Atten Percept Psychophys (2014) 76:489–507
DOI 10.3758/s13414-013-0580-4

Seeing is believing: Utilization of subliminal symbols requires a visible relevant context

Surya Gayet · Stefan Van der Stigchel · Chris L. E. Paffen

Abstract Sensory input that is not available for conscious report can still affect our behavior. Recent findings suggest that such subliminal information has the potency to influence behavior in a way that is dependent on the observer's current intentions. Here, we investigate whether conscious observation of stimulus relevance provides an incentive for the utilization of nonconscious stimuli. We manipulated the predictive power of directional cues to selectively affect the incentive to utilize them for a subsequent target detection task. Central arrow cues rendered invisible by interocular suppression elicited a facilitatory cuing effect, but only when intermixed with visible arrow cues that were highly predictive with respect to (i.e., 80 % congruent with) the subsequent target location. When the visible cues were nonpredictive (50 % congruent), no subliminal cuing effect was found. An analysis of learning effects corroborates these findings; Cuing effects elicited by both visible and invisible cues increased over the course of the experiment, but only when intermixed visible cues were highly predictive. In a second experiment, we demonstrated that the intrinsic relevance of invisible cues (either 50 % or 100 % congruent) has no effect on the utilization of visible cues. We conclude that conscious perception is required to make statistical inferences about the relevance of symbolic cues. Once statistical information is extracted consciously, it affects subsequent nonconscious processing in a way that fits the current context. Accordingly, one of the possible functions of consciousness could be to extract general rules out of the conscious information, to provide guidelines for future behavior.

Keywords Consciousness · Visual awareness · Subliminal processing · Task relevance · Symbolic cuing · Attention · Interocular suppression

Introduction

The world around us provides us with much sensory input, most of which will fail to reach our conscious experience. Even though this subliminal information is not available to conscious report, it is now widely believed that it can nonetheless influence our behavior (e.g., Eimer & Schlaghecken, 1998; Klotz & Neumann, 1999; Neumann & Klotz, 1994). It is still a matter of debate, however, how extensively this subliminal information is processed (for reviews, see Kouider & Dehaene, 2007; Lin & He, 2009). The traditional view holds that subliminal stimuli can influence behavior only in an acquired, automatic manner and are insensitive to volitional control (McCormick, 1997; Posner & Snyder, 1975; Schneider & Shiffrin, 1977). In this context, the physical properties of a stimulus directly influence behavior. This behavior includes phenomena such as attention shifts toward sudden unperceived onsets (for a review, see Mulckhuyse & Theeuwes, 2010) and stimulus–response mappings, where an invisible prime facilitates responding to a subsequent target with perceptual similarities after repeated motor responses to the visible target (Abrams & Greenwald, 2000; Damian, 2001). Recent lines of research, however, have shown that task relevance and goal directed control settings can modulate the way subliminal stimuli

---

Electronic supplementary material The online version of this article (doi:10.3758/s13414-013-0580-4) contains supplementary material, which is available to authorized users.

S. Gayet (✉) · S. Van der Stigchel · C. L. E. Paffen
Helmholtz Institute, Department of Experimental Psychology, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands
e-mail: S.Gayet@UU.nl

S. Van der Stigchel
e-mail: S.VanderStigchel@UU.nl

C. L. E. Paffen
e-mail: C.L.E.Paffen@UU.nl

affect behavior (Ansorge & Heumann, 2006; Ansorge & Neumann, 2005; Jaskowski, Skalska, & Verleger, 2003; Kiefer & Martens, 2010; Schlaghecken & Eimer, 2004). These results suggest that the way in which subliminal information influences behavior is dependent on the current cognitive state of the observer. Hence, effects of prime–target combinations might not be fixed but, rather, affect behavior differently, depending on the current task demands.

The potency of task relevance to affect nonconscious processing was recently demonstrated by Ansorge, Horstmann, and Worschech (2010). In this study, four colored stimuli were meta-contrast masked by four visible nonsingleton color stimuli. Participants were instructed to locate the target of a particular color and to report whether it was a diamond or a square. The masked stimulus at the target location either did or did not match the subsequent target color and was either a square or a diamond. The results showed that participants responded more quickly when the prime was valid (i.e., at the same position as the target), as compared with invalid (i.e., at a different position than the target). Interestingly, however, this effect was restricted to cues that matched the target color. These findings suggest that the masked color singletons captured attention when they matched the observers' task set (e.g., to "look for the red target") but failed to capture (stimulus-driven) attention when they were task irrelevant. Indeed, the masked cues elicited an N2pc—a negative event-related potential in the visual cortex contralateral to the location in space where a stimulus is attended (Luck & Hillyard, 1994)—in task relevant, but not in task irrelevant, trials. Hence, top-down incentives affected early processing of nonconsciously perceived stimuli.

The *contingent involuntary orienting* hypothesis (Folk, Remmington, & Johnston, 1992) provides a plausible framework for the results described above. Folk and colleagues argued that, under conditions of spatial uncertainty, a stimulus with a feature property that is critical to the performance of the task at hand (e.g., color) will incite involuntary attentional capture. Ansorge et al. (2010) showed that this involuntary orienting to task-relevant stimuli can occur even when these stimuli are not consciously perceived. The selective utilization of subliminal stimuli as depending on predetermined conditions can also be framed within the *action trigger* hypothesis (Kiesel, Kunde, & Hoffmann, 2007; Kunde, Kiesel, & Hoffmann, 2003). While Kunde and colleagues focused on motor priming rather than attentional priming, these two frameworks have much in common in terms of primed automaticity. According to the action trigger hypothesis, observers build up expectations with regard to specific (visible) stimuli, on the basis of prior experience or task instructions. Subsequently presented matching stimuli, referred to as *action triggers*, directly activate the corresponding response, irrespective of their conscious identification. In contrast to the framework of Folk et al., however, these stimuli are not required to perceptually match the subsequently presented supraliminal target. Rather, stimuli are categorized on a relevant cognitive dimension, on the basis of the current task demands. Thus, in our interpretation, whenever there is an incentive to use a stimulus—that is, when it forms an action trigger—the stimulus will trigger a response (e.g., attentional capture, eye movement, motor response, etc.). Conscious knowledge about the context in which a behavior is performed, provides an incentive to utilize visual information. This information, whether consciously perceived or not, then affects behavior in a way that fits the current cognitive context.

In the present study our aim was to investigate whether the utilization of subliminal symbolic cues is dependent on contextual knowledge. To this end, participants performed a peripheral target detection task with either visible or suppressed central arrow cues. While the suppressed arrow cues were always 50 % congruent with, and therefore not predictive for, the subsequent target location, the visible arrow cues were either nonpredictive (50 % congruent) or highly predictive (80 % congruent). In the latter case, the predictive value of the supraliminal (visible) arrow cues provided an incentive to utilize arrow cues, which was expected to result in shorter reaction times (RTs) on congruent, as compared with incongruent, trials (Posner, 1980). On the basis of the idea of action triggers, we predicted that the visible arrow cues would form a cognitive context in which an arrow predicts the location of the subsequent target. By this, the arrows become action triggers, leading to faster responses on congruent trials even when invisible—that is, when they do *not* predict the subsequent target location.

Our methodology was motivated by two main considerations. First, we aimed to investigate whether prime–target congruency effects of subliminal primes extend to cases without perceptual similarities between the prime and the target. This is important since identical prime–target pairs are known to facilitate responding (Bodner & Dypvik, 2005; Koechlin, Naccache, Block, & Dehaene, 1999), a phenomenon known as repetition priming. In the aforementioned study by Ansorge et al. (2010), special care was taken to avoid repetition priming by instructing participants to look for either of two colors. Cuing effects were still observed when the cue and the target were of different colors. However, the cue was part of the "to-be-searched-for" task set: for instance, participants were instructed to look for the blue or red stimulus and subsequently report its shape. In the present study, participants were instructed to react to a peripheral target (requiring spatial information) and were, therefore, not predisposed to react to the central cue (providing symbolic information). Rather than being perceptually similar, the cue and the target had a semantic (or symbolic) relation. Whether the information contained in the cues appeared to be advantageous for subsequent behavior depended on the statistical context.

The second and important consideration was that we aimed to show that a subliminal stimulus can affect behavior when it is, in itself, not informative for the task at hand. For this purpose, we manipulated the incentive to utilize the subliminal cues by altering the statistical context in which they were embedded, without altering the predictive value of the subliminal cues themselves. Recently, Reuss, Pohl, Kiesel, and Kunde (2011) conducted a study with intermixed unmasked and metacontrast masked arrow cues. This study revealed a facilitatory cuing effect of 7 ms when cues were predictive, but not when cues were nonpredictive. However, the predictive value of both the masked cues and the unmasked cues was manipulated simultaneously. As such, it was unclear whether conscious observation of cue validity was required for nonconscious cue utilization to occur, or whether the validity in itself was enough to promote subliminal cue utilization (see the "General Discussion" section for further elaboration on this point). In the present experiment, subliminal arrow cues had no predictive value (i.e., they were 50 % congruent with the subsequent target location) in either the predictive or the nonpredictive condition. The only factor that varied was the incentive to utilize these cues, on the basis of the predictive value of the intermixed supraliminal arrow cues. Using this method, we aimed to isolate the effect of cognitive context on the utilization of information presented outside of visual awareness.

To render cues invisible, we used flash suppression (Wolfe, 1984), which is derived from the phenomenon of binocular rivalry (for reviews, see Alais & Blake, 2005; Blake, 2001). Binocular rivalry occurs when each eye of an observer views a different image (e.g., a car for the left eye and a house for the right eye). In this situation, perception will alternate between the two images. Crucially, the image presented to one eye (the suppressed eye) is erased from perceptual awareness, while still impinging on the retina. Even though invisible, the suppressed image elicits substantial activity in dorsal areas (Fang & He, 2005) and, in some cases, in ventral areas (Jiang & He, 2006) or the amygdala (Williams, Morris, McGlone, Abbott, & Mattingley, 2004; Pasley, Mayes, & Schultz, 2004). In terms of behavior, suppressed stimuli can trigger eye movements (Rothkirch, Stein, Sekutowicz, & Sterzer, 2012), direct orientation-specific grasping (Roseboom & Arnold, 2011), and affect behavior performed on targets presented to the nonsuppressed eye (e.g., Stuit, Paffen, van der Smagt, & Verstraten, 2011), despite the complete absence of conscious experience. The potency of suppressed stimuli to affect behavior makes binocular rivalry, and the different methodologies derived from this phenomenon, an ideal tool for uncovering the mechanisms of conscious and nonconscious visual processing (Koch, 2004).

This masking method has three major advantages over backward masking, a widely used method to block stimuli from visual awareness. First, the total retinal input between the supraliminal and the subliminal condition can be kept more similar; in backward masking, either an extra stimulus (the mask) has to be added, or the onset asynchrony between the mask and the target has to be shortened in the subliminal condition, as compared with the supraliminal condition. Although a (contra-ocular) stimulus is needed to suppress a target with flash suppression as well, this "suppressor" can be presented to the background (ipsi-ocular) in supraliminal trials. Hence, the presentation chronology is constant between visibility conditions. Second, the subliminal cue can be presented for up to several seconds without reaching awareness, as compared with less than 50 ms with backward masking (e.g., Breitmeyer, 2007). Third, in most models, interocular suppression is accounted for by reciprocal inhibition of eye-selective channels (Blake, 1989; Tong, 2001; Tong, Meng, & Blake, 2006). As such, the feedback of information to lower visual areas remains largely uninterrupted under interocular suppression (Macknik & Martinez-Conde, 2004), whereas it is disrupted by backward masking (Di Lollo, Enns, & Rensink, 2000; Lamme & Roelfsema, 2000). Disrupting these feedback connections might limit processing of subliminal stimuli to simpler visuo-motor processes, for which only feedforward connections are needed (Lamme, 2001). Similarly, while CFS largely spares V1 spiking responses to suppressed stimuli (Wilke, Logothetis, & Leopold, 2006), backward masking interferes more with V1 spiking activity (Macknick & Martinez-Conde, 2004). As such, backward masked stimuli elicit a weaker signal in the early visual cortex than do interocularly suppressed stimuli, thereby reducing its capacity to affect subsequent behavior (Bargh & Morsella, 2008; Hassin, 2013; Sweeny, Grabowecky, & Suzuki, 2011).

Recently, Al-Janabi and Finkbeiner (2012) conducted a similar experiment using eye-gaze cues and showed that backward-masked gaze cues produced a cuing effect only when they appeared in the context of highly valid unmasked gaze cues. When intermixed unmasked cues were nonpredictive, no cuing effect was observed for the masked cues. Although gaze cues and arrow cues both affect attention orienting when they are uninformative of the subsequent target location (Ristic, Friesen, & Kingstone, 2002), gaze cues seem to draw on the reflexive component to a greater extent than do arrow cues, the latter being more strongly influenced by volitional control. For instance, the more reflexive nature of gaze cues is supported by the finding that counterpredictive gaze cues still elicit validity effects in the cued direction, whereas counterpredictive arrow cues do not (Friesen, Ristic, & Kingstone, 2004). Another argument comes from studies on inhibition of return (IOR), a phenomenon known to occur exclusively when attention is captured exogenously (Godijn & Theeuwes, 2004; Klein, 2000; Posner & Cohen, 1984). Under conditions of brief exposure, gaze cues can elicit IOR

(Frischen, Smilek, Eastwood, & Tipper, 2007; Frischen & Tipper, 2004). In contrast, more endogenous cues, such as arrows, do not elicit IOR (Posner & Cohen, 1984; Rafal, Calabresi, Brennan, & Sciolto, 1989). Furthermore, uninformative central arrows shorten detection times on subsequent targets to a greater extent when they are presented as task-relevant rather than task-irrelevant cues (e.g., Pratt & Hommel, 2003). Within the same experimental setup, however, the task relevance assigned to gaze cues does not affect subsequent target detection times (Ristic, Wright, & Kingstone, 2007). Hence, in contrast to arrow cues, gaze cues are not influenced by top-down volitional control. Accordingly, neuroimaging studies revealed that attentional orienting induced by arrow cues is more related to dorsal fronto-parietal systems (Corbetta & Shulman, 2002; Hietanen, Leppänen, Nummenmaa, & Astikainen, 2008) associated with voluntary shifts of attention, whereas gaze-induced attentional orienting relies more on ventral fronto-parietal (Corbetta & Shulman, 2002; Hietanen et al., 2008) and oculomotor (Nummenmaa & Hietanen, 2006) systems associated with involuntary shifts of attention. These studies have therefore shown that gaze cuing is based on a strong exogenous component, which is in contrast to the effect of arrow cues, which are strongly influenced by volitional control. Whereas a wealth of studies has shown cuing effects of masked exogenous cues, the present study aimed to test whether a predominantly endogenous cue, which requires intention and interpretation, affects subsequent target detection when it is not consciously perceived.

Experiment 1

The aim of Experiment 1 was to investigate whether symbolic cues can elicit cuing effects in the absence of visual awareness—specifically, when current task settings provide an incentive for cue utilization. In the supraliminal condition, in which the arrow cues were visible, it was expected that both highly predictive (e.g., Folk et al., 1992; Jonides, 1981; Yantis & Jonides, 1990) and, to a lesser extent, nonpredictive (Hommel, Pratt, Colzato, & Godijn, 2001; Tipples, 2002) arrow cues would provide facilitation in a target detection task. Subliminally presented arrow cues, however, were expected to facilitate target detection only if the supraliminal arrow cues were sufficiently informative. This would show that subliminal cue utilization is selective to situations in which the cognitive context provides an incentive to use them. Furthermore, we investigated the time course within which cuing effects tend to increase or decrease as a function of the (visible) informative value of the cues.

Subliminal cues were kept outside of perceptual awareness using (interocular) flash suppression, in which a high-contrast mask presented to one eye suppresses awareness of the stimulus presented to the other eye. Recent studies using various forms of interocular suppression have shown that nonconsciously presented monocular (peripheral) cues can affect RTs to visible target stimuli in the nonsuppressed eye (e.g., Jiang, Costello, Fang, Huang, & He, 2006; Self & Roelfsema, 2010; Zhaoping, 2008), making it an ideal method to elicit cuing effects with invisible stimuli.

The cuing method was based on that of Hommel et al. (2001), who used isosceles triangles with a 2:1 length-to-width ratio acting as central arrow cues. Leftward- and rightward-pointing triangles were superimposed to form an elongated "star of David" on the side (see Fig. 1). At cue onset, three portions of the overlapping triangles were removed, such that a single arrow cue remained. Both triangles intersected at the centroid on the center of fixation, such that all triangle stimuli (star and arrows) had equal perceptual weight on both sides of the fixation cross. This ensured that cuing effects would originate from the symbolic meaning of the arrow cue, rather than reflect an exogenous shift of attention caused by a change in the center of mass.

The star stimulus was presented to one eye, to initiate ocular dominance and enhance the strength of the subsequent flash suppressor presented to the other eye (Tsuchiya, Koch, Gilroy, & Blake, 2006). The target was presented to the eye that was made dominant by means of the flash suppression, since pop-out stimuli in a specific eye during binocular rivalry are known to enhance dominance of the ipsi-ocular percept (Ooi & He, 1999). The complete sequence of events in a trial is depicted in Fig. 1.

Method

Participants

Nineteen students from Utrecht University, 19–36 years of age ($M = 23.4$ years, $SD = 4.36$), signed informed consent before participating for course credits or payment. All participants were right-handed, had normal or corrected-to-normal vision, and were tested for stereoscopic vision (TNO test for stereoscopic vision, 12th edition; Laméris Ootech b.v., 1972).

Apparatus and stimuli

All experiments were conducted in a dimly lit room, using an Apple dual 2-GHz PowerPC G5, fitted with a linearized 22-in. LaCie Electron blue IV CRT monitor (1,024 × 768; 100 Hz) and an Apple keyboard, which was used for response registration. Stimulus presentation and response collection were managed using the Psychophysics Toolbox 3 (Brainard, 1997; Pelli, 1997) in MATLAB R2010a (The Mathworks, Natick, MA). The participant's head was supported by a chinrest, on which a dichoptic mirror setup was mounted. This resulted in an effective viewing distance of 57 cm.

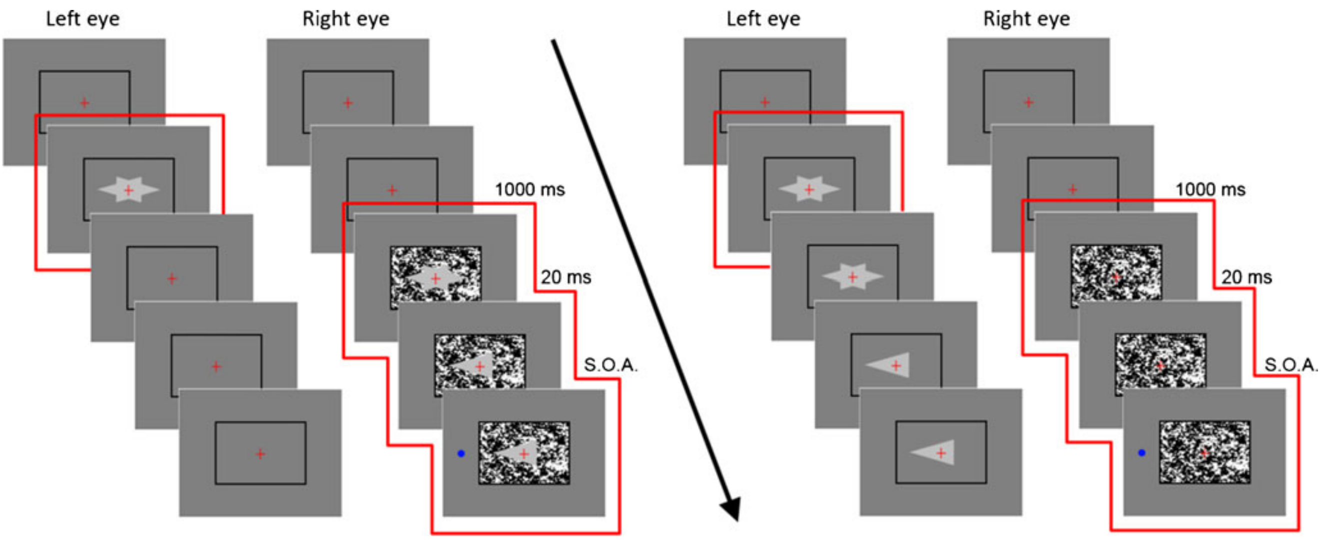

Fig. 1 Sequence of events in supraliminal (left) and subliminal (right) trials. The red line indicates the dominant percept. Target and cue remained on screen until a response was given

All stimuli were presented on a uniform gray background with a luminance of 28.6 cd/m^2. In order to facilitate binocular fusion of the two complementary images, a black frame (91 % Weber contrast) that subtended a visual angle of 5.8° × 5.8° was presented to each eye during the entire experiment. Flash suppression masks were created by (1) filtering pink (1/f) noise by a rotationally symmetric Gaussian low-pass filter (sigma = .3) and by (2) making the resulting grayscale image binary with maximum contrast (91 % Michelson). A new mask was generated on every trial. The gray arrow cue (luminance of 32.7 cd/m^2 and length of 2.3° of visual angle) had a Weber contrast of 14 % with the background and of 29 % with the mask. The blue target stimulus (8.27 cd/m^2, $x = .168$, $y = .094$) had a radius of 0.2° of visual angle, a Weber contrast of 71 %, and an eccentricity of 3.8° of visual angle with respect to the red fixation cross (10.4 cd/m^2, $x = .590$, $y = .357$).

Design and procedure

All participants took part in two experimental conditions (with nonpredictive and with predictive visible cues) on different days and a control experiment at the end of the second day. The order of conditions was counterbalanced across participants. All experimental factors (visibility of the cue, predictive value of the cue, stimulus onset asynchrony) and balancing conditions (suppressed eye, target location) were fully counterbalanced within participants. The number of trials per condition is given in Table 1.

The experiments consisted of a target detection task, for which participants were instructed to respond as quickly and accurately as possible to the location of a blue dot, by means of the left and right arrow keys. This target appeared either to the left or to the right of fixation and was preceded by a central arrow cue. Participants were informed about the predictive value of visible arrow cues but were naïve with respect to the existence of subliminal arrow cues. The visible arrow cues (75 % of the trials) were either nonpredictive (50 % congruent) or highly predictive (80 % congruent), whereas the suppressed arrow cues (25 % of the trials) were always nonpredictive. The main purpose of the visible trials was to form a statistical incentive to utilize arrow cues, by creating an experimental context in which arrow cues appeared either predictive of the subsequent target location or not. Therefore, the trials that were used for the manipulation of statistical information outnumbered the (nonpredictive) subliminal trials.

On both sessions, participants first took part in a 24-trial practice block before starting the six experimental blocks of 160 trials each. After the second session, participants performed an additional 120 trials in a control experiment that verified whether masked cues were indeed invisible. Stimulus presentation and counterbalancing were identical to those in the experimental task, but only subliminal trials were performed. Participants were explained that they would see a mask and that, after a while, an arrow would appear. They were instructed to detect as quickly and accurately as possible the direction in which the arrow pointed and report it by means of the left and right arrow keys. A trial was aborted whenever participants failed to respond within 6 s.

Temporal differences in subliminal and supraliminal processing of emotional stimuli (e.g., Lidell, Williams, Rathjen, Shevrin, & Gordon, 2004; Williams et al., 2004) and between endogenous and exogenous cuing (e.g., Egeth & Yantis, 1997; Mulckhuyse & Theeuwes, 2010) suggest that subliminal stimuli might be processed in a different time course than supraliminal stimuli. Therefore, different onset asynchronies (SOAs) between cue and target stimulus were implemented: 100, 500, and 900 ms.

Table 1 Overview of trials per condition for each stimulus onset asynchrony

Condition	Nonpredictive				Predictive			
Cue visibility	Visible		Invisible		Visible		Invisible	
	240		80		240		80	
Congruency	Con.	Incon.	Con.	Incon.	Con.	Incon.	Con.	Incon.
	120	120	40	40	192	48	40	40

Trial selection and inclusion criteria

Determining the effects of visual processing outside of awareness requires dissociating subliminal and supraliminal stimuli. This should be done with special care when, as in the present experiment, the subliminal stimuli are expected to influence behavior in the same direction as the supraliminal stimuli (i.e., a quantitative rather than qualitative dissociation). Therefore a number of precautions have been taken to make sure a genuine subliminal effect was measured.

First, since suppression durations in flash suppression are relatively short-lived, it is important to verify that the flash suppressed cues remained unseen until the target response is initiated. Thus, for each participant, suppression durations of subliminally presented cues should be assessed and compared with the participant's RTs on subliminal trials. For this purpose, a particularly stringent control task (discussed in the "Design and Procedure" section and further elaborated in the "General Discussion" section) was implemented in which participants were required to report the direction of the *cue* as quickly as possible, rather than the location of the target. Since cues preceded targets in the main experiment, longer RTs in response to suppressed cues in the control experiment, as compared with visible targets in the main experiment, would indicate that the subliminal cues in the main experiment were not consciously perceived. Subliminal trials with the longest RTs in the experiment pose a bigger threat of being "infected" with consciously perceived arrow cues. Therefore, for each participant, RTs in the main experiment (target detection) longer than the 5th percentile RT in the control task (i.e., the 5 % shortest RTs in cue detection) were removed (the rightmost gray area in Fig. 2). The onset of a monocular stimulus—in this case, the target—can affect the duration of interocular suppression (Ooi & He, 1999). Therefore, the threshold was calculated for each SOA condition separately.

Second, to retain comparable RT distributions between participants, all participants for which this procedure would result in discarding more than 5 % of their trials (i.e., who might have perceived more than 5 % of the cues in the subliminal condition) were excluded from further analyses.

Third, when analyzing the presence of cuing effects (i.e., the difference between RTs on congruent trials and RTs on incongruent trials) in the subliminal conditions, we took into account the fraction of potentially unsuccessfully suppressed cues (i.e., the black area in Fig. 2). This fraction was based on the RTs in the control experiment (cue detection). For instance, if all RTs in the cue detection task were longer than the longest RT in the target detection task (subliminal condition), this gives an estimated 0 % "infected" cues. Accordingly, if the overlap was larger than 5 %, this gives an estimated 5 % "infected"' cues. Note that 5 % is the maximum, since all experimental RTs longer than this threshold were removed. These cues, for which suppression possibly failed, can be expected to elicit a cuing effect that is, at most, similar in magnitude to the cuing effects of supraliminally presented cues. To compensate for this spurious effect, we subtracted the cuing effect of supraliminal cues, multiplied by the estimated fraction of unsuccessfully suppressed cues, from the cuing effect elicited by subliminal cues. This was done on an individual participant basis. For instance, one (purely illustrative) participant had an estimated 3 % trials with unsuccessfully suppressed cues in the SOA 500 condition. Computation of the participant's median RTs revealed a cuing effect (incongruent vs. congruent RT) of 70 ms in the SOA 500 supraliminal condition and of 15 ms in the SOA 500 subliminal condition. Thus, this participant's subliminal cuing effect in the SOA 500 condition was corrected to $15 - (70 * .03) = 12.9$ ms for the analysis of cuing effects over all participants. As such, if the analyses reveal facilitatory cuing effects of cues in the subliminal condition, this effect could not be the result of "infected" (i.e., unsuccessfully suppressed) cues.

Results

Analyses

The "Results" section comprises an analysis of the control task, an analysis of cuing effects, an analysis of learning effects, and analyses of RTs and accuracy. All analyses are conducted using IBM SPSS Statistics 19 and start with a full factorial repeated measures ANOVA. When three-way interactions are found, subsequent ANOVAs are conducted for each SOA condition for a better understanding of the mutual relation between factors. If these new analyses reveal interactions, paired-sample *t*-tests are then used to determine the source of the interactions. Finally, one-sample *t*-tests are conducted to assess in which conditions RTs are affected by

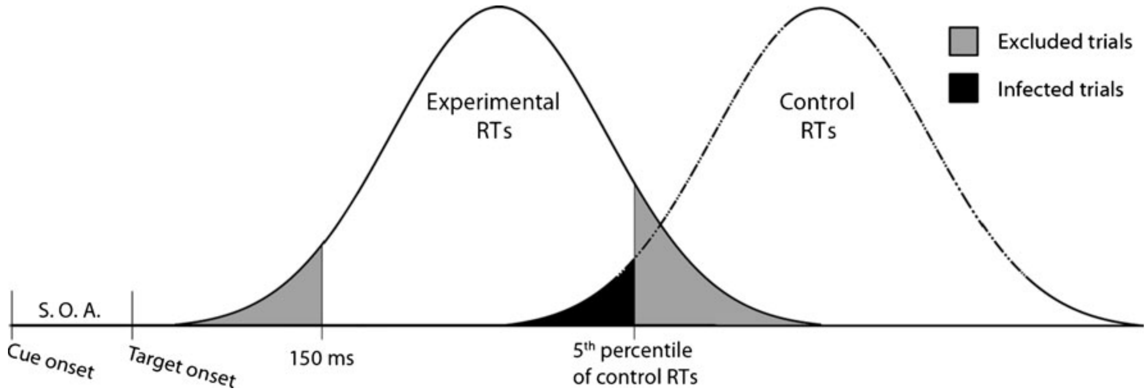

Fig. 2 Schematic representation of reaction time (RT) distributions on subliminal trials. Experimental RTs reflect the target detection times on subliminal trials in the experimental phase, whereas Control RTs reflect the detection time of arrow directions in the control task

the factors included in our design (i.e., whether our experimental manipulations affect cuing).

Control condition

The control condition was used to assess participants' detection times of the direction of subliminal arrow cues. Comparing cue detection times with RTs in the experimental blocks gives a conservative estimate of the fraction of subliminally presented cues that were consciously perceived during the experiment. On the basis of the RTs in the control task, for many participants, an SOA of 900 ms appeared to be too long to exclude the possibility that some suppressed arrow cues were consciously perceived. This SOA condition was therefore excluded from further analyses. Applying the exclusion criteria on the data of the SOA 100 and SOA 500 conditions resulted in the exclusion of 6 out of 19 participants.

The results of the control task are depicted in Fig. 3. Participants included in the analysis were unable to detect 22.4 % of the arrow directions within 6 s, while 0.5 % of the trials on which participants responded within 6 s yielded an incorrect response. Consequently, 77.1 % of the cues were accurately detected (M = 2.5 s, SD = 1.3) within the time limit. On the basis of the participants' performance on the control task and their RTs on subliminal trials of the actual experiment (the two distributions in Fig. 2), the estimate of consciously perceived arrow cues in the subliminal condition of the experiment (the black area in Fig. 2) was 2.1 % in the SOA 500 condition and 0.8 % in the SOA 100 condition. Mean detection times in the control task did not differ between different SOAs, $t(12)$ = .481, p = .64, d = .13, suggesting comparable suppression length of subliminal cues in both SOAs. Finally, the difference between the blocked presentation of subliminal stimuli, as used in the control experiment, and intermixed presentation (with supraliminal trials intermixed), as used in the main experiments, was found to have no impact on suppression durations (see Supplementary Materials 1).

Cuing effects

Trials on which participants reported an incorrect location of the target (0.9 %), trials with RTs shorter than 150 ms (0.2 %), and trials with RTs longer than the participants 5th percentile RT on the control task (2.9 %; varying between 0 % and 5 % for individual participants) were excluded from RT analyses. Subsequently, cuing effects were computed by subtracting RTs on congruent trials from RTs on incongruent trials. All cuing effects are depicted in Fig. 4. A positive cuing effect reflects facilitation in target detection elicited by the cues (i.e., shorter RTs on congruent as compared with incongruent trials). Conversely, negative cuing effects would reflect inhibition. Before analyzing which conditions led to significant cuing effects, we first assess whether the difference in RT between congruent and incongruent trials is different for different SOAs. An overall factorial 2 × 2 × 2 repeated measures ANOVA was conducted, with the factors SOA (100 and 500 ms), cue visibility (subliminal and supraliminal), and cue relevance (predictive and nonpredictive). This analysis revealed main effects of SOA, $F(1, 12) = 24.05$, $p < .001$, $\eta^2 = .67$, relevance, $F(1, 12) = 21.52$, $p = .001$, $\eta^2 = .64$, and visibility, $F(1, 12) = 58.75$, $p < .001$, $\eta^2 = .83$. These effects reflected that longer SOAs elicited a stronger cuing effect than did shorter SOA's, highly predictive cues elicited a stronger cuing effect than did nonpredictive cues, and visible cues elicited a stronger cuing effect than did subliminal cues.

There was an interaction effect between SOA and relevance, $F(1, 12) = 9.35$, $p = .010$, $\eta^2 = .44$, between SOA and visibility, $F(1, 12) = 18.42$, $p = .001$, $\eta^2 = .61$, and between relevance and visibility, $F(1, 12) = 66.03$, $p < .001$, $\eta^2 = .85$, showing that cuing effects depended on the factors included in this design: predictive value of the visible

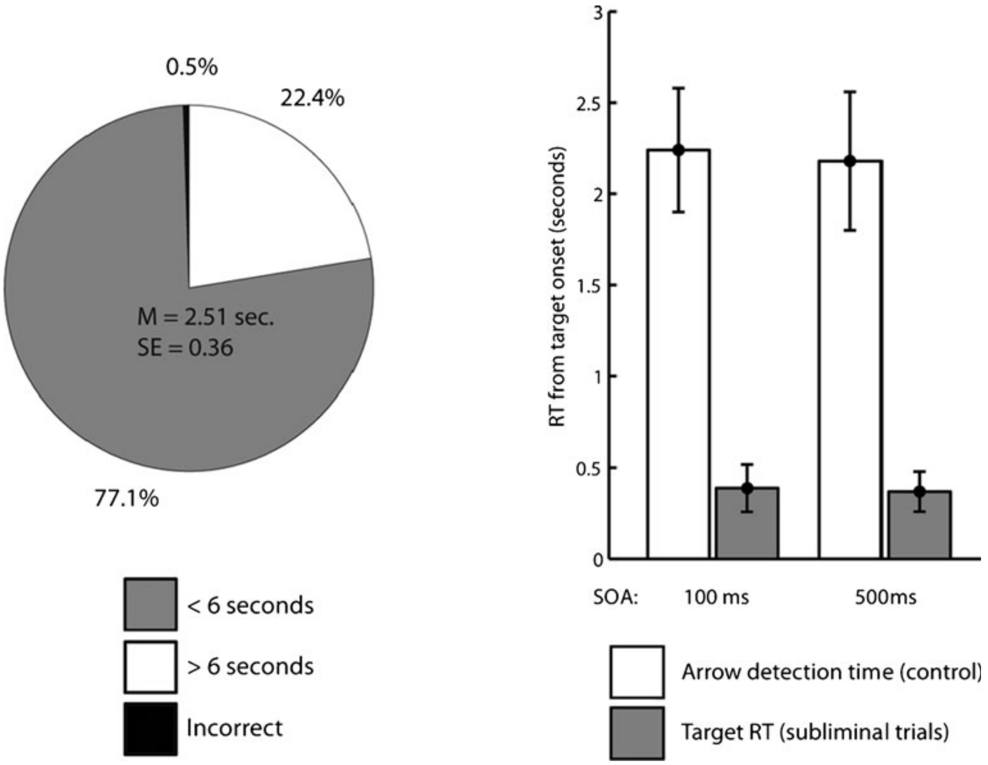

Fig. 3 Results of the control task. Left: The cue remained invisible for 6 s on 22.4 % of the control trials, while its direction was identified correctly within 2.51 s on 77.1 %. Right: Correct arrow detection times in the control task compared with target detection times on subliminal trials

cues, visibility of the cues, and SOA. To further examine these effects subsequent repeated measure analyses were conducted for the 100-ms and 500-ms SOA conditions separately, with cue relevance and cue visibility as within-subjects factors.

SOA 100 condition

The data from the SOA 100 condition is depicted on the left part of Fig. 4. There was a main effect of cue visibility, such

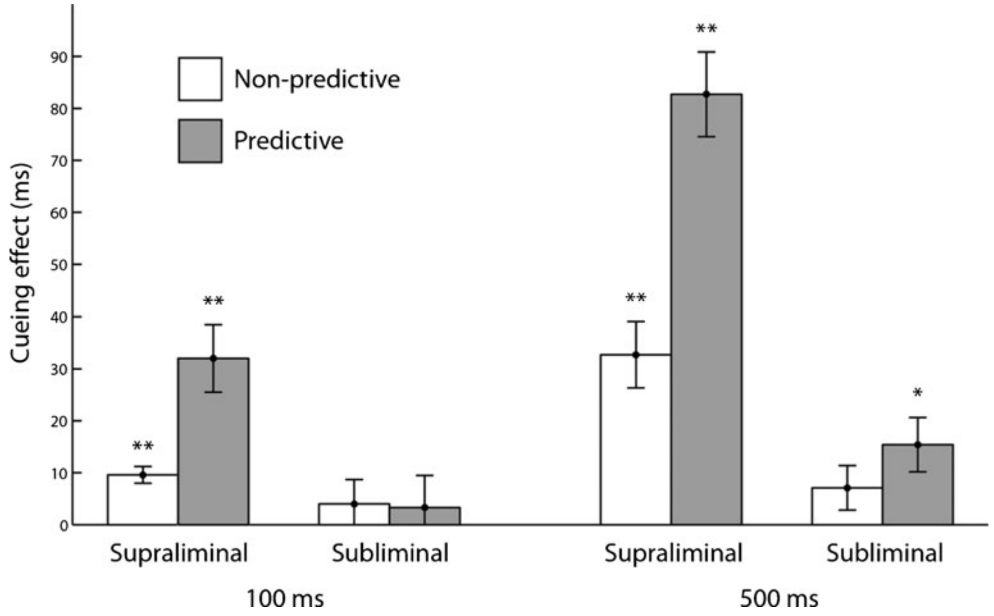

Fig. 4 Cuing effects in all experimental conditions. Cuing effects were calculated by subtracting reaction times (RTs) on trials with congruent cues from RTs on trials with incongruent cues. Positive cuing effects reflect facilitation. Error bars depict the standard error of the mean. * $p < .05$, ** $p < .005$

that supraliminal cues elicited more facilitation than did subliminal cues, $F(1, 12) = 12.11$, $p = .005$, $\eta^2 = .50$. Although there was no significant main effect of cue relevance, $F(1, 12) = 3.24$, $p = .097$, $\eta^2 = .21$, an interaction was found between cue relevance and cue visibility, $F(1, 12) = 6.10$, $p = .029$, $\eta^2 = .34$, such that in the supraliminal condition, predictive arrow cues (*M* = 32.0 ms, *SD* = 23.4) elicited stronger cuing effects than did nonpredictive arrow cues (*M* = 9.6 ms, *SD* = 5.8), $t(12) = 3.25$, $p = .007$, $d = .90$, whereas cuing effects on subliminal trials did not differ between relevance conditions, $t(12) = -.08$, $p = .938$, $d = -.02$. These findings show that even with SOAs as short as 100 ms, the predictive value of the cue affects supraliminal cue utilization.

Additional one-sample *t*-tests revealed that supraliminal cues in the predictive, $t(12) = 4.94$, $p < .001$, $d = 1.37$, and nonpredictive, $t(12) = 5.98$, $p < .001$, $d = 1.66$, conditions facilitated response RTs, whereas subliminal cues in the predictive, $t(12) = .54$, $p = 6.0$, $d = .15$, and nonpredictive, $t(12) = .85$, $p = .41$, $d = .23$, conditions did not elicit facilitation. Thus, with an SOA of 100 ms, subliminal stimuli did not affect behavior, irrespective of the predictive value of the subliminal cues.

SOA 500 condition

Another repeated measures ANOVA with visibility and relevance as within-subjects factors revealed that in the 500-ms SOA condition, supraliminal presentation led to stronger cuing effects than did subliminal presentation, $F(1, 12) = 65.14$, $p < .001$, $\eta^2 = .84$, and predictive cues led to stronger cuing effects than did nonpredictive cues, $F(1, 12) = 45.13$, $p < .001$, $\eta^2 = .79$. Also, these two factors interacted, $F(1, 12) = 38.06$, $p < .001$, $\eta^2 = .76$, such that supraliminal cues elicited stronger cuing effects in the predictive than in the nonpredictive condition, $t(12) = 7.65$, $p < .001$, $d = 2.12$, whereas cuing effects on subliminal cues did not differ in magnitude between relevance conditions, $t(12) = 1.97$, $p = .073$, $d = .55$.

Importantly, subsequent one-sample *t*-tests revealed that supraliminal cues elicited facilitation when they were both predictive (*M* = 82.7 ms, *SD* = 29.4), $t(12) = 8.86$, $p < .001$, $d = 2.81$, and nonpredictive (*M* = 32.7 ms, *SD* = 23.1), $t(12) = 5.04$, $p < .001$, $d = 1.42$. In the subliminal condition, however, the predictive cues (*M* = 15.6 ms, *SD* = 18.7) elicited facilitation, $t(12) = 2.95$, $p = .012$, $d = .82$, whereas the nonpredictive cues (*M* = 7.1 ms, *SD* = 15.5) did not, $t(12) = 1.66$, $p = .123$, $d = .46$. These effects show that subliminal arrow cues elicit facilitation only when intermixed supraliminal cues reliably predict the subsequent target location. Note that all *t*-tests of cuing effects in and between subliminal conditions were performed using the corrected subliminal cuing effects (see the "Trial Selection and Inclusion Criteria" section for a description of this correction method). These corrections consisted of a reduction of cuing effects between 0 and 3.1 ms for individual participants (*M* = 1.9 ms, *SD* = 1.1) in the subliminal predictive condition and between 0 and 1.1 ms for individual participants (*M* = .5, *SD* = .4) in the subliminal nonpredictive condition.

Learning effects

The analysis of cuing effects revealed a significant effect of subliminal facilitation in the predictive condition, whereas no such effects approached significance in the nonpredictive condition. This cuing effect might have come about by task instructions that elicited a top-down incentive to either utilize or ignore arrow cues. If this were the case, cuing effects in subliminal conditions would have been present from the start and remained constant throughout the entire experiment. Alternatively, the utilization of arrow cues might have been based upon statistical evidence of the predictive value of the cue, which is accumulated throughout the experiment. The latter predicts that cuing effects on subliminal trials would increase throughout the experiment. To dissociate between these two possible origins of subliminal cuing effects, we analyzed whether cuing remained constant or increased throughout the course of the experiments. That is, we assessed whether learning occurred within an experimental session, as a function of cue relevance.

Due to the large number of counterbalanced factors, not all conditions were equally represented in each block. Rather, the whole design was repeated twice, as a result of which the first half (blocks 1–3) and the second half (blocks 4–6) were fully counterbalanced. Therefore, cuing effects were compared between the first half and the second half of both experimental sessions, by computing learning effects (i.e., cuing effect in blocks 1–3 subtracted from cuing effect in blocks 4–6). These are depicted in Fig. 5.

In the 100-ms SOA condition, no learning effects were observed. For supraliminal trials, neither the predictive condition, $t(12) = .287$, $p = .779$, $d = .08$, nor the nonpredictive condition, $t(12) = -.658$, $p = .523$, $d = -.18$, yielded significant learning effects. Similarly, for subliminal trials, neither the predictive, $t(12) = -.452$, $p = .659$, $d = -.13$, nor the nonpredictive, $t(12) = -.708$, $p = .493$, $d = -.20$, condition yielded learning effects. In the 500-ms SOA condition, however, there was a main effect of relevance, $F(1, 12) = 22.02$, $p = .001$, $\eta^2 = .65$, such that stronger learning effects were observed in the predictive than in the nonpredictive condition. This learning effect did not depend on cue visibility, since there was no main effect of visibility, $F(1, 12) = 1.27$, $p = .282$, $\eta^2 = .10$, nor was there an interaction between visibility and relevance on learning effect, $F(1, 12) = 2.55$, $p = .136$, $\eta^2 = .18$. Indeed, subsequent paired-sample *t*-tests revealed that, for supraliminal trials, the learning effect was larger in the predictive than in the

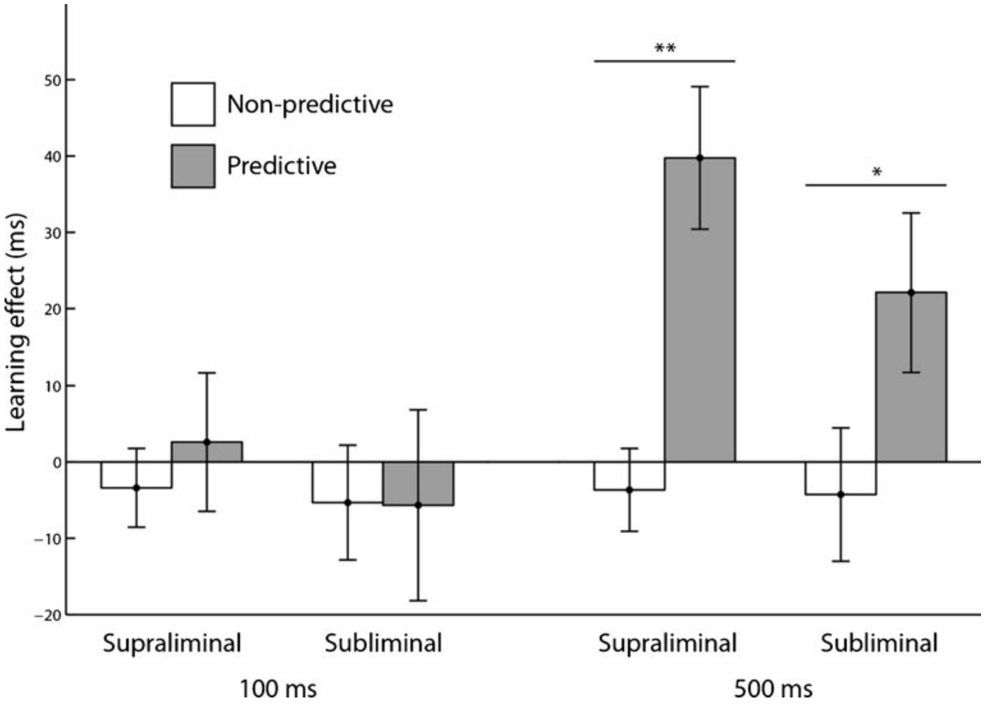

Fig. 5 Learning effects in Experiment 1. Learning effects were quantified as the difference in cuing effects between the first half and the second half of an experimental session. Error bars represent the standard error of the mean

nonpredictive condition, $t(12) = 5.038$, $p < .001$, $d = 1.40$. Importantly, this was also true for subliminal trials, $t(12) = 2.739$, $p = .018$, $d = .76$. These findings show that both supraliminal and subliminal cue utilization depend on statistical relevance, as deduced from perceptual evidence (i.e., predictive visible cues).

Finally, to test for learning effects between experimental sessions, we examined whether the order in which participants took part in the nonpredictive and the predictive experimental sessions influenced cuing effects. Session order was entered as a between-subjects factor in a repeated measures ANOVA with the within-subjects factors visibility, relevance, and SOA. None of the interactions between session order and the experimental within-subjects manipulations approached significance ($p > .6$).

Reaction times and accuracy

The analyses of RTs and accuracy (see Supplementary Table 1) are implemented to control for unexpected inconsistencies, reflecting differing response strategies between conditions. Mean RT on the target detection task across all experimental conditions was 389 ms (*SD* = 44.9). A repeated measures ANOVA with SOA, relevance, visibility, and congruency as within-subjects factors revealed a main effect of SOA, $F(1, 12) = 19.83$, $p = .001$, $\eta^2 = .62$, reflecting that RTs were shorter when cues were presented 500 ms (*M* = 402 ms, *SD* = 49.8), as compared with 100 ms (*M* = 377 ms, *SD* = 41.8), before target onset. This result is likely to reflect a preparation for response execution prior to stimulus delivery (Sommer, Leuthold, & Schubert, 2001). The main effect of cue visibility was also significant, $F(1, 12) = 5.69$, $p = .034$, $\eta^2 = .32$, showing that target detection was slightly faster after supraliminal cues (*M* = 387 ms, *SD* = 44.7), as compared with subliminal cues (*M* = 391 ms, *SD* = 45.4). The latter finding probably reflects the greater cuing effects in supraliminal than in subliminal trials.

Mean accuracy on the target detection task over all experimental conditions was 98.8 % (*SD* = 1.0 %) correct responses, with a minimum of 97.3 % and a maximum of 100 % for individual participants. We conducted 2 × 2 × 2 repeated measure ANOVAs on accuracy (percentage of incorrect responses on target detection), with the factors relevance, visibility, and congruency, for each SOA condition in Experiment 1. This revealed a three-way interaction in the SOA 100 condition, $F(1, 12) = 6.648$, $p = .024$, $\eta^2 = .36$. Subsequent paired-sample t-tests clarified this interaction by showing that, in the predictive condition, more errors were made after visible incongruent cues than after visible congruent cues $t(12) = 2.97$, $p = .012$, $d = .82$, whereas no such difference was observed for invisible cues $t(12) = .00$, $p = 1.00$, $d = .00$. In the nonpredictive condition, however, no difference in accuracy was observed after congruent, as compared with incongruent, cues, in either supraliminal, $t(12) = -.18$, $p = .861$, $d = -.05$, or subliminal, $t(12) = .37$, $p = .721$, $d = .10$, trials. In the SOA 500 condition, the same three-way interaction was found, $F(1, 12) = 5.430$, $p = .038$, $\eta^2 = .31$. Again, this interaction was carried by the predictive condition, in which more errors were made after visible incongruent cues than after visible congruent cues, $t(12) = 2.65$, $p = .021$, $d = .49$, whereas no such difference was observed for invisible cues, $t(12) = -.365$, $p = 721$, $d = -.10$. In the nonpredictive condition, no difference in accuracy was observed after congruent, as compared with incongruent, cues, in either supraliminal, $t(12) = 1.50$, $p = .160$, $d = .42$, or subliminal, $t(12) = -1.00$, $p = .337$, $d = .28$, trials. The finding that subliminal cues in the predictive condition did not affect accuracy, even though they did affect RTs, is in line with the idea that subliminal signals are too weak to trigger a new behavior but are strong enough to affect the time course of an initiated behavior (e.g., Van Gaal, Lamme, Fahrenfort, & Ridderinkhof, 2011). Finally, all observed effects of accuracy (reported above) reflected qualitatively similar differences of performance as the analyses of cuing effects (reported earlier); faster responses were accompanied by higher accuracy and vice versa. As such, there was no indication for a speed–accuracy trade-off (see Supplementary Table 1 for a complete overview of all RTs and accuracy per condition).

Discussion

The results of Experiment 1 show that visible arrow cues facilitated target detection in the cued location, irrespective of the predictive value of these arrow cues. Facilitation was observed even when an arrow appeared 100 ms before target onset (see the "General Discussion" section). Importantly, subliminal arrow cues also produced cuing effects, but only when supraliminal arrows predicted the location of the target. Also, cuing on subliminal trials was observed only when cues appeared 500 ms before target onset.

Some caution is required when interpreting these results, since it is impossible to disambiguate whether the null result in the nonpredictive condition reflects a genuine absence of cuing effects or a lack of statistical power. This is especially relevant, since the subliminal cuing effects only marginally differed between relevance conditions. As such, a post hoc power analysis was conducted for these two conditions, based on the effect size, the number of participants, and the .05 (two-sided) alpha level. This revealed that the present experiment could detect the subliminal cuing effect of 15.6 ms in the predictive condition with .78 power, which is at about the power level generally considered as adequate (e.g., Cohen, 1992). In the nonpredictive condition, however, the experimental power for the (nonsignificant) subliminal cuing effect was .33 (i.e., it had a 33 % probability of being "detected"). We conducted an additional power analysis based on the observed sample variance in the nonpredictive condition (for the fixed alpha level of .05, two-sided, and the fixed number of participants) to assess at what magnitude a cuing effect could, in theory, be reliably detected in the latter condition (for a motivation of this approach, see Thomas, 1997). This revealed that the present experiment allowed for detecting an effect of 13.2 ms with 80 % certainty (i.e., with a power of .8), which is almost twice the magnitude of the cuing effect that was measured (7.1 ms). Thus, while the experimental power allowed for detecting a smaller effect in the nonpredictive condition than in the predictive condition, a facilitatory subliminal cuing effect was detected only in the predictive condition. From this, we conclude that, in the SOA 500 condition, the occurrence of subliminal cuing effects was indeed dependent on the predictive value of the visible cues. The analysis of learning effects corroborates the findings based on cuing effects, since it reveals a qualitative, rather than quantitative, dissociation between cue relevance conditions. Including block as an experimental factor in the design revealed a learning pattern in the cuing effects, which was dependent on the predictive value of the (visible) cues. While subliminal cues in the predictive condition showed a learning effect that was similar to that of supraliminal cues, subliminal cues in the nonpredictive condition showed no learning at all. This null effect is unlikely to be caused by a lack of statistical power (as deductible by a post hoc power analysis), since the mean was below zero. This finding demonstrates that the utilization of subliminal arrow cues is dependent on the gradual building up of statistical knowledge about the informative value of the supraliminal cues. Thus, the potency of symbolic cues to evoke cuing effects may vary with their relevance to the current task, as deduced from visible statistical evidence.

In this first experiment, statistical learning relied on the relevance of visible cues. Since this learning was a gradual process rather than an instant one (reflecting a direct effect caused by top-down task instructions), we next address the question of whether visual awareness is necessary for statistical learning of symbol predictiveness to occur. Indeed, recent studies show that some forms of statistical learning can occur outside of visual awareness (Turk-Browne, Scholl, Chun, & Johnson, 2008) and trigger perceptual anticipation effects (Turk-Browne, Scholl, Johnson, & Chun, 2010). For this purpose, we reversed our paradigm to investigate whether the predictive value of subliminal cues can influence the incentive to utilize the supraliminal cues. This would be demonstrated by a stronger cuing effect in the supraliminal condition when subliminal cues are predictive, rather than nonpredictive.

Experiment 2

Stimuli, test setting, and presentation methods were identical to those in Experiment 1. However, in Experiment 2, the subliminal cues served as a manipulation of cue relevance and, therefore, accounted for 75 % of the trials. Consequently, on 25 % of the trials, the cue was presented supraliminally. Again, participants took part in two experimental sessions on two different days, the order of which was counterbalanced across participants. In both experiments, the supraliminal cues were 50 % congruent (nonpredictive), whereas the subliminal cues were 50 % congruent in Experiment 2a (nonpredictive) and 100 % congruent in Experiment 2b (predictive). Because an SOA of 900 ms appeared to be too long to guarantee the invisibility of the cues, this SOA condition was omitted from Experiment 2. The last session ended with the same control task as in Experiment 1.

If the validity of subliminally presented arrow cues elicits statistical learning, this should evoke an incentive to use them on both visible and invisible trials. Consequently, subliminal learning should be reflected in larger cuing effects on supraliminal trials in the predictive condition, as compared with the nonpredictive condition. Conversely, if no such effect is found, it would suggest that statistical learning of cue validity is a process requiring visual awareness.

Results

Participants and control

Eighteen participants, 18 to 31 years of age (M = 22.8 years, SD = 4.21), took part in Experiment 2, 5 of which had also participated in Experiment 1. All participants were selected for normal or corrected-to-normal vision, stereoscopic vision, and right-handedness. Exclusion criteria were identical to those in Experiment 1, such that 13 participants were included in the analyses.

These 13 participants were unable to detect 12.2 % of the cues within the 6-s time limit, and a remaining 1.2 % of control trials yielded incorrect responses. Consequently, 86.6 % of the cues were accurately detected (M = 2.2 s, SD = .7) within the time limit (Fig. 6). Similar to Experiment 1, mean detection times in the control task did not differ between different SOAs $t(12) = .687$, $p = .505$, $d = .19$, suggesting comparable suppression times for both SOAs.

Cuing effects

Analogous to Experiment 1, trials on which participants reported an incorrect location of the target (0.7 %), trials with RTs shorter than 150 ms (0.1 %), and trials with RTs longer than the participants 5th percentile RT on the control task (3.0 %; varying between 0 % and 5 % for individual participants) were excluded from RT analyses. Subsequently, the RTs on congruent trials were subtracted from the RTs on incongruent trials, in all SOA × relevance × visibility conditions. The resulting measure reflects the cuing effect for each condition and is depicted in Fig. 7. These analyses in Experiment 2 focus on the supraliminal condition, since the subliminal condition was implemented only as a manipulation of cue utilization. An analysis of the subliminal condition is provided in Supplementary Materials 2. First, an overall factorial 2 × 2 repeated measures ANOVA was conducted, with the factors SOA (100 and 500 ms) and relevance (predictive and nonpredictive). This analysis showed that the magnitude of cuing effects did not depend on SOA, $F(1, 12) = 3.39$, $p = .091$, $\eta^2 = .22$, or relevance, $F(1, 12) = .18$, $p = .675$, $\eta^2 = .02$, nor did these factors interact, $F(1, 12) = .02$, $p = .887$, $\eta^2 = .00$. Moreover, the effect of relevance did not differ between the first half and the second half of the experiment in either the short $t(12) = 1.2$, $p = .242$, $d = .34$ or the long, $t(12) = -1.59$, $p = .137$, $d = -.44$, SOA condition, reflecting that no learning occurred on the basis of the predictive value of the subliminal cues.

Additional one-sample t-tests revealed that facilitatory cuing effects were observed in all supraliminal conditions; in the 100-ms SOA nonpredictive condition, $t(12) = 4.63$, $p = .001$, $d = 1.28$, and predictive condition, $t(12) = 3.61$, $p = .004$, $d = 1.00$, and in the 500-ms SOA nonpredictive condition, $t(12) = 3.01$, $p = .009$, $d = .86$, and predictive condition, $t(12) = 4.40$, $p = .001$, $d = 1.22$, such that facilitation was observed in every supraliminal condition. Subsequent paired-sample t-tests revealed that these cuing effects were not affected by the predictive value of subliminal cues in either the short SOA, $t(12) = -.25$, $p = .807$, $d = -.07$, or long SOA, $t(12) = -.33$, $p = .745$, $d = -.09$, condition.

Reaction times and accuracy

Analogous to Experiment 1, RTs and accuracy (see Supplementary Table 2) were analyzed, to verify that overall performance was comparable between relevance conditions. Overall, mean RT for Experiment 2 was 365 ms (SD = 40.1). A repeated measures ANOVA with the factors SOA, relevance, and congruency showed a main effect of SOA, $F(1,12) = 27.07$, $p < .001$, $\eta^2 = .69$, showing that RTs were shorter when cues were presented 500 ms (M = 349 ms, SD = 38.8), as compared with 100 ms (M = 381 ms, SD = 43.5), before target onset. The predictive value of subliminal cues did not affect RT on supraliminal trials, as was revealed by the absence of a main effect of relevance, $F(1, 12) = .34$, $p = .570$, $\eta^2 = .03$.

Overall, response accuracy on supraliminal trials was 98.4 % (SD = 2.1), with individual participants ranging between 93.8 % and 100 %. An overall repeated measures ANOVA with the factors relevance, SOA, and congruency on the response accuracy on supraliminal trials revealed no main effect of relevance, $f(1, 12) = 1.31$, $p = .273$, $\eta^2 = .10$, nor did the factor relevance interact with SOA, $F(1, 12) = .16$, $p = .700$, $\eta^2 = .01$, or congruency, $F(1, 12) = 1.16$, $p = .303$, $\eta^2 = .09$. As such, the predictive value of the subliminal cue affected neither the RTs, nor the accuracy on supraliminal

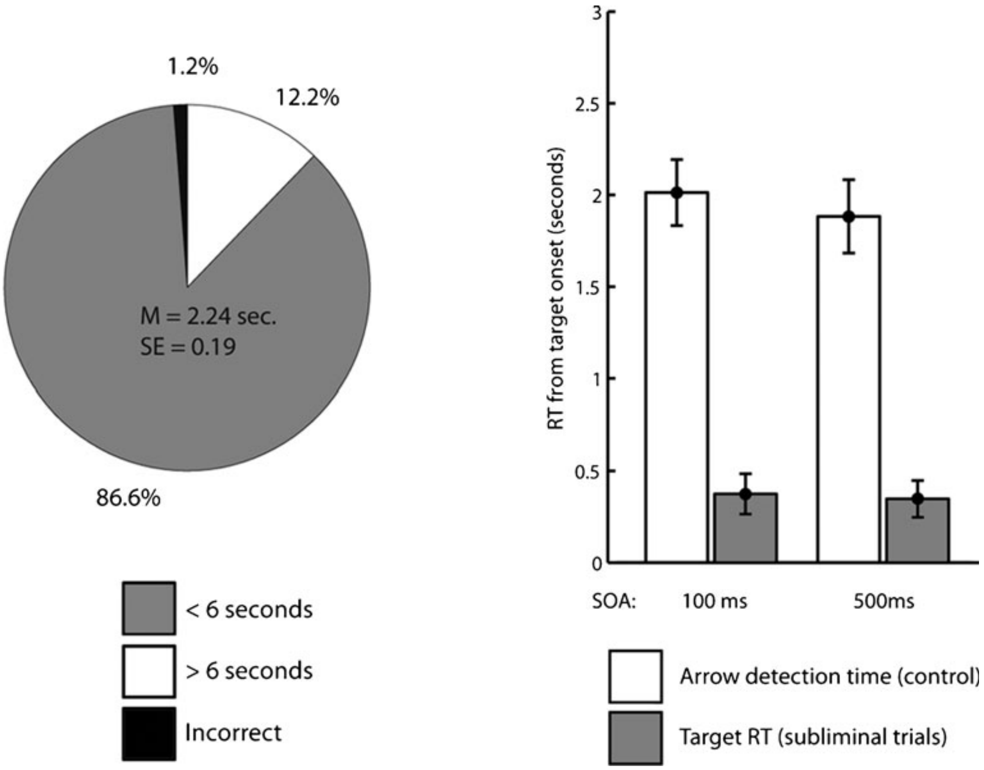

Fig. 6 Results of the control task. Left: The cue remained invisible for 6 s on 12.2 % of the control trials, while its direction was identified correctly within 2.24 s on 86.6 %. Right: Correct arrow detection times in the control task compared with target detection times on subliminal trials

trials (see Supplementary Table 2 for a complete overview of all RTs and accuracy per condition).

Discussion

Cuing effects on supraliminal trials were not affected by the predictive value of intermixed subliminal cues, which either were always congruent or had no predictive value. Hence, the predictive value of subliminal cues does not appear to elicit statistical learning, as measured by supraliminal cue utilization. In contrast, Experiment 1 showed that highly relevant visible stimuli affected both supraliminal and subliminal cuing effects and that the effects of cue relevance gradually emerged throughout the experiment. The combination of both findings shows that statistical learning of symbolic cue relevance requires visual awareness of the cues.

General discussion

The main finding of this study is that the utilization of subliminal symbolic cues is dependent on the predictive value of the cues, as deduced from visible statistical evidence. As a result, subliminal symbolic cues elicit facilitatory cuing effects on subsequent target detection, but only when intermixed supraliminal arrow cues are highly predictive of (i.e., 80 % congruent with) the subsequent target location. Importantly, these effects emerged gradually throughout the experiment, as more evidence on the predictive value of arrow cues was accumulated. When the supraliminal cues were nonpredictive (50 % congruent), no cuing effects were found, nor did they build up over the course of the experiment. The subliminal cues themselves were always nonpredictive as to the subsequent target location. Thus, when the relevance of visible arrow cues provides an incentive for cue utilization, the elicited facilitatory effect persists for arrows that are not consciously perceived. Conversely, Experiment 2 showed that the predictive value of subliminal cues (50 % or 100 % congruent) does not affect cuing effects of intermixed (nonpredictive) visible arrow cues. We conclude that, at least in the case where supraliminal and subliminal cues are intermixed, conscious perception is required to make statistical inferences about the relevance of symbolic cues. Once this statistical information is consciously extracted, it may affect subsequent nonconscious processing in a context-dependent way.

In this study, we took special care to ensure that the observed cuing effects on subliminal trials were indeed elicited by cues that were invisible to participants. This was done by (1) estimating the fraction of cues in the subliminal condition that were unsuccessfully suppressed and (2) correcting the cuing effects in the subliminal condition for

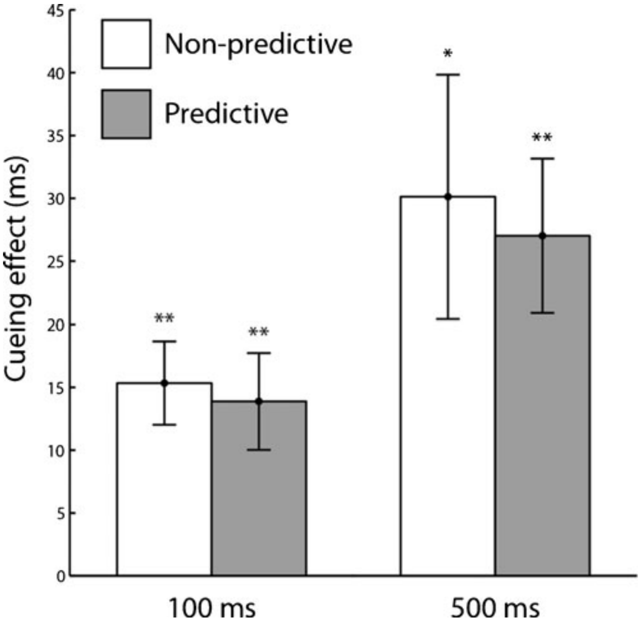

Fig. 7 Cuing effects in the supraliminal condition of Experiment 2. Calculated by subtracting reaction times (RTs) on trials with congruent cues from RTs on trials with incongruent cues. Positive cuing effects reflect facilitation. The predictive value reflects the cue validity of the subliminal arrow cues (100 % or 50 %). Error bars depict the standard error of the mean. * $p < .05$, ** $p < .005$

this fraction of trials on which the cue might have been visible. Regarding the first point, it is important to note that suppressed cues were not likely to be visible on the basis of the current data: The average RT in the main experiments was about 400 ms, whereas about a quarter of the cues in the control task remained unseen during the 6-s time limit. The remainder of the cues in the control task were detected after an average delay of around 2.5 s, more than 6 times as long as the mean RT on experimental trials. Moreover, we argue that the control task gave a conservative estimate of the detection times of subliminal cues. This claim is based on two arguments that rely on differences between the control task and the subliminal trials in the main experiment. First, in the experimental task, (covert) attention was directed to the periphery, where the target was expected to appear. Since attention at a location away from rivalrous stimuli slows down alternations (Paffen, Alais, & Verstraten, 2006), the masked cue probably took longer to break through suppression in the experimental trials, as compared with the control trials. Second, on the experimental trials, attention was directed to the target, which was always presented to the eye that was made dominant with flash suppression. Directing attention to a target in a specific eye enhances the competition strength of the entire ipsi-ocular stimulus (Zhang, Jiang, & He, 2012). In our case, attending to the monocular target would have enhanced the dominance of the mask (suppressor), which was always presented to the same eye as the target. Consequently, this would have strengthened the suppression of the arrow cue (presented to the other eye) on experimental trials, as compared with control trials. In sum, we believe that this control task gave a low estimate of the suppression durations of subliminal cues in the actual experiment. Regarding the second point, the correction method applied in this study provides a conservative approach for detecting subliminal cuing effects. Cuing effects in the subliminal condition (Experiment 1) were corrected to account for the estimated fraction of trials on which cues were unsuccessfully suppressed. The contributions that this this fraction of trials would make to the cuing effect in the subliminal condition (if fully visible) was subtracted from the measured subliminal cuing effect. This method was thus based on the conservative assumption that unsuccessfully suppressed cues potentially elicit as much facilitation as supraliminal cues. However, it is likely that unsuccessfully suppressed cues produce less facilitation than supraliminal cues, since they are less clearly visible, as well as visible for a shorter duration than arrows in the supraliminal condition. Moreover, they might even impede subsequent target detection, since interocular conflict (mask vs. arrow) is known to attract attention (Paffen, Hessels, & Van der Stigchel, 2012) in this case, to the center of fixation and, as such, away from the target. The fact that a significant cuing effect is still observed using this conservative approach provides strong support of genuine nonconscious processing of suppressed arrow cues.

A possible concern that needs to be addressed relates to the finding that supraliminal arrow cues elicited cuing effects after both 100- and 500-ms SOAs, whereas subliminal cuing was observed only after an SOA of 500 ms. It could be argued that the absence of cuing effects on subliminal trials after short SOAs casts doubt on the potency of invisible symbols to elicit genuine subliminal cuing at longer SOAs. Indeed, a longer SOA provides more time for ocular dominance to switch back to the eye in which the arrow cue is presented, hence making it more likely to become visible before target onset. However, the control task demonstrated that the short and long SOA conditions did not differ in arrow suppression duration, as measured from target onset. Therefore, differences in subliminal cuing effects between the two SOA conditions are unlikely to be the result of differences in suppression length. Moreover, the absence of cuing effects in the short SOA condition can be accounted for by a low-level explanation. On subliminal trials, the (suppressed) cue and the (nonsuppressed) target were presented to different eyes, whereas on supraliminal trials, both the cue and the target were presented to the same (nonsuppressed) eye. A study by Self and Roelfsema (2010) revealed that monocular cues affect contra-ocular target detection only when the cue–target asynchrony is 150 ms or longer. The onset asynchrony of 100 ms used in the present study was probably too short to reach binocular channels and elicit intra-ocular cuing effects.

A final concern regarding the findings of Experiment 1 is that, while subliminal cuing effects were found in the predictive condition but not in the nonpredictive condition, these cuing effects did not significantly differ between relevance conditions. This statistical limitation, however, does not jeopardize the conclusions of the present study. Indeed, comparable studies tend to look only at cuing effects within relevance conditions, rather than compare cuing effects between conditions (e.g., Al-Janabi & Finkbeiner, 2012; Reuss et al., 2011). In these and similar studies, the subliminal stimulus is expected to elicit an effect that is qualitatively similar to that of its supraliminal counterpart (i.e., facilitation rather than inhibition) but is generally found to be smaller in magnitude (i.e., 5–15 ms; Al-Janabi & Finkbeiner, 2012; Mulckhuyse, Talsma, & Theeuwes, 2007; Palmer & Mattler, 2013; Reuss et al., 2011). As such, the main concern is to avoid contamination from supraliminal stimuli and to assess whether an effect is genuinely elicited by the subliminal stimuli. In the present study, this was achieved by means of the correction method described in the "Trial Selection and Inclusion Criteria" section, which was more stringent in the predictive condition than in the nonpredictive condition (i.e., corrections were computed from participants' supraliminal cuing effects, which were larger in the predictive than in the nonpredictive condition). Thus, since both conditions were corrected differently, this does not allow for direct comparisons of cuing effects on subliminal trials between the two relevance conditions. In addition, it is important to point out that our general conclusion (i.e., the visible statistical context modulates the utilization of subliminal cues) does not solely rely on whether or not cuing effects are observed in the different relevance conditions. In addition to the cuing effects, the analysis of learning effects (i.e., difference in cuing effect between the first and second halves of the experiment) shows a different behavioral pattern between relevance conditions. In Experiment 1, a clear learning effect was observed for both supraliminal and subliminal cues in the predictive condition, whereas no learning effect was observed in the nonpredictive condition. This finding reveals an additional dissociation between the predictive and nonpredictive subliminal conditions. It shows that these conditions do not simply differ in the magnitude of the subliminal cuing effect, such that only one reaches the threshold of significance. Rather, it shows that two different processes are at play. On both supraliminal and subliminal trials, it is the gradual accumulation of statistical evidence that provides an increasing incentive either to utilize the cues or to disregard the cues. Thus, the analysis of learning effects provides in itself compelling evidence for our general conclusion that statistical context modulates the utilization of subliminal cues.

The present findings are in line with the view that prior to nonconscious processing, conscious observation is required to construct a cognitive context that can guide behavior in a goal-directed and relevant manner. Our experimental setup was particularly well suited to demonstrate this action trigger hypothesis (Kiesel et al., 2007; Kunde et al., 2003), since it allowed dissociating the observed relevance of a subliminal stimulus, as based on the consciously accessible context, from the actual relevance of the subliminal stimulus (which had no predictive value). The finding that subliminal arrow cues elicit cuing effects does, however, not imply that they receive full semantic analysis. In contrast with supraliminal cues, subliminal cues did not elicit cuing effects in the nonpredictive condition. It appears then, that the semantic meaning of the cues was not automatically analyzed but, rather, required an incentive to do so. We suggest that cues are included in a predetermined set of action triggers on the basis of their physical properties, but only when visible cues provide a cognitive context that favors cue utilization. Thus, when the cognitive context forms an incentive to utilize subliminal information, an adequate response is triggered, irrespective of the relevance of the subliminal stimulus itself. It is important to note, however, that, while the aim of the present study was to unveil the necessary preconditions for subliminal stimuli to influence behavior (i.e., elicit cuing effects), the nature of these cuing effects remains elusive. Since the task was to respond to the location of a target rather than its identity, a cue that was informative of the target location was also informative of the required response. As such, it is impossible to unequivocally dissociate between motor priming effects (such as those described by Kunde et al., 2003) and attentional cuing (e.g., Ansorge et al., 2010; Folk et al., 1992).

Recently, Reuss et al. (2011) performed an experiment with meta-contrast masked arrow cues. Similarly to the present study, they found a facilitatory cuing effect of subliminal cues when cues were highly predictive, whereas no facilitation was observed for subliminal cues in the nonpredictive condition. Their paradigm was different from ours, however, in the sense that the predictive value of the subliminal cues was manipulated simultaneously with the predictive value of the supraliminal cues. Hence, this methodology did not allow for dissociating between the two possible origins of the cuing effect in the subliminal condition. Although it is debatable whether invisible arrow cues should be considered as a separate class of cues, there are two reasons to consider them as such in light of their predictive value. First, they elicit a percept that differs from that of visible cues, as a result of which different statistical relevance could be assigned to both "cue-percepts" (compare, e.g., arrows of different colors). Second, Experiment 2 shows that participants' predictive set is not affected by the predictive value of arrow cues when they are not consciously perceived. Hence, it appears that the predictive set of visible and invisible arrow cues cannot be lumped together but should be manipulated independently. By manipulating only the relevance of the supraliminal cues, we demonstrated that the predictive value of visible arrow cues formed an incentive to utilize arrow cues, which was then transferred to masked arrow cues. We thereby disproved the alternative explanation that the intrinsic predictive value of the subliminal cues elicited cuing effects by means of nonconscious statistical learning.

As was mentioned above, the predictive value of subliminal cues did not modulate the cognitive context, such as to affect the utilization of (supraliminal) cues. This is at odds with recent studies showing that statistical learning can occur without awareness (Turk-Browne et al., 2010) and can bias spatial attention, even when completely unrelated to the current goals of the observer (Zhao, Al-Aidroos, & Turk-Browne, 2013). In contrast to these studies, however, the subliminal stimuli (either predictive or nonpredictive) in the present study were intermixed with nonpredictive supraliminal stimuli. Possibly, the stronger perceptual evidence provided by the latter overruled the statistical learning of subliminal stimuli. Accordingly, the arrow cues were judged behaviorally irrelevant, on the basis of the visible cues, irrespective of the statistical relevance of the subliminal cues.

From another perspective, the observed dissociation between supraliminal learning (Experiment 1) and the absence of subliminal learning (Experiment 2) can be framed within the *adaptation to the statistics of the environment* (ASE) model (Kinoshita, Forster, & Mozer, 2008; Kinoshita, Mozer, & Forster, 2011). This model makes predictions about speeded responses to prime–target pairs, based on a response control process that takes into account the (recent) history of events. This control process relies on response costs, which are computed from the relative cost of waiting (RT cost), and the cost of possibly making an incorrect response (accuracy cost). According to this model, swiftly reacting to primes in blocks with more incongruent prime–target pairs might result in a higher risk of making an erroneous response. Conversely, reacting to primes in blocks with more congruent prime–target pairs yields a lower risk of erroneous responses and, thus, a relative higher benefit of fast responses. In the present study, a visible statistical context provided the means to modulate cuing effects (Experiment 1), whereas an invisible statistical context did not (Experiment 2). While the history of events of Experiment 1 and of Experiment 2 are similar from a statistical perspective (i.e., cues that had either a high or a low predictive value), these experiments might differ in terms of evidence accumulation. Indeed, the effects of suppressed stimuli may start to decay within hundreds of milliseconds after presentation (Kiefer & Brendel, 2006; Kiefer & Spitzer, 2000), such that information about these suppressed stimuli might not be accumulated over multiple trials (Humphreys, Besner, & Quinlan, 1988). Kinoshita et al. (2011) showed that, whereas evidence of visible primes can accumulate over longer periods of time (i.e., a block), masked primes are mostly sensitive to recent history (i.e., trial n and trial $n-1$). This short temporal window within which a masked prime is accessible to (nonconscious) cognition is probably too short to infer the predictive value of prime–target pairs. In line with the ASE, the manipulation of the predictive value of subliminal cues in Experiment 2 did not provide a statistical context, based on the history of events, leading to an absence of cuing effects in this situation.

Another important finding of the present study that should be discussed in light of the ASE framework is the gradual emergence of cuing effects throughout the experimental sessions: When visible arrows were highly predictive, more facilitation was observed in the second half of the session, as compared with the first half of the session, irrespective of cue visibility (i.e., supraliminal or subliminal). Crucially, these learning effects were not observed when arrow cues were nonpredictive, even though facilitatory cuing effects were still observed in the supraliminal condition. The ASE predicts that, as statistical knowledge about the cues accumulates, the balance between costs (lower accuracy) versus benefits (shorter RTs) will increasingly plead in favor of cue utilization in a predictive context, whereas it will remain unchanged in a nonpredictive context (as compared with the start of the experiment). Thus, the utilization of subliminally (and supraliminally) presented symbolic cues is affected by the gradual building up of statistical knowledge about the informative value of the (visible) cues.

At first sight, our results are at odds with those of Schall, Nawrot, Blake, and Yu (1993). In their study (as in ours), participants performed a speeded detection task, in which interocularly suppressed central arrow cues preceded peripheral targets. Participants were presented with dichoptic stimuli and were instructed to report perceptual dominance with a keypress, thus initiating a trial of the actual cuing task. In contrast to our results, they found no significant cuing effects elicited by subliminal stimuli. The discrepancy between our findings and theirs can be accounted for by a number of factors. First, the longer cue–target onset asynchrony in their study (900 ms) might have resulted in the disengagement of attention from the cued location (e.g., Barbot & Kouider, 2012; Eimer & Schaghecken, 2002). Second, the use of binocular rivalry required participants to wait for a period of dominance and report the dominant percept with a keypress to initiate a trial. The extra noise in the RTs caused by this additional motor task might have reduced the power to detect cuing effects of relatively small magnitudes (~15 ms).

The existence of context-dependent subliminal processing as shown here is informative for the debate on the nature of nonconscious visual processing. On the one side is the view that nonconscious processing is as elaborate as conscious processing (e.g., Dehaene & Naccache, 2001; Koechlin et al., 1999). On the other side is the view that nonconscious stimuli influence behavior through learned stimulus–response mapping (e.g., Abrams & Greenwald, 2000; Damian, 2001). Both these views are unable to fully account for the present findings. In contradiction with the former view, processing of subliminal stimuli was not as extensive as processing of conscious stimuli. Experiment 2 showed that, in contrast to supraliminal cues, manipulating the relevance of subliminal cues did not affect cuing effects. Hence, conscious observation of the stimuli was required for participants to make a statistical inference about the predictive value of the cue. Stimuli presented outside of visual awareness, on the other hand, were not processed sufficiently to elicit such an effect. According to the latter view, repetitively responding to a specific target builds up a stimulus–response memory trace that can subsequently be activated even when this target is not consciously accessible. As such, an acquired stimulus–response mapping between supraliminal target and response would also be triggered by the cue (i.e., a transfer from the "to-be-responded-to" supraliminal stimulus to a similar subliminal stimulus). However, the present findings differ from stimulus–response mappings in two ways. First, the cue was a completely different stimulus, which had no perceptual similarities with the target and, as such, was not repeatedly responded to. It was only by means of the statistical context that an incentive was provided (supraliminally) to utilize the cue. Second, cues in the predictive condition elicited cuing effects in both visibility conditions, whereas a nonpredictive context elicited cuing effects only for supraliminal cues, not for subliminal cues. This difference also emerged in the analysis of learning effects. Thus, the cuing effects elicited by supraliminal cues were transferred to subliminal cues only when the cognitive context provided an incentive to do so. Accordingly, acquired mappings between the peripheral target and the corresponding response cannot account for the facilitatory cuing effects as observed in Experiment 1. Rather, the present findings suggest that the processing of subliminally presented symbolic cues is the result of the gradual building up of statistical knowledge about the informative value of the (visible) cues. The inferred statistical relevance then provides an incentive for cue utilization, such that subliminal cues are selected only when they appear to be relevant for the task at hand.

Conclusion

The present paradigm allowed for disentangling the participants' incentive to utilize subliminal information from the actual relevance of the subliminal information. We showed that nonconscious processing is sufficiently elaborate for utilizing symbolic cues in a way that fits the cognitive context, even when the subliminal information is not relevant by itself. In contrast, this subliminal information is not processed extensively enough to affect behavior performed on visible stimuli by altering the cognitive context. These findings imply that the relevance of a subliminal stimulus is neither necessary nor sufficient to affect behavior. Rather, it is the conscious evaluation of visible information that provides an incentive to utilize (and predetermine the adequate response to) subsequent information, irrespective of its visibility. Accordingly, one of the possible functions of consciousness could be to extract general rules out of the perceptually available information, to provide guidelines for future behavior.

Acknowledgements This research was funded by Grant 404-10-306 from the Netherlands Organization for Scientific Research (NWO) to S. Van der Stigchel and C. L. E. Paffen.

References

Abrams, R. L., & Greenwald, A. G. (2000). Parts outweigh the whole (word) in unconscious analysis of meaning. *Psychological Science, 11*, 118–124.

Alais, D., & Blake, R. (Eds.). (2005). *Binocular rivalry*. Cambridge: MA: MIT Press.

Al-Janabi, S., & Finkbeiner, M. (2012). Effective processing of masked eye gaze requires volitional control. *Experimental Brain Research, 216,* 433–443.

Ansorge, U., & Heumann, M. (2006). Shifts of visuospatial attention to invisible (metacontrastmasked) singletons: Clues from reaction times and event-related potentials. *Advances in Cognitive Psychology, 2*, 61–76.

Ansorge, U., Horstmann, G., & Worschech, F. (2010). Attentional capture by masked color singletons. *Vision Research, 50,* 2015–2027.

Ansorge, U., & Neumann, O. (2005). Intentions determine the effect of invisible metacontrast-masked primes: Evidence for top-down contingencies in a peripheral cueing task. *Journal of Experimental Psychology: Human Perception and Performance, 31,* 762–777.

Barbot, A., & Kouider, S. (2012). Longer is not better: Nonconscious overstimulation reverses priming influences under interocular suppression. *Attention, Perception and Psychophysics, 74,* 174–184.

Bargh, J. A., & Morsella, E. (2008). The unconscious mind. *Perspectives on Psychological Science, 3*, 73–79.

Blake, R. (1989). A neural theory of binocular rivalry. *Psychological Review, 96*, 145–167.

Blake, R. (2001). A primer on binocular rivalry, including current controversies. *Brain and Mind, 2,* 5–38.

Bodner, G. E., & Dypvik, A. T. (2005). Masked priming of number judgments depends on prime validity and task. *Memory & Cognition, 33,* 29–47.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10,* 433–436.

Breitmeyer, B. G. (2007). Visual masking: Past accomplishments, present status, future developments. *Advances in Cognitive Psychology, 3,* 9–20.

Cohen, J. (1992). A power primer. *Quantitative Methods in Psychology, 112,* 155–159.

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience, 3,* 201–215.

Damian, M. F. (2001). Congruity effects evoked by subliminally presented primes: Automaticity rather than semantic processing. *Journal of Experimental Psychology: Human Perception and Performance, 27,* 154–165.

Dehaene, S., & Naccache, L. (2001). Towards a cognitive neuroscience of consciousness: Basic evidence and a workspace framework. *Cognition, 79,* 1–37.

Di Lollo, V., Enns, J. T., & Rensink, R. A. (2000). Competition for consciousness among visual events: The psychophysics of reentrant visual processes. *Journal of Experimental Psychology: General, 129,* 481–507.

Egeth, H. E., & Yantis, S. (1997). Visual attention: Control, representation, and time course. *Annual Review of Psychology, 48,* 269–297.

Eimer, M., & Schlaghecken, F. (1998). Effects of masked stimuli on motor activation: Behavioral and electrophysiological evidence. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 1737–1747.

Eimer, M., & Schlaghecken, F. (2002). Links between conscious awareness and response inhibition: Evidence from masked priming. *Psychonomic Bulletin & Review, 9,* 514–520.

Fang, F., & He, S. (2005). Cortical responses to invisible objects in the human dorsal and ventral pathways. *Nature Neuroscience, 8,* 1380–1385.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human. Perception & Performance, 18,* 1030–1044.

Friesen, C. K., Ristic, J., & Kingstone, A. (2004). Attentional effects of counterpredictive gaze and arrow cues. *Journal of Experimental Psychology: Human Perception and Performance, 30*, 319–329.

Frischen, A., Smilek, D., Eastwood, J. D., & Tipper, S. P. (2007). Inhibition of return in response to gaze cues: The roles of time course and fixation cue. *Visual Cognition, 15,* 881–895.

Frischen, A., & Tipper, S. P. (2004). Orienting attention via observed gaze shift evokes longer term inhibitory effects: Implications for social interactions, attention, and memory. *Journal of Experimental Psychology: General, 133,* 516–533.

Godijn, R., & Theeuwes, J. (2004). The relationship between inhibition of return and saccade trajectory deviations. *Journal of Experimental Psychology: Human Perception and Performance, 30,* 538–554.

Hassin, R. R. (2013). Yes it can: On the functional abilities of the human unconscious. *Perspectives on Psychological Science, 8*, 195–207.

Hietanen, J. K., Leppänen, J. M., Nummenmaa, L., & Astikainen, P. (2008). Visuospatial attention shifts by gaze and arrow cues: An ERP study. *Brain Research, 1215,* 123–136.

Hommel, B., Pratt, J., Colzato, L., & Godijn, R. (2001). Symbolic control of visual attention. *Psychological Science, 12,* 360–365.

Humphreys, G. W., Besner, D., & Quinlan, P. T. (1988). Event perception and the word repetition effect. *Journal of Experimental Psychology: General, 117,* 51–67.

Jaskowski, P., Skalska, B., & Verleger, R. (2003). How the self controls its "automatic pilot" when processing subliminal information. *Journal of Cognitive Neuroscience, 15,* 911–920.

Jiang, Y., Costello, P., Fang, F., Huang, M., & He, S. (2006). A gender- and sexual orientation-dependent spatial attentional effect of invisible images. *Procedures of the National Academy of Science U.S.A., 103,* 17048–17052.

Jiang, Y., & He, S. (2006). Cortical responses to invisible faces: Dissociating subsystems for facial-information processing. *Current Biology, 16,* 2023–2029.

Jonides, J. (1981). Voluntary versus automatic control over the mind's eye's movement. In J. B. Long & A. D. Baddeley (Eds.), *Attention and performance IX* (pp. 187–203). Hillsdale, NJ: Erlbaum.

Kiefer, M., & Brendel, D. (2006). Attentional modulation of unconscious "attentional" processes: Evidence from event-related potentials in masked priming. *Journal of Cognitive Neuroscience, 18,* 184–98.

Kiefer, M., & Martens, U. (2010). Attentional sensitization of unconscious cognition: Task sets modulate subsequent masked semantic priming. *Journal of Experimental Psychology: General, 139,* 464–489.

Kiefer, M., & Spitzer, M. (2000). Time course of conscious and unconscious semantic brain activation. *Neuroreport, 11,* 2401–2407.

Kiesel, A., Kunde, W., & Hoffmann, J. (2007). Mechanisms of subliminal response priming. *Advances in Cognitive Psychology, 3,* 307–315.

Kinoshita, S., Forster, K. I., & Mozer, M. C. (2008). Unconscious cognition isn't that smart: Modulation of masked repetition priming effect in the word naming task. *Cognition, 107,* 623–649.

Kinoshita, S., Mozer, M. C., & Forster, K. I. (2011). Dynamic adaptation to history of trial difficulty explains the effect of congruency proportion on masked priming. *Journal of Experimental Psychology: General, 140,* 622–636.

Klotz, W., & Neumann, O. (1999). Motor activation without conscious discrimination in metacontrast masking. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 976–992.

Klein, R. M. (2000). Inhibition of return. *Trends in Cognitive Sciences, 4,* 138–147.

Koch, C. (2004). *The quest for consciousness: A neurobiological approach*. Englewood, US-CO: Roberts & Company Publishers.

Koechlin, E., Naccache, L., Block, E., & Dehaene, S. (1999). Primed numbers: Exploring the modularity of numerical representations with masked and un- masked semantic priming. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 1882–1905.

Kouider, S., & Dehaene, S. (2007). Levels of processing during non-conscious perception: A critical review of visual masking. *Philosophical Transactions of the Royal Society B, 362,* 857–875.

Kunde, W., Kiesel, A., & Hoffmann, J. (2003). Conscious control over the content of unconscious cognition. *Cognition, 88,* 223–242.

Lamme, V. A. F. (2001). Blindsight: The role of feedforward and feedback corticocortical connections. *Acta Psychologica, 107,* 209–228.

Lamme, V. A. F., & Roelfsema, P. R. (2000). The distinct modes of vision offered by feedforward and recurrent processing. *Trends in Neurosciences, 23*, 571–579.

Lidell, B. J., Williams, L. M., Rathjen, J., Shevrin, H., & Gordon, E. (2004). A temporal dissociation of subliminal versus supraliminal fear perception: An event-related potential study. *Journal of Cognitive Neuroscience, 16,* 479–486.

Lin, Z., & He, S. (2009). Seeing the invisible: The scope and limits of unconscious processing in binocular rivalry. *Progress in Neurobiology, 87,* 195–211.

Luck, S. J., & Hillyard, S. A. (1994). Spatial filtering during visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 1000–1014.

Macknik, S., & Martinez-Conde, S. (2004). Dichoptic visual masking reveals that early binocular neurons exhibit weak interocular suppression: Implications for binocular vision and visual awareness. *Journal of Cognitive Neuroscience, 16,* 1049–59.

McCormick, P. A. (1997). Orienting attention without awareness. *Journal of Experimental Psychology: Human Perception and Performance, 23,* 168–180.

Mulckhuyse, M., & Theeuwes, J. (2010). Unconscious attentional orienting to exogenous cues: A review of the literature. *Acta Psychologica, 134,* 299–309.

Mulckhuyse, M., Talsma, D., & Theeuwes, J. (2007). Grabbing attention without knowing: Automatic capture of attention by subliminal spatial cues. *Visual Cognition, 15*, 779–788.

Neumann, O., & Klotz, W. (1994). Motor responses to nonreportable, masked stimuli: Where is the limit of direct parameter specification? In C. Umilta & M. Moskovitch (Eds.), *Attention and performance XV* (pp. 123–150). Cambridge, MA: MIT Press.

Nummenmaa, L., & Hietanen, J. K. (2006). Gaze distractors influence saccadic curvature: Evidence for the role of the oculomotor system in gaze-cued orienting. *Visual Research, 46,* 3674–3680.

Ooi, T. L., & He, Z. J. (1999). Binocular rivalry and visual awareness: The role of attention. *Perception, 28,* 551–574.

Paffen, C. L. E., Alais, D., & Verstraten, F. A. J. (2006). Attention speeds binocular rivalry. *Psychological Science, 17,* 752–756.

Paffen, C. L. E., Hessels, R. S., & Van der Stigchel, S. (2012). Interocular conflict attracts attention. *Attention, Perception & Psychophysics, 74,* 251–256.

Palmer, S., & Mattler, U., (2013). Masked stimuli modulate endogenous shifts of spatial attention. *Consciousness and Cognition, 22*, 486–503.

Pasley, B. N., Mayes, L. C., & Schultz, R. T. (2004). Subcortical discrimination of unperceived objects during binocular rivalry. *Neuron, 42,* 163–172.

Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10,* 437–442.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32A,* 3–25.

Posner, M. I., & Cohen, Y. P. C. (1984). Components of visual orienting. In H. Bouma & D. Bouwhuis (Eds.), *Attention and performance X* (pp. 531–556). London: Erlbaum.

Posner, M. I., & Snyder, C. R. R. (1975). Attention and cognitive control. In R. L. Solso (Ed.), *Information processing and cognition* (pp. 55–85). Hillsdale, NJ: Erlbaum.

Pratt, J., & Hommel, B. (2003). Symbolic control of visual attention: The role of working memory and attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 835–845.

Rafal, R., Calabresi, P., Brennan, C., & Sciolto, T. (1989). Saccade preparation inhibits reorienting to recently attended locations. *Journal of Experimental Psychology: Human Perception and Performance, 15,* 673–685.

Reuss, H., Pohl, C., Kiesel, A., & Kunde, W. (2011). Follow the sign! Top-down contingent attentional capture of masked arrow cues. *Advances in Cognitive Psychology, 7,* 82–91.

Ristic, J., Friesen, C. K., & Kingstone, A. (2002). Are eyes special? It depends on how you look at it. *Psychonomic Bulletin & Review, 9,* 507–513.

Ristic, J., Wright, A., & Kingstone, A. (2007). Attentional control and reflexive orienting to gaze and arrow cues. *Psychonomic Bulletin & Review, 14,* 964–969.

Roseboom, W., & Arnold, D. H. (2011). Learning to reach for ‘invisible’ visual input. *Current Biology, 21,* 493–494.

Rothkirch, M., Stein, T., Sekutowicz, M., & Sterzer, P. (2012). A direct oculomotor correlate of unconscious visual processing. *Current Biology, 22,* 514–515.

Schall, J. D., Nawrot, M., Blake, R., & Yu, K. (1993). Visually guided attention is neutralized when informative cues are visible but unperceived. *Vision Research, 33,* 2057–2064.

Schlaghecken, F., & Eimer, M. (2004). Masked prime stimuli can bias “free” choices between response alternatives. *Psychonomic Bulletin & Review, 11,* 463–468.

Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. *Detection, Search, and Attention. Psychological Review, 84,* 1–66.

Self, M. W., & Roelfsema, P. R. (2010). A monocular, unconscious form of visual attention. *Journal of Vision, 10*. Article 17.

Sommer, W., Leuthold, H., & Schubert, T. (2001). Multiple bottlenecks in information processing? An electrophysiological examination. *Psychonomic Bulletin & Review, 8,* 81–88.

Stuit, S. M., Paffen, C. L. E., van der Smagt, M. J., & Verstraten, F. A. J. (2011). Suppressed images selectively affect the dominant percept during rivalry. *Journal of Vision, 11*. Article 10.

Sweeny, T. D., Grabowecky, M., & Suzuki, S. (2011). Awareness becomes necessary between adaptive pattern coding of open and closed curvatures. *Psychological Science, 22*, 943–950.

Thomas, L. (1997). Retrospective power analysis. *Conservation Biology, 11,* 276–280.

Tipples, J. (2002). Eye gaze is not unique: Automatic orienting in response to uninformative arrows. *Psychonomic Bulletin & Review, 9,* 314–318.

Tong, F. (2001). Competing theories of binocular rivalry: a possible resolution. *Brain and Mind, 2*, 55– 83.

Tong, F., Meng, M., & Blake, R. (2006). Neural bases of binocular rivalry. Trends in Cognitive Sciences, 10, 502–511.

Tsuchiya, N., Koch, C., Gilroy, L. A., & Blake, R. (2006). Depth of interocular suppression associated with continuous flash suppression, flash suppression, and binocular rivalry. *Journal of Vision, 6,* 1068–1078.

Turk-Browne, N. B., Scholl, B. J., Chun, M. M., & Johnson, M. K. (2008). Neural evidence of statistical learning: Efficient detection of visual regularities without awareness. *Journal of Cognitive Neuroscience, 21,* 1934–1945.

Turk-Browne, N. B., Scholl, B. J., Johnson, M. K., & Chun, M. M. (2010). Implicit perceptual anticipation triggered by statistical learning. *The Journal of Neuroscience, 30,* 11177–11187.

Van Gaal, S., Lamme, V. A. F., Fahrenfort, J. J., & Ridderinkhof, R. K. (2011). *Journal of Cognitive Neuroscience, 23,* 91–105.

Wilke, M., Logothetis, N. K., & Leopold, D. A. (2006). Local field potential reflects perceptual suppression in monkey visual cortex. *Proceedings of the National Academy of Sciences, 103*, 17507–17512.

Williams, M. A., Morris, A. P., McGlone, F., Abbott, D. F., & Mattingley, J. B. (2004). Amygdala responses to fearful and happy facial expressions under conditions of binocular suppression. *Journal of Neuroscience, 24,* 2898–2904.

Wolfe, J. M. (1984). Reversing ocular dominance and suppression in a single flash. *Vision Research, 24,* 471–478.

Yantis, S., & Jonides, J. (1990). Abrupt visual onsets and selective attention: Voluntary versus automatic allocation. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 121–134.

Zhang, P., Jiang, Y., & He, S. (2012). Voluntary attention modulates processing of eye-specific visual information. *Psychological Science, 23,* 254–260.

Zhaoping, L. (2008). Attention capture by eye of origin singletons even without awareness: A hallmark of a bottom-up saliency map in the primary visual cortex. *Journal of Vision, 8*. Article 1.

Zhao, J., Al-Aidroos, N., & Turk-Browne, N. B. (2013). Attention is spontaneously biased towards regularities. *Psychological Science, 24,* 667–677.