Research Article

Psychological Science
2015, Vol. 26(3) 325–334

DOI: 10.1177/0956797614564191
pss.sagepub.com

Anticipatory Control Through Associative Learning of Subliminal Relations: Invisible May Be Better Than Visible

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Abstract

We showed that anticipatory cognitive control could be unconsciously instantiated through subliminal cues that predicted enhanced future control needs. In task-switching experiments, one of three subliminal cues preceded each trial. Participants had no conscious experience or knowledge of these cues, but their performance was significantly improved on switch trials after cues that predicted task switches (but not particular tasks). This utilization of subliminal information was flexible and adapted to a change in cues predicting task switches and occurred only when switch trials were difficult and effortful. When cues were consciously visible, participants were unable to discern their relevance and could not use them to enhance switch performance. Our results show that unconscious cognition can implicitly use subliminal information in a goal-directed manner for anticipatory control, and they also suggest that subliminal representations may be more conducive to certain forms of associative learning.

Keywords
consciousness, cognitive processes, subliminal perception, associative processes, attention, open data, open materials

Received 4/10/14; Revision accepted 11/24/14

The studies presented in this article examined whether predictive information contained in subliminal cues could be used to potentiate goal-directed cognitive control. As a result of past associations or explicit knowledge, subliminal presentation of a stimulus can influence cognition by activating perceptual processes (Bar & Biederman, 1998), semantic processes (Draine & Greenwald, 1998), or even control-related processes (e.g., task set, response inhibition, and attentional shift) linked to the stimulus (Lau & Passingham, 2007; Manly et al., 2014; Reuss, Kiesel, Kunde, & Wühr, 2012; van Gaal & Lamme, 2012). However, such activations tend to be reflexive: When the necessary conditions are fulfilled (Kunde, Reuss, & Kiesel, 2012), the subliminal stimulus activates its linked process regardless of its relevance to the goal. Consequently, if the process is congruent with task demands, the task is facilitated, but if not, the task is impeded. Accordingly, it remains unclear how these automatic, passive effects are relevant to controlled cognition.

We investigated whether cognition can extract and use control-relevant information contained in the subliminal stimulus, rather than being passively swayed by such stimuli. Specifically, we tested whether information contained in subliminal cues that predict future task difficulty could be used to enhance proactive control. By subliminal, we mean that participants report seeing nothing at all and cannot guess the identity of the stimulus (Merikle, Smilek, & Eastwood, 2001); clearly, any utilization of information contained in such stimuli could only be implicit. In this regard, many studies have shown that cognition makes implicit use of control-relevant information contained in visible aspects of task context (Bugg & Crump, 2012). For example, in a Stroop task, performance improves at locations where conflicting configurations occur more frequently (Crump, Gong, & Milliken, 2006); in task-switch paradigms, switch costs are lower at frequent switch locations (Crump & Logan, 2010). Such implicit regularities can even alter proactive preparations (Ghinescu, Schachtman, Stadler, Fabiani, & Gratton,

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2010). Although the predictive information in these studies was derived from consciously perceived sources, it is possible that similar information derived from subliminal aspects of task context could also be used. Cognition would certainly be much more efficacious if it made use of control-relevant information present in aspects of the task environment that were not consciously perceived.

Our study links two streams of research: One investigates cognitive processes that can be elicited through subliminal cues (van Gaal & Lamme, 2012), and the other investigates implicit instantiation of control through control-relevant statistical relations in the task context (Bugg & Crump, 2012). Our interest in this topic arose from studies outlined earlier in which a different masked prime was linked to each of the specific tasks between which participants had to switch (e.g., Lau & Passingham, 2007; Manly et al., 2014). Our starting point was trying to determine whether the requirement to switch could be facilitated independently of task. Many of the important differences between those studies and the current study arose through pilot testing. These included having longer durations between the masked cue and the stimulus (2–3 s vs. around 100 ms) and placing the participants under considerable time pressure. Formal investigations of these two factors are presented in Experiments 5 to 8. Experiments 9 and 10 investigated whether the cues needed to be subliminal for the effect to operate.

In our experiments, participants performed task-switching tests. On each trial, participants saw a colored rectangle that indicated which of two tasks should be performed on the numbers or letter inside it. A couple of seconds before these were presented, one of three subliminal cues appeared: One cue predicted a switch from the prior task, another cue predicted a repetition of the prior task, and a third cue was nonpredictive (and could therefore appear before either type of trial). The cues were not linked to any task set; rather, they predicted the switch/repeat status of the trial, and therefore the participants could use them to make proactive goal-directed changes in the currently active cognitive set.

Experiment 1

Method

Participants. Twenty-one healthy participants (13 women, 8 men; age range = 18–40 years) were recruited through the Medical Research Council Cognition and Brain Sciences Unit (MRC-CBU) volunteers' panel. They gave written informed consent before the experiment and were paid £8.50 for their participation. All had normal or corrected-to-normal vision. Sample size was determined via pilot testing and with reference to recent studies of task-set priming (Lau & Passingham, 2007; van Gaal, Ridderinkhof, Fahrenfort, Scholte, & Lamme, 2008; Zhou & Davis, 2012).

Stimuli and procedure. Participants sat at a comfortable distance (around 50 cm) from the cathode ray tube monitor (refresh rate = 85 Hz). Before the main experimental session, participants practiced 6 trials of each task (12 trials total), after which they were told that from then on the color of a rectangle would indicate which task to perform. Trials began with a brief presentation (11.67 ms) of one of the three cue letters ("O," "M," and "T"; 40-point Arial type) followed by a blank screen (23.2 ms). This was immediately followed by a mask consisting of a pattern of five *X*s to render the cue letter subliminal (Fig. 1). The mask remained on-screen for 500 ms and was followed by the stimulus after 1.5 to 2.5 s. One cue letter (e.g., "M") preceded only switch trials and occurred before 50% of such trials. Another cue letter (e.g., "T") preceded only repeat trials and occurred before 50% of such trials. The final cue letter (e.g., "O") preceded switch trials and repeat trials with equal frequency and occurred before the remaining 50% of trials of each category. The actual identities of cues in each of these roles varied across participants. We had confirmed through pilot studies that almost all participants remained ignorant of the presence of cues in our experimental set-up.

In each trial, two different numbers (selected from all integers from 1 through 99) were presented 0.5° to each side of the central fixation spot. In each pair of numbers, one appeared in large type (60-point Arial) and the other appeared in small type (30-point Arial). The numbers were surrounded by a colored rectangle. Participants responded by pressing one of two keys on a standard QWERTY keyboard (press "Z" with the left index finger for left or number pad "3" with the right index finger for right; i.e., manually and spatially congruent with the targets). A blue rectangle indicated that participants should press the key on the same side as the number with the lower value; a green rectangle indicated that participants should press the key on the same side as the number in smaller type. On 75% of trials, the task was the same as in the previous trial; in the remaining 25% of trials, the task switched. The tasks were assigned in random order. The stimulus was displayed until a response was made. Incorrect responses triggered feedback in the form of a low-frequency tone. The next trial began after a gap of 2 to 3 s, during which participants saw a fixation cross.

After the initial run of 50 trials of the main experimental session, an instruction screen informed the participants that subsequent responses had to be both accurate and fast; accurate but slow responses would be considered "incorrect" and would be accompanied by the error feedback tone. The threshold for speed was set at the

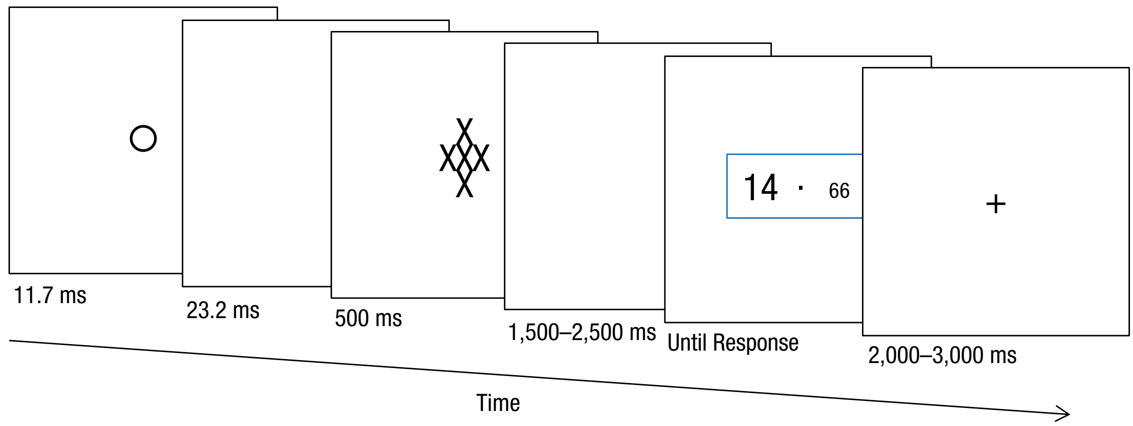

Fig. 1. Task schematic for Experiment 1. Trials began with a brief presentation of a cue letter, which was then immediately masked to render it subliminal. The stimulus appeared after the mask and consisted of two numbers of unequal value and font size. The color of the rectangle around the numbers indicated which of the two tasks participants should perform; blue instructed participants to choose the number with the smaller value, and green instructed them to choose the number in the smaller font. The stimulus remained on the screen until a response was made. The next trial proceeded after a gap of 2 to 3 s.

60th percentile for that participants' correct response times (RTs) on the preceding repeat trials (i.e., if that distribution of responses continued, 40% would now be errors). This threshold was revised after 100 trials. Participants were not informed that the speed threshold applied only to repeat trials. This manipulation was intended to drive faster responses, increasing the challenge of the infrequent switch trials and the goal-directed value of the subliminal cues.

The experiment consisted of 250 trials. Earlier pilot experiments indicated that the unconscious cue effect was most evident early in the experiment and became weaker as task performance became more habitual. This trial number was chosen in an attempt to optimally balance generating sufficient numbers of switch trials and minimizing task habituation. Compared with practiced performance, initial trials on a novel task tend to produce greater fluctuations in RT and a higher number of outliers. Consequently, unless stated otherwise, the statistical tests were performed on the more stable median values rather than mean values.

Cue perception. Before the experimental session, the participants were told that *X*s would precede each trial and were to be ignored. They were not told about the cue letters. On postexperiment questioning about the presence of cues, most participants (18 of 21) had been completely unaware that anything other than the *X*s had been displayed. The rest (3 of 21) said that they were aware that something had been presented before the mask but did not know its identity and did not know whether the subliminal cues involved digits, letters, symbols, or a combination. None of them knew the number of cue types presented.

To create a more objective measure, we asked participants to respond to 30 presentations of the three cues followed by the mask as in the main experiment. After each presentation, participants had to guess the cue identity by selecting the corresponding key from the keyboard (letter, number, or standard keyboard symbols). Although they were encouraged to guess if they could not see anything, they were also given the option of pressing "Enter" if they did not want to guess. Note that this procedure will overestimate the cue visibility during the actual experiment because, unlike in the experiment, participants were now trying to identify the cue.

Most participants (16) pressed "Enter" on all trials or made incorrect choices (mostly of letters or numbers that had never been presented as cues in the experiment). The remaining 5 participants made correct choices on two to seven trials. In each of these cases, only one of the three cues was correctly identified.

Results

Performance on switch trials, relative to repeat trials, incurred a switch cost that was evident in longer RTs (836 vs. 689 ms) and lower accuracy rates (79% vs. 92%). If participants were able to learn the predictive value of the cue that preceded only switch trials and could instantiate relevant anticipatory control in response to it, the performance on switch trials preceded by this cue would be better than on switch trials preceded by the nonpredictive cue. This was indeed the case (mean RT—predictive cue: 819 ms; nonpredictive cue: 871 ms; mean difference = 52 ms, 95% confidence interval, or CI = [19.5, 84.4]), two-tailed paired $t(20) = 3.34$, $p < .01$. However, error rates did not differ across these two groups of switch trials (predictive cue: 78.9%; nonpredictive cue: 78.8%), p = .8.

Faster responses alone do not necessarily indicate better control, because they may result from a trade-off in accuracy. To address this issue, we calculated a performance metric in which we divided accuracy by RT. An increase in this metric would occur only if RT or accuracy improved without compromising the other.

This more global index of performance also indicated that the subliminal cues had been used to enhance relevant control (predictive cue: 10.33; nonpredictive cue: 9.63; mean difference = 0.70, 95% CI = [0.04, 1.36]), two-tailed paired $t(20)$ = 2.2, p = .04. The difference in the performance metric on switch trials preceded by the predictive cues and those preceded by nonpredictive cues was divided by its standard deviation to get a Cohen's d value of 0.48.

Subliminal cues that predicted repeat trials were also linked with improved performance on these trials (performance metric = 14.2 for trials preceded by a predictive cue and 13.5 for trials preceded by a nonpredictive cue; mean difference = 0.63, 95% CI = [−0.03, 1.3]), Cohen's d = 0.43, two-tailed paired $t(20)$ = 1.98, p = .06.

Experiments 2 and 3

Given the recent controversy regarding some experiments on unconscious biasing (Shanks et al., 2013), we replicated the current findings in two other experiments involving different tasks and participant groups.

Method

Participants. Twenty (11 women, 9 men; Experiment 2) and 19 (9 women, 10 men; Experiment 3) healthy participants (age range = 18–40 years) were recruited through the MRC-CBU volunteers' panel. They gave written informed consent before the experiment and were paid £8.50 for their participation. All had normal or corrected-to-normal vision.

Stimuli and procedure. Experiment 2 was similar to Experiment 1, except that the cues consisted of one of three numbers ("2," "4," or "8"), and the stimuli consisted of a single letter presented in a colored rectangle. The letters and cues were presented in 48-point Arial type. The rectangle's color again indicated which task to perform. A blue rectangle indicated that participants were to categorize the letter as a vowel (by pressing the left key) or as a consonant (by pressing the right key); a green rectangle indicated that participants were to categorize the letter as lowercase (left key) or uppercase (right key). As in the earlier experiment, one number only preceded switch trials, another only preceded repeat trials, and another preceded both switch and repeat trials.

Experiment 3 was similar to Experiment 1, except that the cues consisted of one of three letters ("O", "M", or "T,"), and stimuli consisted of a single number (0–100) presented in a colored rectangle at the center of the monitor. The number was presented in either 48-point or 24-point Arial type. The color of the rectangle again indicated the relevant task. A blue rectangle indicated that participants were to categorize the number as less than 50 (by pressing the left key) or greater than 50 (by pressing the right key); a green rectangle indicated that participants were to categorize the type size as large (left key) or small (right key). The cues had the same predictive relationships as in Experiment 1, and the actual identities of the cues in these roles varied across participants.

Cue perception. Postexperiment testing for cue perception yielded results similar to those for Experiment 1. None of the participants in either experiment was aware of the identity or number of cues. Participants then saw 30 presentations of cues. Although none of the participants in Experiment 3 could identify cues on any trial, 4 participants from Experiment 2 were able to make correct identification on one to six trials.

Results

Table 1 summarizes performance in these experiments. In both experiments, performance on switch trials that were preceded by the predictive cue was better than on switch trials preceded by the nonpredictive cue. In Experiment 2, the mean difference in the performance metric was 1.0 (95% CI = [0.45, 1.57]), Cohen's d = 0.84, two-tailed paired $t(19)$ = 3.8, p = .001. In Experiment 3, the mean difference in the performance metric was 0.7 (95% CI = [0.02, 1.14]), Cohen's d = 0.5, two-tailed paired $t(18)$ = 2.2, p = .04. The performance on repeat trials was not affected by the cues (Experiment 2—predictive cue: 10.8; nonpredictive cue: 10.6; 95% CI of the difference = [−0.3, 0.8]; Experiment 3—predictive cue: 16.09; nonpredictive cue: 16.10, 95% CI of the difference = [−0.6, 0.6]).

Having established that predictive cues were used to enhance control, we next investigated whether this use was flexible (as should be the case if goal relevance was a prerequisite for the effect). Specifically, we examined whether participants would adapt to regain advantage if the relation between cue and trial type changed midtask.

Experiment 4

Method

This experiment consisted of two separate but consecutive blocks. In Block 1, the cues and stimuli were identical to those in Experiment 2; in Block 2, the subliminal cues exchanged roles. The results in Block 1 were

Table 1. Summary of Performance in Experiments 2, 3, and 5 Through 10

Measure and cue type	Experiment 2	3	5	6	7	8	9	10
RT (ms)								
Switch trials[a]	1,385	855	858	1,186	997	1,196	1,021	1,262
Nonpredictive cues	**1,384**	**879**	856	1,133	1,002	1,191	998	1,246
Predictive cues	**1,251**	**843**	871	1,237	1,004	1,213	1,032	1,301
Repeat trials	1,035	600	669	784	834	931	756	899
Accuracy (%)								
Switch trials	91	86	81	87	90	89	88	93
Nonpredictive cues	89	85	83	87	91	90	88	92
Predictive cues	92	87	80	86	89	88	88	92
Repeat trials	96	93	91	95	95	94	94	97
Performance on switch trials (accuracy divided by RT)[b]								
Nonpredictive cues	**6.4**	**9.8**	10.2	8.1	9.4	8.2	8.8	7.6
Predictive cues	**7.4**	**10.5**	9.9	7.5	9.3	7.9	8.5	7.4

Note: RT = response time. For Experiments 2 and 3, boldface type highlights which measures differed significantly between trials with nonpredictive cues and trials with predictive cues (two-tailed paired-sample t test, $p < .05$).
[a]The 95% confidence intervals for the RT difference between trials with nonpredictive and predictive cues are as follows—Experiment 5: [−22, 52]; Experiment 6: [3, 193]; Experiment 7: [−46, 48]; Experiment 8: [−69, 115]; Experiment 9: [−42, 107]; Experiment 10: [−25, 117]. [b]The 95% confidence intervals for the performance difference between switch trials with nonpredictive and predictive cues are as follows—Experiment 5: [−1.2, 0.5]; Experiment 6: [−1.2, 0.2]; Experiment 7: [−0.62, 0.43]; Experiment 8: [−0.93, 0.36]; Experiment 9: [−0.75, 0.13]; Experiment 10: [−0.37, 0.17].

expected to be the same as in Experiment 2. In Block 2, we tested whether the previously learned association could be unconsciously revised given a change in task-context relations and whether the new contingencies could be used to enhance control. Hence, in Block 2, better performance was expected on switch trials preceded by the newly predictive but previously nonpredictive cue.

Participants. Twenty-one healthy participants (age range = 18 to 40 years, 12 women, 9 men) were recruited through the MRC-CBU volunteers' panel. They gave written informed consent before the experiment and were paid £8.50 for their participation. All had normal or corrected-to-normal vision.

Stimuli and procedure. Block 1 consisted of 220 trials and was identical to Experiment 2. Block 2 consisted of 400 trials, but cues exchanged roles. The cue that predicted switch trials in Block 1 became nonpredictive and preceded 50% of switch trials and 50% of repeat trials, and the cue that was nonpredictive became predictive and preceded the remaining 50% of switch trials. The cue that predicted the other 50% of repeat trials did not change. Because we could not be sure how long it would take for participants to learn the changed relations, we excluded the first 100 trials of Block 2 from analysis.

Cue perception. Postexperiment testing for cue perception revealed that no participant was aware of the identity or number of cues. On direct testing, 2 participants made correct guesses on five and seven trials.

Results

In Block 1, on switch trials preceded by the predictive cue rather than by the nonpredictive cue, participants had faster RTs (predictive cue: 1,088.8 ms; nonpredictive cue, 1,193.6 ms; 95% CI of the difference = [40, 170]), two-tailed paired $t(20) = 3.35$, $p < .01$; higher accuracy rates (predictive cue: 88.2%; nonpredictive cue: 82.6%; 95% CI of the difference = [1.9, 9.2]), two-tailed paired $t(20) = 3.2$, $p < .01$; and higher scores on the performance metric (predictive cue: 8.5; nonpredictive cue: 7.2; 95% CI of the difference = [0.6, 2.0]; Fig. 2), two-tailed paired $t(20) = 3.8$, $p = .001$, Cohen's $d = 0.86$.

In Block 2, participants' performance was better on switch trials that followed the currently predictive but previously nonpredictive cue than on the other switch trials. This manifested as faster RTs (777 vs. 799 ms; 95% CI of difference = [0.8, 43.0]), one-tailed paired $t(20) = 2.16$, $p = .02$, and higher scores on the performance metric (11.0 vs. 10.6; 95% CI of difference = [−0.17, 1.00]), one-tailed paired $t(20) = 1.5$, $p = .07$; Cohen's $d = 0.33$. This flexibility in using subliminal cues is in sharp contrast to effects seen with priming task sets in prior work. Priming effects

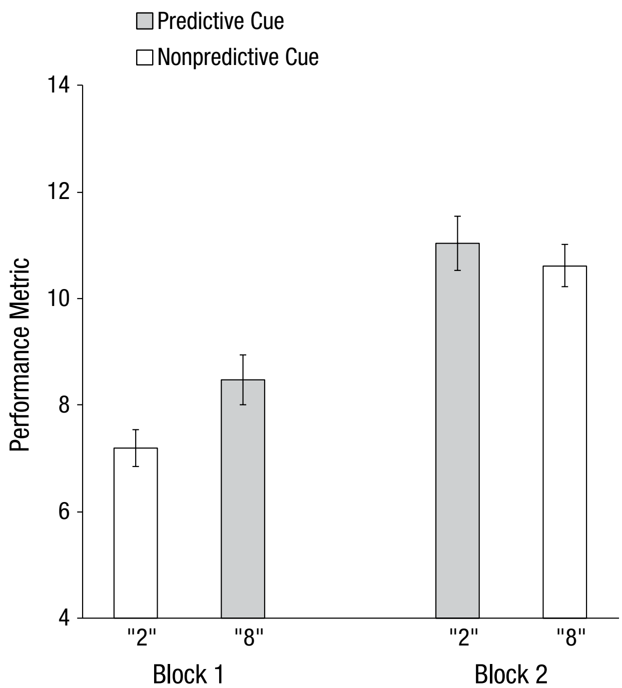

Fig. 2. Mean value of the performance metric as a function of block and predictive-cue assignment. The performance metric was calculated as response time divided by accuracy. Error bars represent standard errors.

seem to work from the bottom up and occur irrespective of their relevance to the current goal. Hence, such effects linger even when the cue is no longer associated with a particular task set (Manly et al., 2014; Zhou & Davis, 2012).

A repeated measures analysis of variance revealed that the magnitude of the cue effect was significantly greater in Block 1 (change in performance metric = 1.3) than in Block 2 (change in performance metric = 0.4), $F(1, 20) > 11.5$, $p < .003$. This was not unexpected: In our pilot testing, the presence of stronger cueing effects in early trials than in late trials (and as illustrated in subsequent experiments) indicated that the goal-directed use of these cues appears greatest when that goal is most difficult. In this experiment, by the time participants reached Block 2, the tasks had become habitual and therefore relatively less demanding.

Experiments 5 and 6

We next investigated the temporal nature of the control observed in the previous experiments. The 2- to 3-s gap between cues and trials suggests that this control instantiated in response to predictive cues was proactive, akin to control preparations that occur when imminent switch is explicitly cued (Monsell, 2003). Such explicitly cued switches require at least 1 s of preparation for maximum benefit. In contrast, reflexive control effects are instantiated after control need has arisen (Braver, 2012), and control effects of subliminal priming of task sets are optimally seen at durations of around 100 ms (van Gaal & Lamme, 2012). We predicted that if the control demonstrated in Experiments 1 to 4 was strictly prospective, it would disappear at smaller intervals typical of priming experiments.

Method

Stimuli and procedure. Experiments 5 and 6 were very similar to Experiments 1 and 2, respectively, except that the mask succeeding the cue was presented for 81.63 ms and was immediately followed by the stimulus. Consequently, the gap between the subliminal cue and the stimulus was 104.8 ms, rather than 2 to 3 s as in Experiments 1 and 2.

Participants. Twenty healthy participants (11 women and 10 men in Experiment 5; 10 women and 11 men in Experiment 6; age range = 18–40 years) were recruited for each of the two experiments through the MRC-CBU volunteers' panel. They gave written informed consent before the experiment and were paid £8.50 for their participation. All had normal or corrected-to-normal vision.

Cue perception. Postexperiment testing for cue perception showed that none of the participants in either of the two experiments had been aware of the identity or the number of cues. None of them made a single correct detection on explicit testing.

Results

Table 1 summarizes performance in these experiments. In Experiments 5 and 6, unlike Experiments 1 and 2, performance did not differ on switch trials preceded by the predictive cue compared with those preceded by the nonpredictive cue ($p > .35$). The shorter gap between cue and stimulus presentation in Experiments 5 and 6 compared with Experiments 1 and 2 significantly reduced the benefit of predictive cues in switch-trial performance, $F(1, 79) = 17.9$, $p < .001$. In fact, in Experiment 6, the switch-trial RT after predictive cues was significantly slower than that after nonpredictive cues (1,237 vs. 1,133 ms, respectively).

Thus, reducing the time available removed or even slightly reversed the switch-cost benefit after predictive cues. This makes it unlikely that results in Experiments 1 to 4 represent a phenomenon akin to priming a specific task set. It also makes it unlikely that the control in question could be elicited reflexively through the task stimulus. The current results support our previous assertion that the switch-cost benefit accrues from relevant proactive changes to anticipatory control.

Experiments 7 and 8

We argued earlier that a highly challenging switching task is necessary to observe goal-directed use of subliminal cues. We attempted to demonstrate this effect in Experiments 7 and 8, which again adopted the methods of Experiments 1 and 2, respectively. In these experiments, however, we made switching easier by removing the requirement for fast responses and by making switch trials more frequent (50% rather than 25%). If challenge is important, we would expect to see diminished predictive cue benefits on switch trials. However, if the mere association between cues and switch trials is sufficient to activate relevant processes (as tends to be the case with many unconscious effects), we might expect the benefits to persist, or even increase, because of the greater exposure to cue-switch trial pairings created by making switch trials more frequent.

Method

Participants. Twenty healthy participants (10 women and 10 men in Experiment 5; 12 women and 8 men in Experiment 6; age range = 18–40 years) were recruited for each of the two experiments through the MRC-CBU volunteers' panel. They gave written informed consent before the experiment and were paid £8.50 for their participation. All had normal or corrected-to-normal vision.

Stimuli and procedure. Experiments 7 and 8 were very similar to Experiments 1 and 2, respectively, with two exceptions: Half of all trials were switch trials, and no response deadline was imposed, although participants were asked to respond as quickly as possible without making errors.

Cue perception. Postexperiment testing for cue perception showed that none of the participants in either of the experiments had been aware of the identity or number of cues. None of them made a single correct detection on explicit testing.

Results

Table 1 summarizes performance in these experiments. In Experiments 7 and 8, unlike Experiments 1 and 2, performance did not differ on switch trials preceded by the predictive cue compared with those preceded by the nonpredictive cue ($p > .35$). The increase in frequency of switch trials and the lack of a deadline in Experiments 7 and 8 compared with Experiments 1 and 2 significantly reduced the benefit of predictive cues in switch-trial performance, $F(1, 79) = 17.9$, $p < .001$. Thus, mere association between subliminal cues and switch trials was not sufficient for using the control-relevant information contained in them, which occurred only when switching was very challenging.

This result seems to suggest that cue use may depend on the magnitude of the control demands predicted by the cue. We speculate that increased strength of control processes in response to higher control demands increased the top-down control over information in sensory cortices and facilitated the subsequent utilization of subliminal information in these regions.

Experiments 9 and 10

In Experiments 9 and 10, we again used the methods of Experiments 1 and 2, except that we made the cues consciously visible by removing the visual mask. Participants were not told about the relationship between cues and the subsequent trial types. They were informed only that before every trial, they would see a letter or number that was to be ignored.

Method

Participants. Twenty-three participants (13 women and 10 men; Experiment 9) and 21 participants (11 women, 10 men; Experiment 10) were recruited through the MRC-CBU volunteers' panel. All participants (age range = 18 to 40 years) were healthy. They gave written informed consent before the experiment and were paid £8.50 for their participation. All had normal or corrected-to-normal vision.

Stimuli, procedure, and cue perception. Experiments 9 and 10 were very similar to Experiments 1 and 2, respectively, except that the mask was not presented, making the cue preceding each trial visible. Participants were instructed that trials would begin with the presentation of a letter (Experiment 9) or a number (Experiment 10) that was to be ignored. After the experiment, participants were asked, "What was the significance of the letter/number that preceded each trial?" Because none of the participants answered correctly, we asked, "Was there anything special about trials that followed M/2 in relation to the preceding trial?" None of the participants knew the answer. When we asked participants to guess, most of them tried to relate cues with other characteristics of a trial (e.g., "Did it precede when the numbers involved were made of two digits?").

Results

Table 1 summarizes performance in these experiments. There was no difference in switch performance on trials preceded by the predictive cues than on those preceded by nonpredictive cues ($p > .2$). Accordingly, the absence of the mask and the visibility of the cue in Experiments 9 and 10 compared with Experiments 1 and 2 significantly reduced the benefit of predictive cues in switch-trial performance, $F(1, 79) = 17.9$, $p < .001$, $F(1, 83) = 20.0$, $p < .001$.

It is possible that cue utilization would have been apparent if the experiment had been longer (cf. Crump & Logan, 2009; Ghinescu et al., 2010). However, the current results nonetheless show that the dynamics of the associative learning or of the implicit instantiation of control (or both) differ when they are based on unconscious versus conscious perceptual representations. Conscious awareness of the cue seems to have slowed or abolished its implicit utilization. Raio, Carmel, Carrasco, and Phelps (2012) reported similar findings: Fear learning occurred faster when it was based on unconscious representations. These findings also suggest that qualitative differences may exist between conscious and unconscious perceptual representations; unconscious representations may be more than poor, noisy versions of conscious representations.

Discussion

Despite participants' being entirely unaware of subliminal cues in a series of challenging switch tasks, cues predicting switch trials were reliably associated with improved performance. This robust effect was observed across four variants of stimuli and tasks in four independent participant groups. The results of Experiments 1 to 3 showed that, without meta-awareness, participants quite rapidly acquired and used the statistical relations between cue and trial type to improve performance. This was confirmed by Experiment 4, in which the relations were altered midway through the test, and participants adapted and regained the advantage from the predictive cues.

Experiments 5 and 6 examined the time course of the effects and, specifically, whether processes similar to those seen in recent task-set priming studies (van Gaal & Lamme, 2012) might be at play. In fact, the benefits of predictive cues were abolished when presented at a cue-stimulus interval similar to the intervals used in those studies (104 ms). On the basis of our pilot testing, we speculated that the use of subliminal cues might be greatest when they were of highest value for goal attainment. This was examined in Experiments 7 and 8, in which switch trials were made easier via increased frequency and no time pressure. Cue benefits seen in otherwise identical earlier experiments were no longer apparent; this result was consistent with the idea that goal relevance determined the presence of cue benefits. This may be relevant to the inconsistent benefits of predictive cues for the easier repeat trials across the studies. In Experiments 9 and 10, the cues were clearly visible. The absence of predictive benefit suggests that conscious representation interfered with or overrode the processes that had facilitated performance in the otherwise identical earlier experiments.

Extending previous demonstrations of implicit proactive control (Ghinescu et al., 2010), we showed in the current study that such control can be based on information derived from aspects of the task environment outside awareness and conscious knowledge and that subliminal information can be utilized via associative learning even when there is no a priori plan for its use (cf. Kunde et al., 2012). This is important because learning arbitrary and novel relations requires cognitive control reserves (Han et al., 2003; Knight, Cheng, Smith, Stein, & Helmstetter, 2004; Mitchell & Le Pelley, 2010) and has therefore been thought to require consciousness (Clark, Manns, & Squire, 2002; Mitchell, De Houwer, & Lovibond, 2009).

These results have important theoretical implications. Identifying cognitive activities that require consciousness is useful in thinking about why consciousness occurs at all; key arguments in this respect have included that it is necessary for flexible, intentional cognitive control (e.g., Dehaene & Changeux, 2011; Posner, 1994; Shallice & Cooper, 2011). Activity elicited by subliminal stimuli is believed to be localized to the relevant sensory cortex, and such information is thought to be encapsulated within one or more dedicated processing modules (Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006). In contrast, control is argued to require long-range connections in which information from one module becomes available more widely, and frontoparietal connections to sensorimotor regions are particularly important (Miller & Cohen, 2001). Indeed, according to an influential view, this global broadcasting of information is synonymous with conscious awareness (Dehaene & Changeux, 2011). For subliminal stimuli to enhance proactive control, either their representations must extend beyond sensory regions or top-down processes must reach such regions and extract relevant information in the absence of conscious intention, representation, or insight. Either way, the implication is that nonconscious information can be available for global cognitive processes (cf. Baars, 2005). Furthermore, if models relating cognitive control to widespread frontoparietal activation are correct (Duncan, 2013), our results suggest that information relating to the subliminal cues is represented in a sustained (2–3 s) form within these connections and yet remains unconscious.

The important differences between the current results and previous demonstrations of priming of specific control-related processes, such as inhibition or particular task set (for review, see van Gaal & Lamme, 2012), suggest distinct underlying mechanisms. In those studies, very short prime-task intervals were required, and the priming itself appears effortless and rigid (primes activate the associated process irrespective of the situation; Zhou

& Davis, 2012). In contrast, cues in the current studies were separated from trials by 2 to 3 s, they were flexibly utilized (Experiment 4), and they enhanced switch control rather than any particular task set, but only in effortful task situations (Experiments 7 and 8).

However, at least three previous studies on unconscious control (Lau & Passingham, 2007; Manly et al., 2014; Zhou & Davis, 2012) share an intriguing similarity with our results: The effect was reduced or abolished when the cues were made more visible. This may be because nonconscious processing is more efficient than conscious processing in certain domains (e.g., Gentilucci, Chieffi, Daprati, Saetti, & Toni, 1996; Raio et al., 2012). In particular, with regard to the current study, information contained in disparate cognitive representations may be integrated more efficiently unconsciously than consciously (Dijksterhuis, Bos, Nordgren, & van Baaren, 2006). It is also possible that participants in the current studies complied with the instruction to ignore visible cues, but the secondary effect of doing so was to suppress further processing of the cues. Conversely, if participants were unaware of the subliminal cues they could not, by definition, apply the same gating. Further work is needed on the effect of visible cues under different instructions.

The current results question the dichotomy proposed by most dual-system approaches to cognition (Evans & Stanovich, 2013; Kahneman, 2011). In such approaches, processes are nonconscious, fast, associative, automatic, rigid, and subjectively effortless, or they are conscious, slow, propositional, controlled, flexible, and effortful. The mode of cognition evidenced here, however, was unconscious and dependent on associative learning but controlled, flexible, and more adaptive in effortful situations.

Author Contributions

A. A. Farooqui and T. Manly developed the study concept. A. A. Farooqui designed the studies and conducted the experiments. Both authors wrote the manuscript and approved the final version.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Funding

This work was supported by United Kingdom Medical Research Council Grant MC-A060-5PQ20.

Open Practices

All data and materials have been made publicly available via the Open Science Framework and can be accessed at https://osf.io/4m2bq. The complete Open Practices Disclosure for this article can be found at http://pss.sagepub.com/content/by/supplemental-data. This article has received badges for Open Data and Open Materials. More information about the Open Practices badges can be found at https://osf.io/tvyxz/wiki/view/ and http://pss.sagepub.com/content/25/1/3.full.

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