Working memory without consciousness

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Working memory allows individuals to maintain information in the focus of the mind's eye in the service of goal-directed behavior. Current psychological theories (for example, Baddeley's influential model of working memory) [1], computational models [2] and neurobiological accounts of working memory are based on the assumption that working memory operates on consciously represented information. Models of the capacity limits of working memory [3] are silent on this issue. While there has been some suggestion that working memory may be engaged by incidental exposure to visible items [4], current understanding indicates that the encoding of information in working memory, maintenance, retrieval and use in decision making of working memory operate on the contents of consciousness. But no study to date has investigated working memory processing for unconscious information. Here we show that observers can encode a subliminal orientation cue, maintain it 'on-line' even in the presence of visible distracters, and perform above chance in subsequent explicit discrimination, namely, whether a supraliminal orientation probe was tilted clockwise or counter-clockwise relative to the earlier unconscious cue. Our findings challenge the currently held view that working memory processes are contingent on conscious awareness.

Observers were presented with a brief (16.67 ms) and masked orientation Gabor cue followed by a delay period and a subsequent Gabor test. They were encouraged to attend and hold the cue in memory even if they could not consciously perceive it and perform explicit cue-target orientation discrimination (Figure 1A; see also the Supplemental Experimental Procedures in the Supplemental Information). Following this, observers gave subjective ratings, on a scale of 1–4, for their awareness of the cue (Supplemental Experimental Procedures) [5]. Subjective reports are critical to assess conscious experience [5,6].

Only trials on which observers were fully unaware of the cue — for example, trials with '1' rating on the 1–4 awareness scale — were included in the analyses across experiments. A first experiment showed that discrimination performance on unaware trials was above chance (50%; t(6) = 4.01; p = 0.006; two tailed; Figure 1B). Experiments 1–3 also included catch trials where the initial cue was absent (50% of trials) to calculate an objective measure of cue sensitivity (see below).

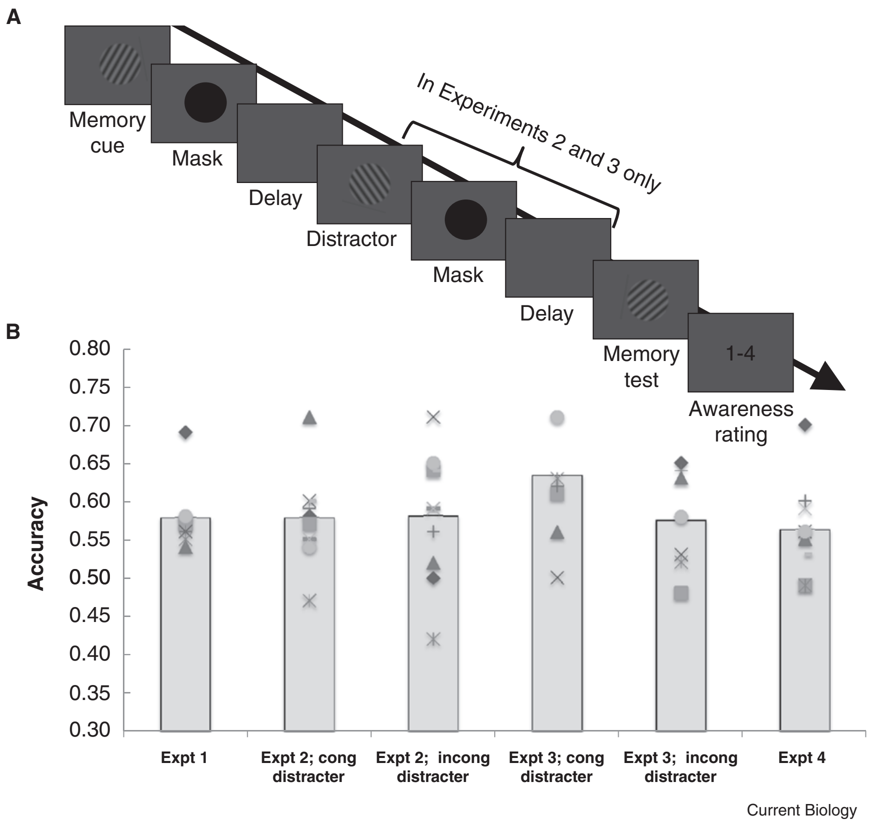

Figure 1. Evidence for working memory without conscious awareness.
(A) Example of the sequence of events during an experimental trial; see below for further details. (B) Memory accuracy across the four Experiments on trials where participants were unaware of memory cue (response 1 on the cue awareness scale). A total of twenty-five healthy volunteers (10 males, mean age: 23 years) were recruited. The study conformed to the ethical standards set in the Declaration of Helsinki. Participants provided informed consent and received monetary compensation for their participation. Experiment 1 (n = 7), Experiment 2 (n = 7) and Experiment 3 (n = 9) used naïve participants. Experiment 4 (n = 9) used seven participants from Experiment 1 and two new participants (the mean performance for the old and new participants in this experiment was similar, namely, 56% for the old and 57.5% for the new participants). The memory cue was a grating contrast with a 0.1 Michelson contrast (spatial frequency: 1 cycle/deg) and could be tilted 10, 40, 70, 100, 130 or 160 deg from the vertical. Its diameter was 3.8 deg of visual angle from a viewing distance of 57 cm. Its duration was 16.67 in Experiments 1–3 and 16.67 or 216.67 ms in Experiment 4. After a delay period (two seconds in Experiments 1 and 4; five seconds in Experiments 2 and 3) there followed a test stimulus that could be tilted 30 degrees either clockwise or anticlockwise relative to the memory cue. Participants were asked to indicate the direction of the tilt. They were then asked to provide a rating of the awareness of the memory cue using the scale: 1, did not see anything; 2, maybe saw something; 3, saw the stimulus but not its orientation; 4, saw the stimulus and its orientation [5]. The proportion of trials for each rating is given in Table S1B. In Experiments 2 and 3, a distracter was presented during the five second delay period. Also Experiments 1–3 contained 50% of catch trials on which no memory cue was presented and the probability of hits and false alarms computed to derive a measure of perceptual sensitivity (d') on '1' rating trials; the 'signal' was defined as the absence of the cue and the 'noise' as the presence of the cue. Thus, '1' rating responses when the cue was absent were labeled as hits and the same responses when the cue was present were labeled as false alarms in order to compute d'.

In Experiment 2, we asked whether observers could maintain the unconscious Gabor cue in the presence of a distracter Gabor. Experiment 2 included an intervening visible orientation Gabor distracter (its duration was 216.67 ms followed by a mask) presented during the cue-test delay (Figure 1A). Distracters could have the same orientation (congruent) or opposite orientation (incongruent) relative to the cue. To ensure that participants attended to the distracter we included 20% of trials with vertical distracters that participants had to report via button press (mean correct: 94%). Discrimination was above chance in both incongruent and congruent conditions ($t(6) = 3.52$; $p = 0.012$ and $t(6) = 2.99$; $p = 0.024$; Figure 1B), suggesting that the representation of the initial subliminal Gabor cue could be maintained 'online' in the presence of a visible distracter of similar physical features. Experiment 3 included brief and masked intervening distracters (16.67 ms duration followed by a mask). Evidence suggests that masked, even invisible, distracters can interfere more with ongoing processing than visible counterparts [7]. We ensured that participants attended to the masked distracters by introducing catch trials where the mask changed to a bigger size (mean correct detection = 98%). Discrimination remained above chance on unaware trials, both in incongruent ($t(8) = 2.7$; $p = 0.027$) and congruent trials ($t(8) = 3.71$; $p = 0.006$).

Psychophysical analyses of perceptual sensitivity do not inform whether or not stimuli reach conscious awareness but they allowed us to learn that observers had poor sensitivity of the cue (mean d' on '1' rating trials across Experiments 1–3 = 0.297; p(Hit) = 0.557; p(False Alarm) = 0.441; Supplemental Table S1A). Across Experiments 1–3 there was no correlation between cue sensitivity and memory discrimination (Supplemental Figure S1; Pearson correlation = –0.18, $p = 0.41$). Also, there were no differences in d' across different task blocks ($Ps > 0.2$), indicating that perceptual sensitivity of the Gabor cue was not affected by the amount of training on the task. Critically, a linear regression analysis following Greenwald [8] with d' as predictor and discrimination as the predicted variable showed that the intercept for the discrimination equation remained above chance (intercept = 60%) at the point where $d' = 0$. Memory discrimination dissociated from perceptual awareness.

Experiment 4 presented observers with two brief Gabor cues; following a delay of 2 seconds, a test Gabor appeared at the location of one of the preceding cues and observers were to report its orientation relative to the cue at that location. The two cues could appear for 16.67 or 216.67 ms, followed by a mask. Observers were instructed that cues could be easy or hard to see. We included visible cues to ensure that observers attempted to maintain the two items in working memory throughout the trials. Discrimination in the visible condition was good (Mean correct = 81%) and remained above chance in the 16.67 ms exposure on unaware trials ($t(8) = 2.97$, $p = 0.018$). Thus, even in the absence of conscious awareness, working memory can exhibit the capacity to hold more than one item at a time.

These findings demonstrate that visual memory can encode, maintain and access unconscious items for explicit discrimination goals. This effect can not be accounted for by unconscious priming mechanisms because: (i) the unconscious cue could be maintained for subsequent discrimination even in the presence of visible distracters which should have overwritten the unconscious cue according to priming accounts; (ii) the effect was observed with cue-target delays of up to five seconds; this contrasts with the short-lived unconscious priming effects typically observed with prime-target intervals of around 100–200 ms [9]; (iii) our task required explicit working memory-guided cue-target discrimination which is difficult to account for based on passive priming.

Our findings challenge the current conceptualization of working memory as operating on the contents of consciousness, which must therefore be expanded in future computational frameworks to incorporate the role of unconscious processing. While prior research has demonstrated that visual selection and awareness may be dissociated [6,10], our evidence for working memory processing on the basis of subliminal cues, even when attention resources are constrained by distracters, suggest that working memory may operate in a rather autonomous fashion independently of both conscious awareness and attention. Further research ought to elucidate the neural basis of this intriguing phenomenon.

Supplemental Information

Supplemental Information contains one Figure, one Table and Supplemental Experimental Procedures and can be found with this article online at doi: 10.1016/j.cub.2011.09.049.

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