Research Article

Is Consciousness a Gradual Phenomenon?

Evidence for an All-or-None Bifurcation During the Attentional Blink

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ABSTRACT—*Several theories of the neural correlates of consciousness assume that there is a continuum of perception, associated with a gradual change in the intensity of brain activation. But some models, considering reverberation of neural activity as necessary for conscious perception, predict a sharp nonlinear transition between unconscious and conscious processing. We asked participants to evaluate the visibility of target words on a continuous scale during the attentional blink, which is known to impede explicit reports. Participants used this continuous scale in an all-or-none fashion: Targets presented during the blink were either identified as well as targets presented outside the blink period or not detected at all. We suggest that a stochastic nonlinear bifurcation in neural activity underlies the all-or-none perception observed during the attentional blink.*

Whether there can be a strict dissociation between conscious and unconscious processing is a debated issue. Some imaging studies of visual perception show a gradual increase in the cortical activity evoked by a stimulus as participants report increased knowledge of the stimulus (Bar et al., 2001; Grill-Spector, Kushnir, Hendler, & Malach, 2000; Moutoussis & Zeki, 2002). For example, Bar et al. (2001), in a study on object recognition, observed a progressive increase in brain activation in several areas of the anterior fusiform gyrus as recognition level increased. According to Farah (2000), "consciousness may be associated only with the higher-quality end of the continuum of degrees of representation" (p. 295). As noted by Kanwisher (2001), signal detection theory and connectionist models have contributed to promote the idea that mental representations are graded rather than discrete.

Other studies, however, challenge this view by showing large all-or-none changes in neural activity when a stimulus fails to be reported compared with when it is reported (Dehaene et al., 2001; Lamme, Super, Landman, Roelfsema, & Spekreijse, 2000; Super, Spekreijse, & Lamme, 2001). Indeed, a qualitative difference between unconscious and conscious processing is generally predicted by theories that view recurrent interactions between distant brain areas as a necessary condition for conscious perception (Dehaene, Kerszberg, & Changeux, 1998; Dehaene & Naccache, 2001; Di Lollo, Enns, & Rensink, 2000; Lamme, 2003; Lamme & Roelfsema, 2000). According to one of these theories (Dehaene et al., 1998), consciousness is associated with the interconnection of multiple areas processing a stimulus through a "neuronal workspace" (Baars, 1989, 1997) within which recurrent connections allow long-distance communication and auto-amplification of activation. Neuronal network simulations (Dehaene, Sergent, & Changeux, 2003) suggest the existence of a fluctuating dynamic threshold. If the primary activation evoked by a stimulus exceeds this threshold, reverberation takes place and stimulus information gains access, through the workspace, to a broad range of areas, allowing, among other processes, verbal report, voluntary manipulation, voluntary action, and long-term memorization. If the activation is below this threshold, however, stimulus information remains unavailable to these processes. Thus, this theory predicts an all-or-none transition between conscious and unconscious perception (see Fig. 1). More generally, many nonlinear dynamic systems with self-amplification are characterized by the presence of discontinuous transitions in internal state, so-called catastrophes (Thom, 1972).

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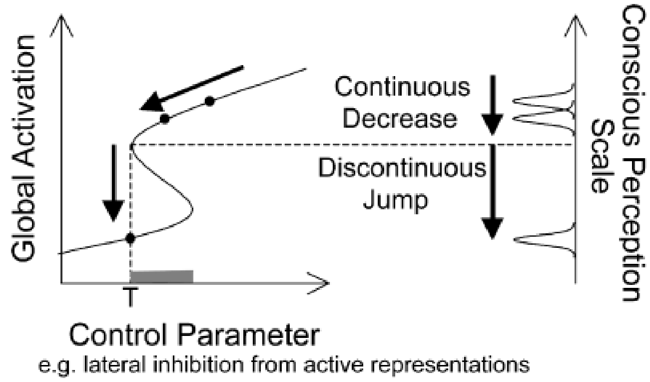

Fig. 1. Prediction of a discontinuous transition in nonlinear dynamic systems with self-amplification. The generic curve on the left describes activation in a nonlinear self-amplifying system (*y*-axis) as a function of a control parameter (*x*-axis) that represents the combined influences of intensity and duration of the current stimulus, as well as inhibitory influences from other concurrently processed stimuli. On the right, predicted response distributions on a subjective visibility scale are shown. Progressively decreasing the control parameter from an above-threshold value (T = threshold) initially leads to a gradual decrease in global activation and thus in subjective visibility. At threshold, however, there is a discontinuous jump to a lower level of activation, corresponding to lack of sustained activation and therefore, according to the global neuronal workspace model, an absence of conscious perception. There is a range of control-parameter values (thick gray segment) within which both high and low states of activation coexist.

In the present study, we tested the all-or-none character of conscious perception using an attentional blink (AB; Raymond, Shapiro, & Arnell, 1992) paradigm. The AB is observed when two targets are embedded in a rapid sequence of distractors: Correct identification of the first target (T1) hinders explicit report of the second target (T2) if they are separated by 200 to 500 ms (Broadbent & Broadbent, 1987). The AB affects a vast range of explicit tasks on T2, but the behavioral measures currently used to detect the AB (accuracy on a forced-choice task) do not allow one to determine whether participants are really unconscious of that target, especially given that accuracy is often slightly above chance level. We examined whether the AB merely degrades the available information on T2 or corresponds to an all-or-none loss of conscious perception of T2. To this end, we asked participants to rate the visibility of T2 on a continuous scale. Using a continuous measure instead of discrete response categories (Bar et al., 2001) allowed us to test the continuous or discontinuous character of perceptual transitions (Massaro & Cohen, 1983). To rule out the possibility that information on T2 had been forgotten by the time the question was asked, we required that the subjective response be made immediately after the presentation of T2.

EXPERIMENT 1: ALL-OR-NONE RESPONDING IN AN AB PARADIGM

We first studied the use of the continuous scale in a classical AB paradigm in which the stimulus-onset asynchrony (SOA), or lag, between T1 and T2 was varied. If the AB merely degrades the available information on T2, the distribution of participants' responses would be expected to shift gradually from the low end of the visibility scale when the AB was strongest (SOA of around 300 ms, corresponding to lag 3 in our experiment) to a higher level of visibility as lag increased. However, if the AB reflects increased probability of an all-or-none loss of conscious perception, responses would be expected to distinguish two types of trials: *not-seen* trials, on which T2 completely failed to be consciously perceived, and *seen* trials, on which T2 was fully perceived. Thus, the distribution of perception ratings would be bimodal. Furthermore, T2 visibility in the seen trials would be unaffected by the T1-T2 lag. Instead, the lag would affect the relative proportions of seen and not-seen trials.

Method

Subjects

Ten right-handed native French speakers (5 women and 5 men; age ranging from 20 to 25) participated in Experiment 1. All had normal or corrected-to-normal vision.

Procedure

Participants were asked to evaluate the subjective visibility of a target (number word) very shortly after the target was presented. Responses were made on a continuous scale, represented by a horizontal bar ($26° \times 2°$) presented at the center of the screen 215 ms after target onset. The bar was labeled "not seen" at the left and "maximal visibility" at the right. Participants moved a cursor on the scale by pressing two designated keys on the computer keyboard, then validated their choice by pressing the space bar. The cursor, a vertical rectangle ($1.2° \times 2°$), could take 21 contiguous positions on the scale that divided the scale by steps of 5% visibility. Its initial position was random. At the beginning of the experiment, participants were instructed to use the scale to rate the visibility of the target as finely as possible and told that there was no time pressure.

Design and Stimuli

The stimuli were presented on a black background at the center of the computer screen (70-Hz refresh) using Expe6 software (Pallier, Dupoux, & Jeannin, 1997). The target for subjective visibility judgment was a four-letter number word, "DEUX," "CINQ," "SEPT," or "HUIT" ($4° \times 1°$), that could be present or absent. In the target-absent condition, an empty screen was presented instead of a number word.

T2 was embedded in a rapid serial visual presentation (RSVP) sequence of distractors (see Fig. 2a). The distractors were strings of four uppercase consonants randomly generated using all consonants except *Q*, *T*, and *X*. The distractors were presented in the same font and at the same spatial location as T2, with the same dimensions. All items in the RSVP sequence were presented for 43 ms and were separated by blanks lasting

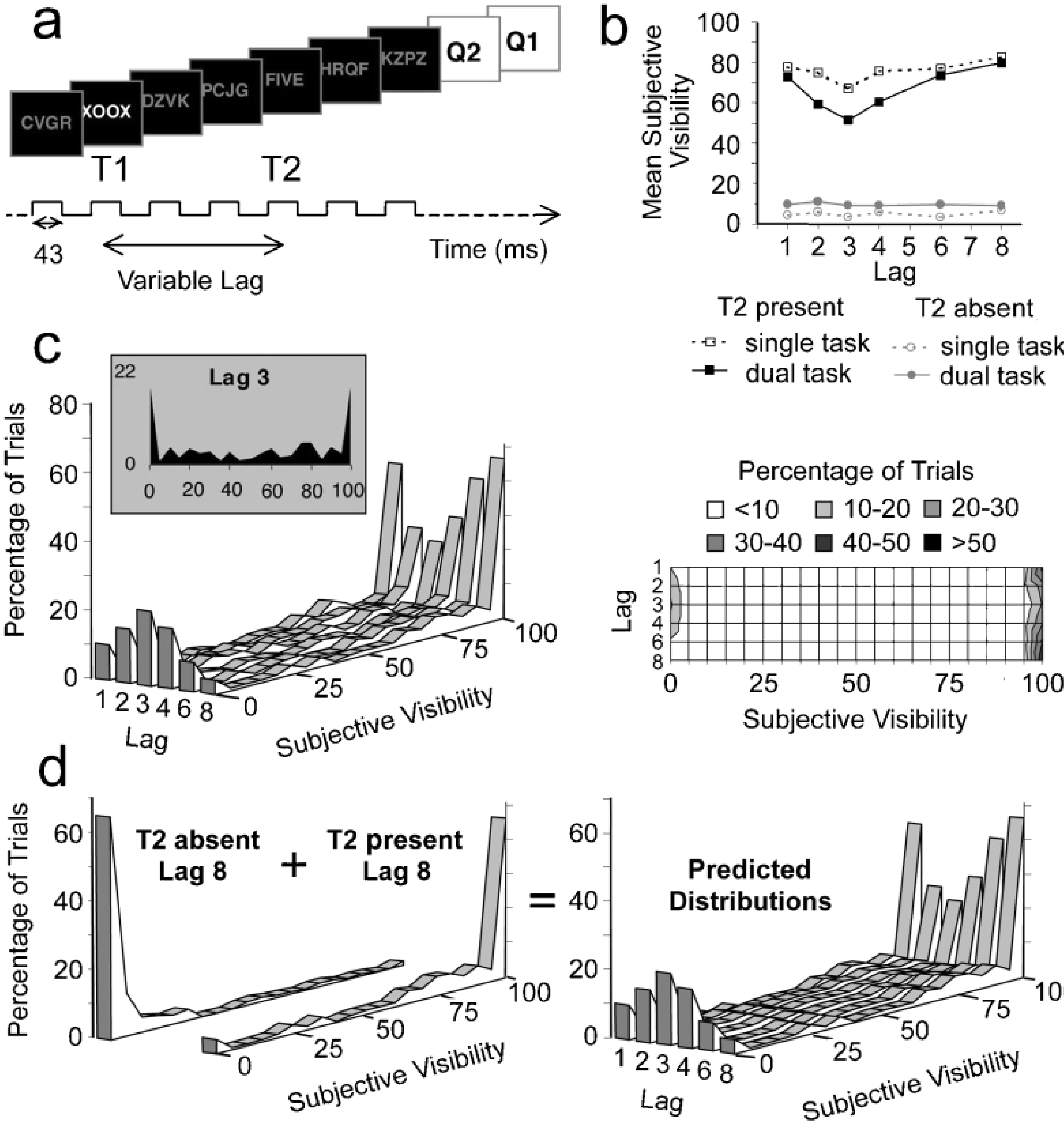

Fig. 2. Design and results of Experiment 1. Each trial (a) consisted of a rapid serial presentation of letter strings, including two targets (T1 and T2) separated by a variable lag, followed by a question on T2 (Q2: visibility scale) and, in the dual-task condition, a question on T1 (Q1). In the actual experiment, T2 was a French number word. The time line represents the succession of presentation and blank periods (downturns of the line). The graph in (b) shows the mean subjective visibility obtained at each tested lag. Results for the single-task and dual-task conditions, with T2 present and absent, are shown separately. The histogram (left) and contour plot (right) in (c) show response distributions in the T2-present, dual-task condition. The distribution for lag 3 is presented in the inset. The graphs in (d) illustrate the multiple linear regression performed on the distributions in (c). These graphs show the distributions for the two predictors (dual task, lag 8, T2 absent and T2 present) and the predicted distributions for all lags. The regression at each lag accounted for more than 91% of the variance in the observed distributions in (c).

43 ms. Except for T1, which was white, all items were presented in blue. T1 was either “XOOX” or “OXXO,” with equal probability, and was either the 7th or the 10th stimulus in the RSVP sequence. T2 was presented at lag 1, 2, 3, 4, 6, or 8 after T1 (corresponding to SOAs of 86, 172, 258, 344, 516, or 688 ms, respectively). To prevent the saliency of T2-absent trials, we replaced some distractors with an empty screen. Specifically, except for the distractors surrounding T1 and T2 and the last distractor in the sequence, each distractor on every trial could be replaced by an empty screen with a 20% probability. The

subjective visibility scale was presented immediately after the offset of the second distractor following T2, hence 215 ms after T2 onset.

In the *single-task* condition, the participant simply evaluated T2 visibility. In the *dual-task* condition, once the participant had evaluated T2 visibility, he or she reported whether the central letters of T1 were "OO" (T1 = "XOOX") or "XX" (T1 = "OXXO"). After a short training period, each participant performed 32 T2-present trials and 32 T2-absent trials for each lag in a dual-task session and 16 T2-present trials and 16 T2-absent trials for each lag in a single-task session. The order of the task conditions was counterbalanced across participants.

Results

Trials with an incorrect response to T1 (2% to 16% across participants) were discarded. Mean T2 visibility rating in the different conditions followed a classical AB pattern (see Fig. 2b). An analysis of variance (ANOVA) restricted to the T2-present condition revealed a significant main effect of task, $F(1, 9) = 21.33$, $p < .001$, $\eta^2 = .70$, and a significant Task × Lag interaction, $F(5, 45) = 4.24$, $p < .005$, $\eta^2 = .32$. In the critical condition (T2-present, dual-task), mean T2 visibility decreased from lag 1 (73%) to lag 3 (51.5%) and then increased again to reach 80% at lag 8, resulting in a significant effect of lag, $F(5, 45) = 10.7$, $p < .0001$, $\eta^2 = .54$. However, at all lags, mean visibility was higher in the single-task condition than in the dual-task condition, and mean visibility in the single-task condition was little affected by lag, $F(5, 45) = 2.7$, $p = .03$, $\eta^2 = .23$. Finally, when T2 was absent, mean subjective visibility was very low (7%) and unaffected by lag, task, or their interaction (Fs < 2).

We then plotted response distributions in each condition and analyzed them with ANOVAs with factors of visibility (21 levels), lag (7 levels), and task (2 levels). When T2 was absent, distributions showed a single peak at 0% visibility (more than 60% of the responses). Conversely, when T2 was present and clearly visible (i.e., at lag 8), the distributions showed a single peak at 100% visibility (47% of the responses in the single-task condition, 49.3% in the dual-task condition). Crucially, during the AB in the T2-present condition, we observed a mixture of those two states (see Fig. 2c). The percentage of responses at 100% visibility dropped and then increased as lag increased, in synchrony with an opposite increase and decrease in the percentage of responses at 0% visibility. At lag 3, the percentage of responses for 0% and 100% visibility were almost equal (21.7% and 21.4%). The ANOVA restricted to the T2-present condition revealed significant Visibility × Task, Visibility × Lag, and Visibility × Task × Lag interactions ($p < .005$, $\eta^2 > .13$).

We tested the hypothesis that responses during the AB are a mixture of discrete seen and not-seen states by submitting the response distribution at each lag to a linear regression, using two predictors: the response distribution observed when T2 was present (*present* predictor) and the distribution observed when T2 was absent (*absent* predictor) at lag 8 in the dual-task condition (see Fig. 2d). For all lags from 1 to 6 in the dual-task condition (i.e., the AB condition), this model accounted for more than 91% of the variance, with significant contributions of both predictors ($p < .005$). In particular, the significant contribution of the *absent* predictor indicated that some of the T2-present trials were subjectively indistinguishable from T2-absent trials. The same regressions in the single-task condition revealed no significant contribution of the *absent* predictor in explaining the response distributions, $t(18) < 2$, $p > .09$, except for a small but significant contribution at lag 3, $t(18) = 3$, $p = .007$. Thus, in the single-task condition, at each lag except lag 3, the *present* predictor was sufficient to give a satisfactory model of the distribution ($r^2 > 90\%$).

In summary, although the subjective visibility scale was designed to be sensitive to continuous changes in perception, participants used it in an all-or-none fashion. The AB did not result in a gradual reduction of T2 visibility, but rather resulted in an increase in the proportion of trials on which T2 was missed and had the same visibility as on target-absent trials. These results support the hypothesis that the AB consists of a stochastic all-or-none loss of conscious access to T2.

EXPERIMENT 2: GRADUAL RESPONDING IN A MASKING PARADIGM

The all-or-none response patterns observed in Experiment 1 could reflect a response bias toward both ends of the scale. Participants might have used a sharp decision criterion, implementing the instructions in such a way that the task became a forced choice between "T2 seen" and "T2 not seen." Experiment 2 rules out this possibility by showing that with the same instructions, participants spontaneously used the scale in a continuous fashion when judging the visibility of masked words of variable durations.

Method

Subjects

Ten right-handed native French speakers (6 women and 4 men; age ranging from 21 to 25) took part in Experiment 2. All had normal or corrected-to-normal vision.

Procedure, Design, and Stimuli

The trial sequence in Experiment 2 is illustrated in Figure 3a. Each trial began with a fixation cross presented at the center of the screen for 301 or 473 ms with equal probability. The cross was followed by the target (number word or blank), a mask, and the same subjective visibility scale used in Experiment 1 (300 ms after target onset). The target number words were the same as in Experiment 1. The total duration of target plus mask was fixed (300 ms). We used six different target durations: 14, 29, 43, 57,

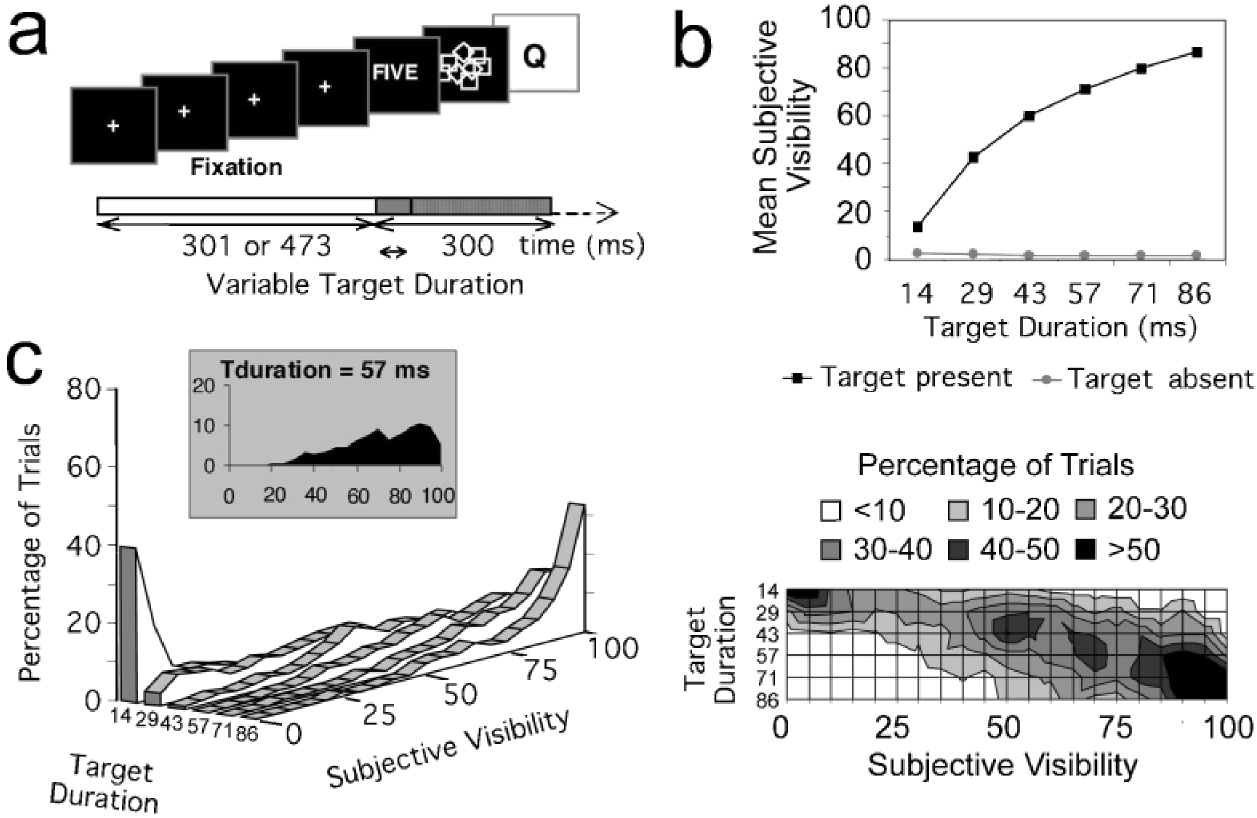

Fig. 3. Design and results of Experiment 2, a masking experiment in which the target duration was varied (a). There was a fixed 300-ms stimulus-onset asynchrony between the target and the question (Q: visibility scale). In the actual experiment, the target was a French number word. The graph in (b) shows the mean subjective visibility obtained at each tested target duration in the target-present and target-absent conditions of this experiment. The histogram (left) and contour plot (right) in (c) show response distributions in the target-present condition. The distribution for a target (T) duration of 57 ms is shown in the inset on the left.

71, and 86 ms. On each trial, the mask was created by semi-random arrangements of diamond and square shapes, covering up the central area of screen where the target appeared (approximately 4.5° × 1.5°). After a short training period, each participant performed 40 target-present trials and 40 target-absent trials in each duration condition.

Results

When the target was absent, duration had no effect on mean visibility ($F < 1$): The response distribution always showed a single peak at visibility 0%. When the target was present, mean subjective visibility increased significantly with duration, $F(5, 45) = 182.6, p < .0001, \eta^2 = .95$ (see Fig. 3b). Response distributions (Fig. 3c) showed a gradual displacement toward higher visibility with increasing target duration, yielding a significant Visibility × Duration interaction, $F(100, 900) = 8.5, p < .0001, \eta^2 = .49$. At each target duration, the distribution was unimodal, with responses clustering around one visibility rating, unlike in Experiment 1.

We conducted a multiple linear regression on the various distributions using as predictors the distributions obtained in the target-present and target-absent conditions at maximal target duration (86 ms). The *absent* predictor did not significantly contribute to these regressions ($ps > .16$), except in the case of the 14-ms duration, $t(18) = 10.43, p < .0001$. Thus, contrary to what was found in the AB experiment, participants did not use the subjective visibility scale in an all-or-none fashion. The scale was sensitive to gradual changes in perception. The contrasting response patterns obtained in the two experiments suggest that the mechanism underlying the AB may be different from a mere perceptual degradation, such as the degradation observed when the duration of a masked target is reduced.

EXPERIMENT 3: COMBINED ALL-OR-NONE AND GRADUAL RESPONDING IN A MIXED AB-MASKING PARADIGM

It could still be argued that responses were biased toward the left and right ends of the scale in Experiment 1, whereas with the simpler stimuli used in Experiment 2, participants succeeded in making the required subtle subjective visibility judgment. We therefore conducted another AB experiment in which we forced participants to use the scale gradually by manipulating the duration of T2. In this experiment, which combined AB with variable T2 durations, we predicted participants would exhibit a mixture of discrete and continuous response patterns: At a long T1-T2 lag, responses would shift gradually toward higher visibility with increasing T2 duration, and at a short lag, the response distribution would split up and become bimodal, with one peak appearing at the "not seen" end of the scale.

Method

Subjects

Ten right-handed native French speakers (5 women and 5 men; age ranging from 21 to 25) took part in Experiment 3. All had normal or corrected-to-normal vision.

Procedure, Design, and Stimuli

Each trial consisted of an RSVP sequence identical to the one used in Experiment 1 except that it ended with a 129-ms blank followed by the target (T2) and mask of Experiment 2, and then the subjective scale (300 ms after T2 onset). (See Fig. 4a.) We used six different T2 durations (14, 29, 43, 57, 71, and 86 ms), two different lags (3 and 8, corresponding to SOAs of 258 ms and 688 ms, respectively), and only the dual-task condition of Experiment 1. After a short training period, each participant performed 32 T2-present trials for each combination of lag and T2 duration and 8 T2-absent trials for each combination of lag and T2 duration.

Results

Trials with an incorrect response to T1 (2% to 11% across participants) were discarded. When T2 was absent, duration had no effect on mean visibility, $F(5, 45) < 1$ (see Fig. 4b). Mean visibility was slightly higher at lag 3 than at lag 8, $F(1, 9) = 9.87$, $p = .012$, $\eta^2 = .52$. There was no significant Lag × Duration interaction, $F(5, 45) < 1$. Response distributions showed a single peak at 0% visibility.

When T2 was present, mean visibility increased significantly with T2 duration, $F(5, 45) = 217.89$, $p < .0001$, $\eta^2 = .96$, and the interaction between duration and lag was significant, $F(5, 45) = 4.31$, $p = .003$, $\eta^2 = .32$, indicative of a significant AB effect. Figure 4c shows the corresponding response distributions: At the two shortest T2 durations (14 and 29 ms), the response distributions showed a peak at 0% visibility. At higher T2 durations, two groups of responses could be distinguished: a peak at 0% visibility that decreased with lag and a peak that gradually shifted toward higher visibility with increasing T2 duration and thus progressively dissociated from the peak at 0%. At T2 duration of 57 ms, the distribution was clearly bimodal for the short lag, with a peak of 15.1% of responses at 0% visibility and another peak around 65% visibility. At the long lag and the same T2 duration, the peak at 0% was much reduced, resulting in a significant Visibility × Lag interaction at this duration, $F(20, 180) = 1.93$, $p = .013$, $\eta^2 = .18$.

Thus, the AB seemed to increase the number of "not seen" responses without affecting the gradual increase in peak visibility with increasing T2 duration. In order to test this hypothesis, for each T2 duration we conducted a linear regression of the distribution obtained at the short lag using as the *present* predictor the corresponding response distribution at the long lag when T2 was present and as the *absent* predictor the distribution obtained at the long lag when T2 was absent and T2 duration was maximal (86 ms). For all T2 durations, r^2 was above 86%. At short (14 ms, 29 ms) and long (71 ms, 86 ms) T2 durations, the contribution of the *absent* predictor was not significant, the *present* predictor being sufficient to model the distribution, $t(18) > 4$, $p < .001$. At T2 durations of 43 ms and 57 ms, however, the contribution of the *absent* predictor was highly significant, $t(18) > 4$, $p < .001$, and the contribution of the *present* predictor remained significant, $t(18) > 3$, $p < .006$.

In summary, although participants used the scale gradually in response to changes in T2 duration, the AB phenomenon still yielded all-or-none response patterns. Because both effects were found within the same trials, the all-or-none response patterns cannot be attributed to response bias. We conclude that whereas reducing the duration of a masked target induces a gradual degradation of subjective perception, the AB deficit causes an all-or-none loss of conscious access.

GENERAL DISCUSSION

Asking participants to rate T2 visibility on a continuous scale allowed us to examine whether the AB results from a continuous degradation or from an all-or-none loss of conscious access. According to the first hypothesis, the AB should have yielded unimodal and gradually shifting response distributions on the visibility scale. Our results invalidate this hypothesis and demonstrate a bimodal distribution: On some trials T2 was entirely invisible, and on others it was as visible as when no T1 task was required.

Because we asked for a subjective visibility judgment on T2 very shortly after T2 was presented (the scale appeared less than 300 ms after T2 onset), our results are unlikely to have been affected by quick forgetting of having seen T2. Rather, among the various psychological accounts of the AB phenomenon, the two-stage model (Chun & Potter, 1995) seems to give the most satisfactory explanation of these results. According to this model, a stimulus must undergo two stages of processing in order to be correctly reported, and the second stage can process only one stimulus at a time. Thus, the AB deficit would reflect the fact that as long as the second stage is occupied by T1, T2 is denied access to this stage and is thus susceptible to being erased by a trailing mask. However, this psychological account

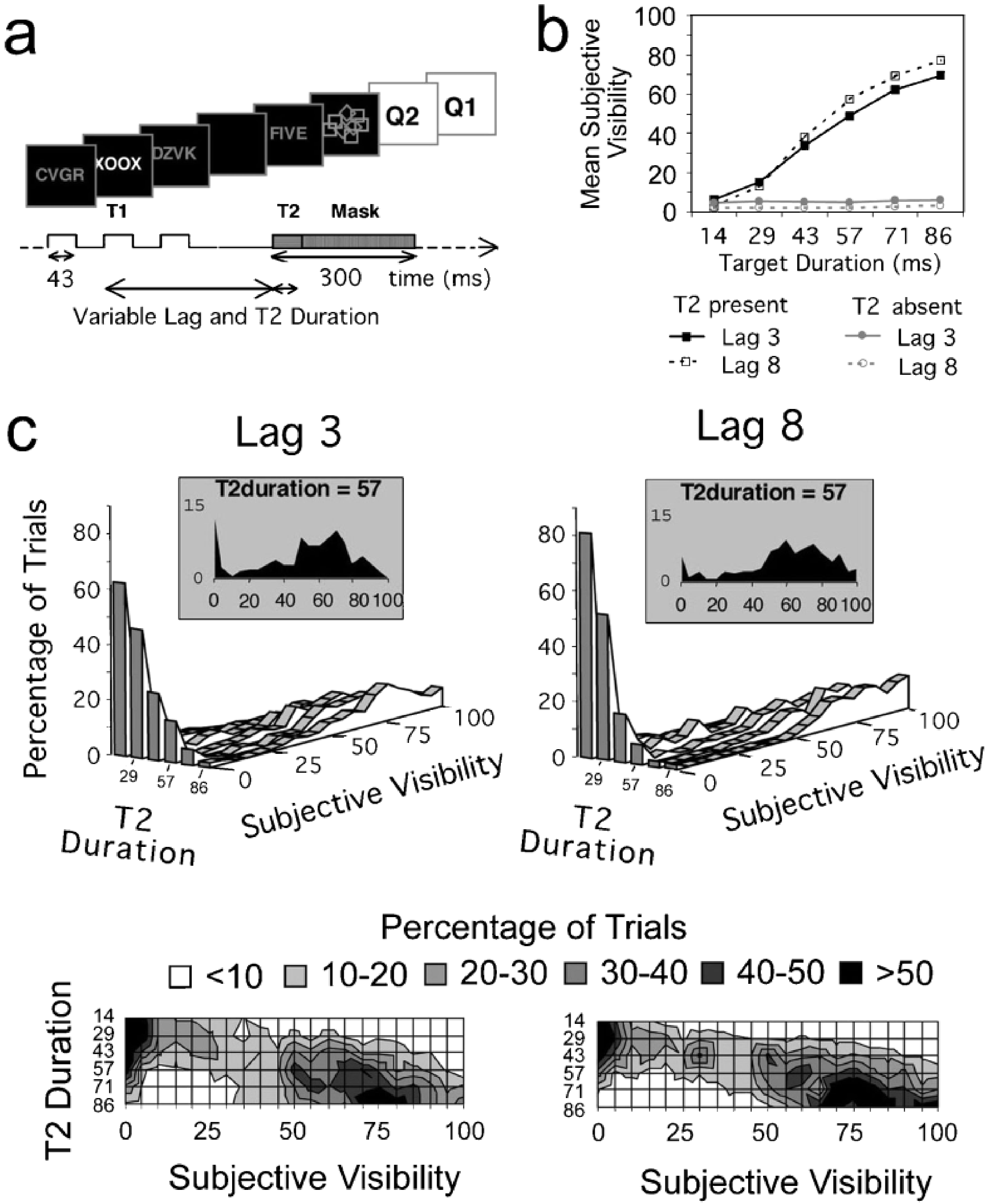

Fig. 4. Design and results of Experiment 3, which mixed the designs of Experiments 1 and 2, varying both the lag between the first target (T1) and the second target (T2) and T2 duration (a). Participants answered questions on both T2 (Q2: visibility scale) and T1 (Q1). In the actual experiment, T2 was a French number word. The time line represents the succession of presentation and blank periods (downturns of the line). The graph in (b) shows the mean subjective visibility obtained at each T2 duration, separately for each combination of lag (3, 8) and T2 presence/absence. The histograms (top) and contour plots (bottom) in (c) show response distributions in the T2-present condition at lag 3 (left) and lag 8 (right). The distributions for T2 duration of 57 ms are shown in the insets.

of the AB does not specify the neuronal mechanisms underlying the two stages, nor their dynamics.

A series of event-related potential studies by Vogel, Luck, and Shapiro (Luck, Vogel, & Shapiro, 1996; Vogel, Luck, & Shapiro, 1998) has shown that several stages of perceptual and semantic processing are unaffected by the AB. However, the P300 wave, which reflects the updating of information in working memory, is suppressed during the AB. These experiments further support the two-stage model of the AB by showing a qualitative difference in the neural processing that takes place inside and outside the AB, with preservation of a first stage of processing and complete disappearance of a second stage of processing during the blink period.

The *global neuronal workspace* model (Dehaene et al., 1998) provides a neural account of the two stages described in psychological models of the AB. According to this theory, the first stage of processing corresponds to what has been called the "feed-forward sweep" (Lamme, 2003), in which a stimulus is automatically processed by a series of brain areas activated sequentially in a bottom-up manner. The second stage corresponds to top-down amplification. On trials in which the stimulus is perceived consciously, bottom-up and top-down inputs reinforce each other until a broad network of cerebral areas becomes ignited via long-distance connections. The entry of the stimulus into this global workspace allows the maintenance of information and the flexibility of processing that characterize conscious perception. If, however, this first activation does not reach the dynamic threshold for self-amplification, activation is confined to a bottom-up transient, and the stimulus cannot be consciously perceived. In this interpretation, the blink acts by cutting the top-down support for T2, because workspace neurons are temporarily occupied coding T1. A neuronal network simulation of this model (Dehaene et al., 2003) was able to reproduce the results from Experiment 1, including the all-or-none response of workspace neurons and the influence of lag on the proportion of trials in which T2 is seen and not seen.

What determines whether a stimulus reaches the threshold for conscious access? It might be small stochastic differences in the first wave of activation or even in the baseline activity preceding the stimulus. Indeed, for threshold stimuli, the blood-oxygen-level-dependent (BOLD) signal in primary visual cortex and the P100 wave were shown to be larger on trials in which the stimulus was seen than on trials in which it was not seen (Pins & Ffytche, 2003). Furthermore, a multiunit recording study in monkeys demonstrated that 100 ms prior to stimulus onset, neural response in primary visual cortex was already stronger for a subsequently reported stimulus than for a not-reported stimulus (Super, van der Togt, Spekreijse, & Lamme, 2003). In the AB, stochastic differences in the time and effort spent to process T1 might determine the all-or-none perception of T2 (Marois, Chun, & Gore, 2000).

We used variable durations of a masked target as a control to demonstrate that subjects could use the visibility scale in a graded manner. The findings suggest that the perception of a masked target increases gradually as a function of its duration. One possible explanation of the observed gradual increase in subjective visibility is that, as target duration increases, the bottom-up wave of activity gains strength and increasingly deeper processing stages are activated. Thus, the information that enters consciousness is increasingly richer. Indeed, subjects reported seeing increasingly more detailed aspects of the masked stimuli—from a few features to single letters, graphemes, and finally the whole word—and they traduced this increasing detail by continuously varying the cursor on the visibility scale. These results do not mean that were we to test a single level of visual perception (e.g., Vernier acuity), we would not find a discontinuous threshold for perception as a function of exposure duration. Indeed, there is a suggestion of a nonlinear threshold effect in Figure 3c, which shows that cursor position seemed to jump as target duration changed from 29 ms to 43 ms. Further research is needed to explore this effect with a higher temporal resolution.

More generally, our work suggests that conscious access is characterized by nonlinear dynamic phenomena, which might ultimately be described mathematically using catastrophe theory (Saunders, 1980; Thom, 1972). The visibility-scale methodology may provide an important tool with which to trace the bifurcation diagrams of subjective perception.

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REFERENCES

Baars, B.J. (1989). *A cognitive theory of consciousness*. Cambridge, MA: Cambridge University Press.

Baars, B.J. (1997). *In the theater of consciousness*. New York: Oxford University Press.

Bar, M., Tootell, R.B., Schacter, D.L., Greve, D.N., Fischl, B., Mendola, J.D., Rosen, B.R., & Dale, A.M. (2001). Cortical mechanisms specific to explicit visual object recognition. *Neuron*, *29*, 529–535.

Broadbent, D.E., & Broadbent, M.H. (1987). From detection to identification: Response to multiple targets in rapid serial visual presentation. *Perception & Psychophysics*, *42*, 105–113.

Chun, M.M., & Potter, M.C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance*, *21*, 109–127.

Dehaene, S., Kerszberg, M., & Changeux, J.-P. (1998). A neuronal model of a global workspace in effortful cognitive tasks. *Proceedings of the National Academy of Sciences, USA*, *95*, 14529–14534.

Dehaene, S., & Naccache, L. (2001). Towards a cognitive neuroscience of consciousness: Basic evidence and a workspace framework. *Cognition*, *79*(1–2), 1–37.

Dehaene, S., Naccache, L., Cohen, L., Bihan, D.L., Mangin, J.F., Poline, J.B., & Riviere, D. (2001). Cerebral mechanisms of word masking and unconscious repetition priming. *Nature Neuroscience*, *4*, 752–758.

Dehaene, S., Sergent, C., & Changeux, J.-P. (2003). A neuronal network model linking subjective reports and objective physiological data during conscious perception. *Proceedings of the National Academy of Sciences, USA*, *100*, 8520–8525.

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.

Farah, M.J. (2000). *The cognitive neuroscience of vision*. Oxford, England: Blackwell.

Grill-Spector, K., Kushnir, T., Hendler, T., & Malach, R. (2000). The dynamics of object-selective activation correlate with recognition performance in humans. *Nature Neuroscience*, *3*, 837–843.

Kanwisher, N. (2001). Neural events and perceptual awareness. *Cognition*, *79*(1–2), 89–113.

Lamme, V.A. (2003). Why visual attention and awareness are different. *Trends in Cognitive Sciences*, *7*, 12–18.

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

Lamme, V.A., Super, H., Landman, R., Roelfsema, P.R., & Spekreijse, H. (2000). The role of primary visual cortex (V1) in visual awareness. *Vision Research*, *40*, 1507–1521.

Luck, S.J., Vogel, E.K., & Shapiro, K.L. (1996). Word meanings can be accessed but not reported during the attentional blink. *Nature*, *383*, 616–618.

Marois, R., Chun, M.M., & Gore, J.C. (2000). Neural correlates of the attentional blink. *Neuron*, *28*(1), 299–308.

Massaro, D.W., & Cohen, M.M. (1983). Categorical or continuous speech perception: A new test. *Speech Communication*, *2*, 15–35.

Moutoussis, K., & Zeki, S. (2002). The relationship between cortical activation and perception investigated with invisible stimuli. *Proceedings of the National Academy of Sciences, USA*, *99*, 9527–9532.

Pallier, C., Dupoux, E., & Jeannin, X. (1997). Expe: An expandable programming language for on-line psychological experiments. *Behavior Research Methods, Instruments, & Computers*, *29*, 322–327.

Pins, D., & Ffytche, D. (2003). The neural correlates of conscious vision. *Cerebral Cortex*, *13*, 461–474.

Raymond, J.E., Shapiro, K.L., & Arnell, K.M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 849–860.

Saunders, P.T. (1980). *An introduction to catastrophe theory*. Cambridge, MA: Cambridge University Press.

Super, H., Spekreijse, H., & Lamme, V.A. (2001). Two distinct modes of sensory processing observed in monkey primary visual cortex (V1). *Nature Neuroscience*, *4*, 304–310.

Super, H., van der Togt, C., Spekreijse, H., & Lamme, V.A. (2003). Internal state of monkey primary visual cortex (V1) predicts figure-ground perception. *Journal of Neuroscience*, *23*, 3407–3414.

Thom, R. (1972). *Stabilité structurelle et morphogénèse*. Paris: Inter-Editions.

Vogel, E.K., Luck, S.J., & Shapiro, K.L. (1998). Electrophysiological evidence for a postperceptual locus of suppression during the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1656–1674.

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