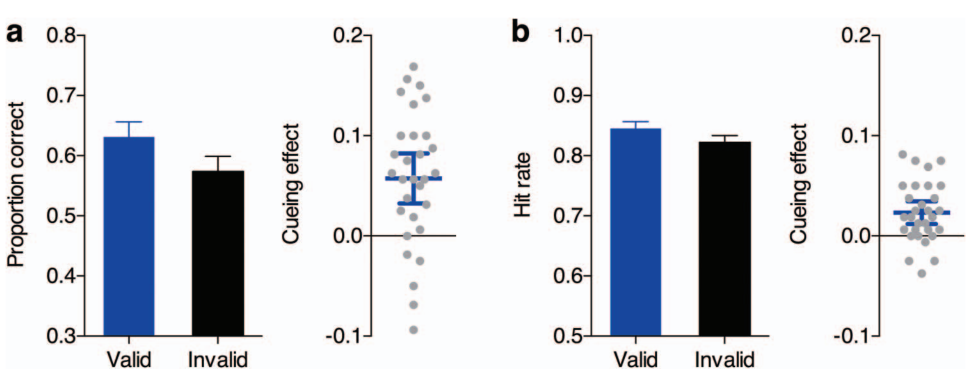

Figure 6. Results from (a) Experiment 2c and from (b) Experiment 2d. The left panels show mean object localization accuracies (Experiment 2c) and mean hit rates for object detection (Experiment 2d) in the valid versus invalid condition. Error bars represent the 95% confidence interval (CI) for the comparison between the two conditions. The right panels show the cueing effect (i.e., the difference in performance between valid and invalid conditions) for individual subjects. The blue horizontal bar denotes the group mean and the blue vertical bar the 95% CI. See the online article for the color version of this figure.

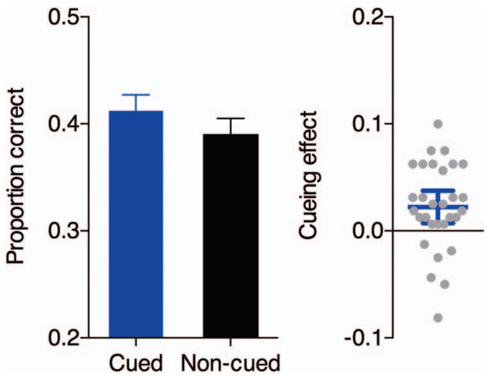

Figure 7. Results from Experiment 3. The left panel shows mean object localization accuracies in the cued and in the noncued condition. Error bars represent the 95% confidence interval (CI) for the comparison between the two conditions. The right panel shows the cueing effect (i.e., the difference in localization performance between the cued and the noncued condition) for individual subjects. The blue horizontal bar denotes the group mean and the blue vertical bar the 95% CI. See the online article for the color version of this figure.

performance for these simple stimuli that could have been detected based simply on their luminance contrast.

Method

Participants. The final sample of Experiment 4a consisted of 30 participants (24 female, age range 18–36 years, mean 24.5 years). The final sample of Experiment 4b included 30 participants (25 female, age range 19–36 years, mean 23.1 years), of whom nine also participated in Experiment 4a. Seven of these nine participants took part in Experiment 4a first, and two took part in Experiment 4b first.

Apparatus and stimuli. The apparatus, displays, and procedure were identical to Experiment 3, with the following exceptions. The light-gray frames had a luminance of 50% black and the target stimulus was a Gabor patch (3.9° × 3.9°, mean luminance 50% black, 25% contrast, spatial frequency 12 cycles per image, $\sigma = 0.4°$, the phase was selected at random for each trial) with one of four orientations: 0° (vertical), 45° (right-tilted), 90° (horizontal), or 135° (left-tilted).

Procedure. The procedure was identical to Experiment 3, with the following exceptions. Word cues now referred to the orientation of the Gabor patches. In Experiment 3a, the word was either "READY" (noncued condition) or the Italian word corresponding to the orientation of the upcoming Gabor target, for example "VERTICALE" in trials with vertical Gabor targets (cued condition). Before starting the experiment, participants were given examples of the orientations of the Gabor patches corresponding to these vertical, horizontal, left, and right cues. Participants were informed that these orientation cues were always valid and were asked to pay attention to the cues. In Experiment 4b, the word always denoted one of the four Gabor orientations, and could either validly or invalidly predict the orientation of the upcoming Gabor target. In valid trials, the word corresponded to the orientation of the upcoming target stimulus. In invalid trials, the word was randomly selected from the three nontarget orientations. Participants were informed that these orientation cues correctly predicted the orientation of the presented Gabor in most, but not all trials, and were asked to pay attention to the cues.

The procedure for stimulus presentation was identical to Experiment 3: The presentation of the Gabor patch in one of the quadrants (33 ms) was preceded and followed by noise masks (see Figure 8). The phase of the Gabor patch was selected at random for every trial.

Each experiment contained 320 trials (separated by obligatory breaks after 80, 160, and 240 trials) in which each combination of two cue conditions (Experiment 4a: cued, noncued; Experiment 4b: valid, invalid), four Gabor orientations, and four target locations occurred 10 times. Trial order was randomized.

Analysis. Mean proportions of correct responses were analyzed using two-way repeated measures ANOVAs with the factors cue (Experiment 4a: cued, noncued; Experiment 4b: valid, invalid) and Gabor orientation (vertical, horizontal, left-tilted, or right-tilted).

Results and Discussion

There were significant main effects of Gabor orientation in both Experiment 4a, $F(2.26, 65.55) = 21.03$, $p < .001$, $\eta_p^2 = .42$, and in Experiment 4b, $F(3, 87) = 20.66$, $p < .001$, $\eta_p^2 = .42$, reflecting better overall performance for cardinal orientations (Experiment 4a: $M = 55.4\%$ correct, Experiment 4b: $M = 48.5\%$ correct) than for oblique orientations (Experiment 4a: $M = 43.7\%$ correct, Experiment 4b: $M = 41.1\%$ correct). More important, the cueing effect was significant in Experiment 4a, $F(1, 29) = 15.75$, $p < .001$, $\eta_p^2 = .35$ (Figure 9a), and in Experiment 4b, $F(1, 29) = 21.64$, $p < .001$, $\eta_p^2 = .43$ (Figure 9b), with better localization performance for validly cued than for noncued or invalidly cued Gabor targets. The two-way interaction between Gabor orientation and cueing was significant in Experiment 4a, $F(3, 87) = 3.45$, $p = .020$, $\eta_p^2 = .11$, reflecting significantly larger cueing effects for vertical and right-tilted Gabors than for left-tilted Gabors, $t(29) = 2.72$, $p = .011$, $d = 0.50$, and $t(29) = 2.45$, $p = .020$, $d = 0.45$, respectively. In Experiment 4b, there was no significant interaction, $F(1.99, 57.54) = 2.57$, $p = .085$, $\eta_p^2 = .02$, indicating that the beneficial effect of prior information did not differ as a function of Gabor orientation.

Thus, these findings show that the beneficial effect of prior information on simple detection is not limited to category information for natural object photographs, but can similarly be found with orientation information for simple Gabor stimuli, both for the comparison of cued versus noncued trials in Experiment 4a ($M = .036$, $SD = .050$, 95% CI [.018, .055], $d = 0.72$; Figure 9a) and for the comparison of valid versus invalid trials in Experiment 4b ($M = .046$, $SD = .054$, 95% CI [.026, .066]; Figure 9b). Again, additional analyses ensured that these cueing effects were not because of bottom-up intertrial priming effects. After exclusion of all trials in which the presented orientation was the same as in the preceding trial (20–32% of all trials), the cueing effects were similar, both in Experiment 4a ($M = .039$, $SD = .062$, 95% CI [.016, .062], $d = 0.63$), and in Experiment 4b ($M = .039$, $SD = .068$, 95% CI [.014, .064], $d = 0.58$).

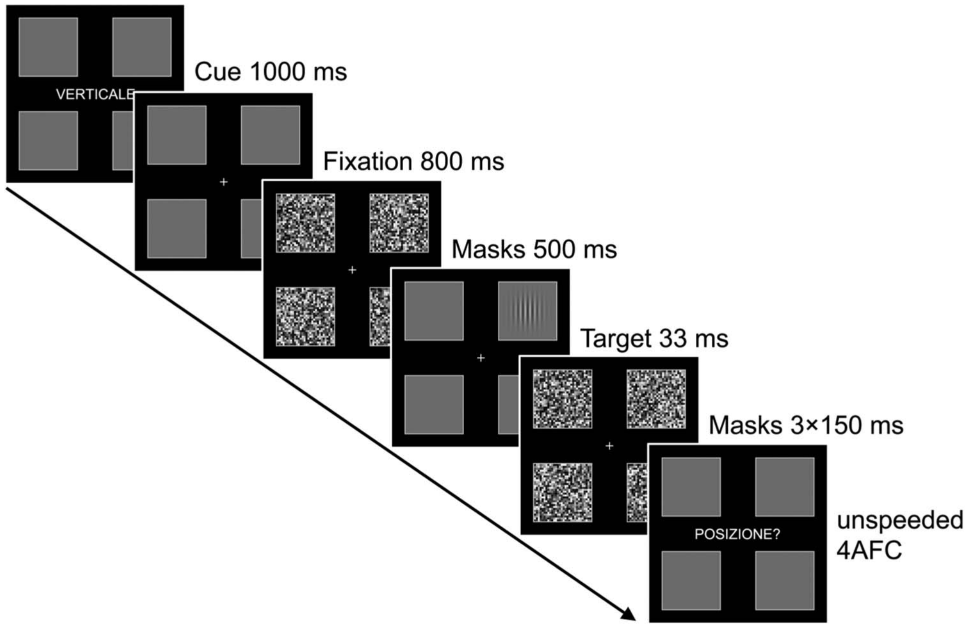

Figure 8. Schematic of an example trial from Experiment 4. At the beginning of a trial a word provided either no information, valid, or invalid information about the orientation of the Gabor patch that was subsequently presented under sandwich masking. The Gabor patch was presented in one of the four quadrants and temporally sandwiched between noise masks. Participants indicated as accurately as possible, without speed pressure, in which quadrant the target stimulus was presented.

Experiment 5

Together, the previous experiments demonstrated the beneficial effect of content-specific expectations on simple localization of both familiar everyday objects and oriented gratings. As these stimuli were sandwiched between noise masks, one may argue that top-down preparation did not directly enhance the signal from the cued target, but rather improved the discriminability of the target location relative to the nontarget locations against the noise masks. Note that differentiating between these two accounts is not critical for the conclusion that content-specific top-down preparation can improve performance even in simple detection or localization. Still, in Experiment 5 we tested whether orientation-specific expectations lead to signal enhancement in simple localization by measuring whether orientation cues would modulate contrast detection thresholds.

Method

Participants. In Experiment 5a, there were 30 participants (25 female, age range 18–53 years, mean 25.0 years). In Experiment

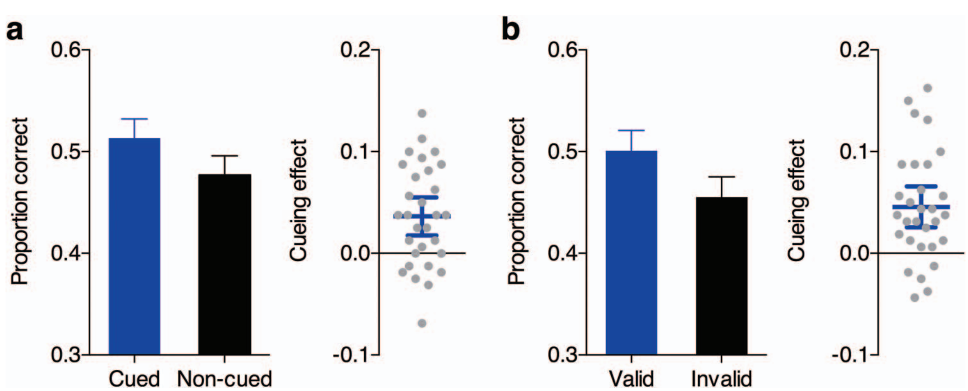

Figure 9. Results from (a) Experiment 4a and from (b) Experiment 4b. The left panels show mean Gabor localization accuracies in the cued versus noncued condition (Experiment 4a) and in the valid versus invalid condition (Experiment 4b), respectively. Error bars represent the 95% confidence interval (CI) for the comparison between the two conditions. The right panels show the cueing effect (i.e., the difference in detection accuracies between cued/valid and noncued/invalid conditions) for individual subjects. The blue horizontal bar denotes the group mean and the blue vertical bar the 95% CI. See the online article for the color version of this figure.

5b, there were 30 participants (25 female, age range 18–53 years, mean 24.7 years) of whom 24 had participated in Experiment 5a before.

Apparatus, stimuli, and procedure. The general setup was similar to the previous experiments, but we linearized the monitor output and presented the stimuli on a gray background (36 cd/m^2), without any frames (using the Psychtoolbox functions; Brainard, 1997). The only stimuli presented against the gray background were a central white fixation cross (turning green or red at the end of a trial to provide feedback), white word cues, and a Gabor target (3.2° × 3.2°, mean luminance 36 cd/m^2, contrast adjusted using an adaptive staircase method (see below), spatial frequency 10 cycles per image, σ = 0.4°, phase selected at random for each trial), presented in one of the quadrants (centered at eccentricities of 3.7°). The trial structure was the same as in Experiment 4, except that only the Gabor target was presented (for 33 ms), without any masks (see Figure 10).

Contrast thresholds were measured using running fit adaptive staircase methods (with a uniform prior distribution between log contrast −2 and 2, corresponding to the "best PEST"; Pentland, 1980) as implemented in the Palamedes toolbox (Prins & Kingdom, 2009). Four staircases with 80 trials each were set up, separately for the two cue conditions (Experiment 5a: cued vs. noncued; Experiment 5b: valid vs. invalid), and for cardinal versus oblique Gabor orientations. These four staircases were randomly interleaved, such that participants completed a total of 320 trials. The threshold for each staircase was taken as the mean of the posterior distribution.

Results and Discussion

There were significant main effects of Gabor orientation in both Experiment 5a, $F(1, 29) = 38.35$, $p < .001$, $\eta_p^2 = .57$, and in Experiment 5b, $F(1, 29) = 16.12$, $p < .001$, $\eta_p^2 = .36$, reflecting lower contrast detection thresholds for cardinal orientations (Experiment 5a: $M = 0.258$ log contrast, Experiment 5b: $M = 0.263$ log contrast) than for oblique orientations (Experiment 5a: $M = 0.308$ log contrast, Experiment 5b: $M = 0.301$ log contrast). More important, the cueing effect was significant in Experiment 5a, $F(1, 29) = 5.57$, $p = .025$, $\eta_p^2 = .16$ (Figure 11a), and in Experiment 5b, $F(1, 29) = 6.29$, $p = .018$, $\eta_p^2 = .18$ (Figure 11b), with lower contrast detection thresholds for validly cued than for noncued or invalidly cued Gabor targets. The two-way interactions between Gabor orientation and cueing was significant in Experiment 5a, $F(1, 29) = 4.81$, $p = .037$, $\eta_p^2 = .11$, reflecting the fact that the beneficial effect of prior orientation information was restricted to cardinal orientations, $F(1, 29) = 11.40$, $p = .002$, $\eta_p^2 = .28$, and was not found for oblique orientations, $F < 1$, $\eta_p^2 < .01$. This could mean that the built-up of orientation-specific expectations is more difficult for oblique orientations. However, no such significant interaction was found in Experiment 5b, $F < 1$, $\eta_p^2 < .01$, indicating that here the beneficial effect of prior information on contrast detection thresholds did not differ between cardinal and oblique Gabor orientations.

In summary, the results from Experiment 5 demonstrate that prior information of specific target orientations can boost contrast sensitivity in simple detection of a Gabor patch against a blank background. Again, this cueing effect was present both for the comparison of cued versus noncued trials in Experiment 5a ($M = 0.011$, $SD = 0.025$, 95% CI [0.001, 0.020], $d = 0.43$; Figure 11a) and for the comparison of valid versus invalid trials in Experiment 5b ($M = 0.012$, $SD = 0.027$, 95% CI [0.002, 0.022], $d = 0.46$; Figure 11b), ruling out a nonspecific beneficial effect of a word cue.

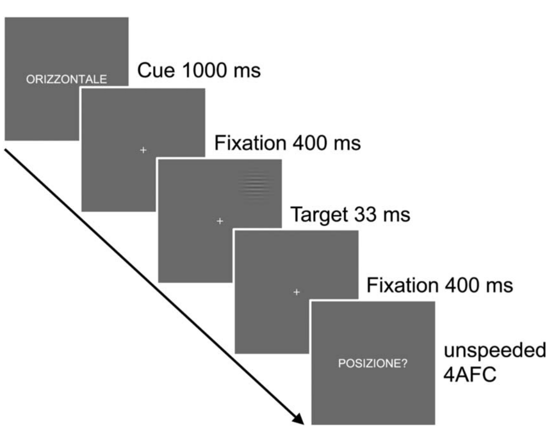

Figure 10. Schematic of an example trial from Experiment 5. At the beginning of a trial a word provided either no information, valid, or invalid information about the orientation of the Gabor patch that was subsequently presented in one quadrant. No masking was applied. The contrast of the target stimuli was adjusted using adaptive staircases. Participants indicated as accurately as possible, without speed pressure, in which quadrant the target stimulus was presented.

General Discussion

The present study was designed to test whether content-specific expectations can modulate initial visual perception. Whereas previous work has demonstrated that voluntary spatial attention can improve simple stimulus detection and localization (e.g., Carrasco et al., 2000; Theeuwes & Van der Burg, 2007; reviewed by Carrasco, 2011; but see Chica & Bartolomeo, 2012), it had remained unclear whether voluntarily attending to nonspatial stimulus information can similarly facilitate visual processing in such simple tasks (Lamy & Kristjánsson, 2013; Theeuwes, 2010, 2013). Our findings now provide comprehensive evidence that prior knowledge about stimulus content improves performance in simple stimulus localization and detection. We obtained this evidence using a range of different experimental approaches, including continuous flash suppression, sandwich masking, and measurements of contrast detection thresholds. Furthermore, we found similar benefits of advance information about the category membership of a to-be-localized object image and of prior knowledge of the orientation of a to-be-localized grating. Thus, top-down preparation to stimulus content represents a general mechanism that can operate on information of different levels of abstractness and enhances the initial perception of stimuli of different complexity, thereby determining whether a stimulus is detected.

A large body of previous research has demonstrated that prior information about a stimulus attribute improves performance in subsequent discrimination tasks on this attribute (reviewed by Carrasco, 2011) and facilitates difficult visual search where spatial attention has to be deployed serially to check whether a spatially attended target matches the search goal (e.g., Wolfe et al., 2004).

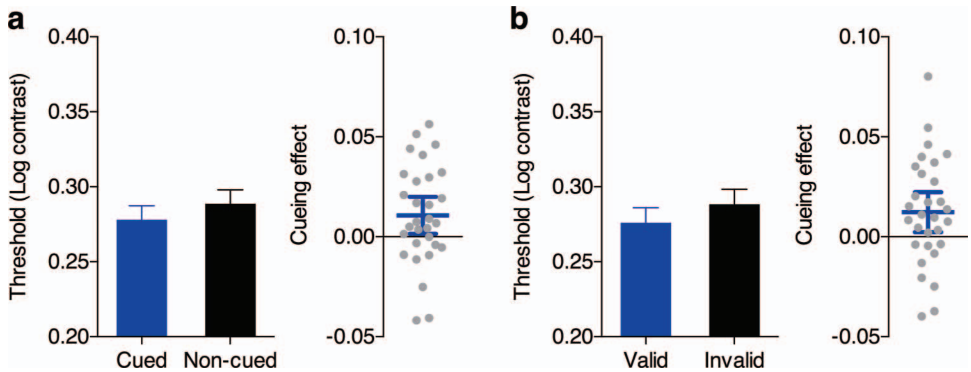

Figure 11. Results from (a) Experiment 5a and from (b) Experiment 5b. The left panels show mean contrast detection thresholds in the cued versus noncued condition (Experiment 5a) and in the valid versus invalid condition (Experiment 5b), respectively. Error bars represent the 95% confidence interval (CI) for the comparison between the two conditions. The right panels show the cueing effect (i.e., the difference in contrast detection thresholds between noncued/invalid and cued/valid conditions) for individual subjects. The blue horizontal bar denotes the group mean and the blue vertical bar the 95% CI. See the online article for the color version of this figure.

In these paradigms the beneficial influence of advance information about the to-be-discriminated stimulus content or about attributes of the search target could reflect an influence on processes occurring after the stimulus has been detected and localized by the observer. Therefore, these classical findings are not conclusive as to whether content-specific expectations can enhance the initial selection and perception of the stimulus, a process that is preceding more elaborate discriminations of the cued stimulus dimension. To test this early influence of content-specific top-down preparation one needs to adopt simple visual search tasks such as feature singleton visual search tasks (cf. Theeuwes, 2013), or simple detection or localization tasks. In these tasks the target is unique in that it cannot easily be confused with distractor stimuli, and performance thus reflects initial visual selection. Following this rationale, throughout the present experiments we used simple localization and detection tasks.[2] With the exception of the recording of suppression times under CFS in Experiment 1 all experiments used a nonspeeded spatial forced-choice task, such that we can be confident that our findings reflect the beneficial effect of content-specific expectations on perceptual sensitivity rather than on decisional, postselection processes that are susceptible to differences in response criteria.

More important, in the present study prior information about an object's category membership or a grating's orientation was provided through word cues. Thus, the cue did not contain a visual representation of the target. This is important because a visual representation of some features of the target can induce bottom-up priming effects. Indeed, the effects obtained in many previous studies that found evidence for expectation-enhanced detection or localization performance could have reflected such bottom-up priming rather than voluntary, top-down preparation (Theeuwes, 2010, 2013). The expectation-induced benefits obtained in the present experiments, by contrast, must reflect voluntary preparation to process visual information conforming to a mental representation induced by prior information provided by the word cue. Previous work that controlled for the contribution of bottom-up priming effects failed to find evidence for an influence of voluntary content-specific preparation in feature-singleton visual search paradigms (e.g., Theeuwes et al., 2006; Theeuwes & van der Burg, 2007). Although the designs of these visual search experiments and the paradigms adopted for the present study differ in various aspects, one key difference may account for the discrepant findings: These previous studies used "compound" visual search paradigms (e.g., Theeuwes, 1991) in which participants searched for a feature singleton defined by shape or color among distractors but responded to the orientation of a line segment inside the singleton stimulus. Top-down expectations were induced by providing participants with advance information about the specific dimension or feature of this pop-out singleton (and not about the oriented line inside the singleton). Although the orientation discrimination task can be very difficult and performance far below ceiling (Theeuwes & van der Burg, 2007), the feature singleton is presented well above the perceptual threshold (i.e., it pops out), such that measurements of localization performance for this singleton would yield ceiling performance even with very short presentation durations and masks. By contrast, in our b-CFS paradigm, in the sandwich-masking paradigm, and in the paradigm for measuring contrast detection thresholds, stimuli were shown at and around perceptual thresholds, that is, in our experiments the visibility of the cued stimulus was much lower than the visibility of the cued

[2] Note that in the literature using a signal detection theory (SDT) framework as well as in psychophysical studies on contrast detection thresholds accuracy in bias- or criterion-free temporal or spatial forced-choice tasks is considered as a measure of stimulus detectability similar to the criterion-free sensitivity measure d' in present-absent (yes/no) tasks, proportion correct obtained using temporal or spatial forced-choice tasks can be converted to d' scores (Macmillan & Creelman, 2005; see Table 1). In most of our experiments we used a spatial 4AFC task because research on the measurement of contrast detection thresholds indicates that 4AFC is the most efficient method for obtaining contrast detection thresholds in naïve subjects (Jäkel & Wichmann, 2006). Note that the terms "detection" and "detectability" are used in slightly different ways in other fields of psychology and vision science, sometimes referring more specifically only to present-absent tasks as implemented in the present Experiment 2d.

stimulus in these previous visual search studies. Thus, it seems possible that presenting target stimuli around perceptual thresholds is critical for unraveling the (modest) effect of top-down preparation on initial visual processing. Presenting the cued stimulus with very high bottom-up strength, such as a feature singleton in a pop-out search display, may leave insufficient room for boosting effective stimulus strength through content-specific expectations and the additional effect of top-down preparation may not be detectable. Please note that although we presented targets with lower bottom-up strength, performance in our tasks was not contaminated by postselection processes, as is the case in difficult serial visual search tasks.

While most previous work on the influence of explicit, content-specific top-down expectations has been carried out using visual search tasks or psychophysical discrimination tasks, another line of research has focused on how the perception of objects in naturalistic scenes is influenced by manipulations of semantic scene context, which can be considered a manipulation of implicit expectations. The presentation of a semantically congruent scene context leads to improved object categorization and identification (e.g., Palmer, 1975, reviewed by Henderson & Hollingworth, 1999), suggesting that such implicitly triggered expectations are associated with similar perceptual benefits as voluntary top-down preparation. However, studies using change detection procedures revealed better change detection for objects that were semantically incongruent rather than congruent with the background scene (e.g., Brockmole & Henderson, 2008; Hollingworth & Henderson, 2000; LaPointe, Lupianez, & Milliken, 2013). While this change detection advantage of semantically incongruent objects in photographs of natural scenes can be regarded as another demonstration of the influence of (implicit) expectations on initial object perception, it seems inconsistent with the advantage of objects with expected attributes in the current simple detection and localization paradigms. Thus, the opposing effects obtained with these different paradigms likely reflect distinct influences of scene congruency and voluntarily initiated expectations on the processing mechanisms underlying object detection: The change detection advantage for incongruent objects may be because of their greater potential to capture attention during the relatively long duration of stimulus presentation in change detection paradigms, possibly reflecting semantic conflict with the context scene or "semantic informativeness" (Hollingworth & Henderson, 2000; LaPointe et al., 2013). While the advantage of incongruent objects in change detection may thus reflect attentional shifts to local areas of the scene in which a semantic conflict with the background is detected (LaPointe et al., 2013), no such effect should be obtained in the present experiments in which only a single target stimulus was presented briefly and conditions did not differ with regard to local semantic conflict. Our findings show that in the absence of such semantic conflict in the input image, voluntary top-down preparation improves rather than impairs the initial perception of objects.

The results of the present study raise several new questions. First, to establish that top-down preparation has an effect on simple localization and detection, the key comparison in the present experiments was between valid prior information and the noninformative baseline condition. We ran a condition where we provided participants with invalid prior information mainly to exclude the possibility that the former comparison reflected nonspecific (e.g., alertness) differences. Future work could more systematically compare valid, noncued, and invalid conditions within participants to determine whether the cost of preparing for the wrong content is similar to the benefit of preparing for the correct content. A previous study using b-CFS suggests that this is in fact the case (Lupyan & Ward, 2013). Second, while we provide evidence that advance information about both more abstract, high-level stimulus content (object categories) and about more simple low-level properties (grating orientation) improves localization of high-level and low-level stimuli, respectively, future studies are needed to more directly study the nature and precision of the mental representations underlying such top-down preparation. While previous visual search studies sought to separate between processes underlying the preparation to basic features, feature dimensions, and objects (e.g., Meeter & Theeuwes, 2006; Müller, Reimann, & Krummenacher, 2003; Wolfe et al., 2003), the beneficial effect of prior information on to-be-detected object categories obtained in the present study could reflect either top-down preparation to detect category-diagnostic basic features or feature combinations or rather more abstract category-specific mental templates. Future studies could adopt newly developed attentional capture paradigms (Reeder & Peelen, 2013; Reeder, van Zoest, & Peelen, 2015) to gain insight into the mental representations observers form during the preparation phase. Similarly, by varying the exact match between prior information and the upcoming target stimulus future work could test the precision of these mental representations (i.e., would the detection of dogs benefit from prior information to detect a cat?). Another important avenue for future work lies in the comparison of the mechanisms involved in content-specific top-down preparation as investigated here and the mechanisms guiding voluntary spatial attention. For example, one possibility is that both processes are largely independent, with content-specific expectations enhancing initial visual processing across the visual field, even in spatially unattended locations (e.g., Peelen, Fei-Fei, & Kastner, 2009; reviewed by Maunsell & Treue, 2006).

Finally, neuroimaging work is necessary to address the neural mechanisms underlying the formation and perceptual consequences of content-specific expectations. Candidates for source regions involved in setting up a mental representation according to prior information include the posterior parietal cortex and the prefrontal cortex, whereas the actual template guiding visual detection may be instantiated in those visual areas that process stimulus contents that are part of the mental target representation (reviewed by Eimer, 2014; Peelen & Kastner, 2014). Thus, depending on the nature and precision of the observer's target representation lower- to higher-visual cortical areas will be recruited in the preparation phase. For example, the category cues used in the present experiments may lead to recruitment of both high-level, category-selective visual cortex (Peelen & Kastner, 2011; Summerfield, Egner, Greene, Koechlin, Mangels, & Hirsch, 2006) as well as lower-level visual areas that encode shape and orientation differences associated with object category, whereas orientation-specific prior information may rather recruit orientation-selective early visual cortex (Harrison & Tong, 2009; Kok et al., 2012; Kok, Failing, & de Lange, 2014; Serences, Ester, Vogel, & Awh, 2009). Such top-down recruitment does not need to be reflected in higher response amplitudes of the corresponding visual areas. Instead, the neural representation of expected stimulus content in visual areas may be associated with reduced activity but a sharpening of the distributed response across the area, consistent with theories of predictive coding (Kok et al., 2012). Whether the behavioral benefit of content-specific top-down expectations that facilitate initial stimulus detection has a similar neural correlate in lowered activity but improved distributed representation remains an important question for future studies.

In conclusion, the present study provides comprehensive evidence that object detectability, measured using localization and detection tasks, is influenced by internally generated expectations about object properties. These influences at least partly reflect changes in perceptual sensitivity. Thus, expectations do not only bias our interpretation and discrimination of visual stimuli but even influence whether a stimulus gains access to awareness in the first place. Content-specific expectations therefore partly determine which objects are perceived and which are missed, even when spatial attention is fully available, bringing our conscious experience of the world in line with what we expect.

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