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Brief article

Subjective visibility depends on level of processing

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ABSTRACT

Is visual awareness graded or binary? Experimental work has provided support for both possibilities, leading to two coexisting but contradictory theoretical accounts. Here we propose a promising candidate factor through which to integrate both accounts: the depth of stimulus processing required by the task. We compared color identification (a low-level task) with numerical judgements (a high-level task) performed on the very same colored number stimuli. Psychophysical curves were analyzed for both objective discrimination performance and subjective visibility ratings on a trial-by trial basis. We observed a graded relationship between stimulus duration and visibility in the low-level task, but a more non-linear relationship in the high-level task. Both patterns of results have previously been consistently associated with the graded and the dichotomous account, respectively. Follow-up experiments that manipulate the level of processing can further unify previously inconsistent results, thus integrating two major theories of visual awareness.

1. Introduction

Understanding the behavioral and neural mechanisms of conscious awareness remains one of the core challenges of cognitive neuroscience. In this respect, a longstanding controversial issue is whether conscious awareness is graded or binary. When we perceive an object, do we become gradually aware of it as evidence accumulates, or does awareness emerge in an all-or-none fashion, with a sharp, thresholded transition between the complete absence of conscious perception and full awareness? While many recent studies have attempted to address this question, their results remain strikingly contradictory, despite substantial similarity in the proposed psychophysical designs, in which performance and subjective reports are collected for a range of different stimulus presentation durations. The results of the experiment presented here propose a candidate factor susceptible to reconcile both accounts. We show that the hierarchical level up to which a stimulus is processed (Hochstein & Ahissar, 2002; Lockhart & Craik, 1990) modulates both task performance and subjective visibility reports. The results mirror patterns found in studies supporting both the graded and the dichotomous account. We frame these results theoretically, discuss limits of the present design, and formulate proposals for follow-up investigation that could further integrate both accounts. First, we present studies that were interpreted in favor of the graded or the dichotomous account.

A series of experiments that were taken as support for the graded account of visual awareness consistently reported gradually increasing performance and subjectively experienced visibility with increasing stimulus durations (Overgaard, Feldbæk Nielsen, & Fuglsang-Frederiksen, 2004; Sandberg, Bibby, Timmermans, Cleeremans, & Overgaard, 2011; Sandberg, Timmermans, Overgaard, & Cleeremans, 2010). Participants were exposed to briefly presented masked geometrical objects and were asked, on each trial, to report the shape of the object as well as to judge the clarity of their visual experience on an ordinal four-point scale (Perceptual Awareness Scale, PAS). When objective

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performance and/or subjective visibility was plotted for all stimulus durations, a gradual increase was observed in all three studies. These results were also found for a psychophysical orientation judgment task on textures consisting of small diagonal lines in two different angles (Overgaard, Rote, Mouridsen, & Ramsøy, 2006). Additionally, an fMRI study with the geometrical shape stimuli and a similar subjective visibility scale confirmed that graded perceptual reports from participants reflect genuine intermediate brain states rather than response artefacts (Christensen, Ramsøy, Lund, Madsen, & Rowe, 2006). Several other studies have presented stimuli that are processed early on in the processing hierarchy, and found recurrent processing between posterior brain regions (Boehler, Schoenfeld, Heinze, & Hopf, 2008; Fahrenfort, Scholte, & Lamme, 2008) to be associated with conscious perception. Such findings have led Lamme (2006), Lamme (2010) to develop a graded account of conscious visual perception, which we will call the Recurrent Processing Hypothesis (RPH): higher and lower visual regions engaging in increasing recurrent interactions subtend the gradual increase of awareness of a stimulus, perhaps by promoting increased stability of the corresponding neural activation patterns.

However, studies using stimuli that are processed at a higher level in the processing hierarchy have brought support for the theory that conscious access always involves a sharp, thresholded transition. Among these studies, a number of experiments consistently reported steeply increasing psychophysical curves around the threshold for conscious access (Del Cul, Baillet, & Dehaene, 2007; Del Cul, Dehaene, & Leboyer, 2006; Del Cul, Dehaene, Reyes, Bravo, & Slachevsky, 2009). Participants performed a number comparison task on postmasked Arabic digits (“Smaller or larger than five?”) and judged the subjective clarity of the stimulus. The average performance and visibility ratings per stimulus duration show a constant increase for the very short and very long durations, but a steep increase for the intermediate durations. The psychophysical curve thus shows a significant non-linear rise around the visibility threshold. This pattern was taken as evidence for the dichotomous nature of awareness when Dehaene, Sergent, and Changeux (2003) and Sergent and Dehaene (2004) established that subjective visibility ratings on a continuous scale show a bimodal distribution in attentional blink tasks, reflecting an all-or-none pattern of stimulus detection (once stimuli cross the threshold of visibility they can be reported reliably; stimuli below the threshold remain mostly unreported, even when intermediate ratings on the continuous scale are possible). Moreover, a series of studies using number or word categorization tasks found non-linear neural dynamics to underlay conscious perception (Del Cul et al., 2007; Del Cul et al., 2009; Gaillard et al., 2009). These converging results have been interpreted as lending support to Global Workspace Theory (GWT), which relates the dichotomous nature of conscious perception to global recurrent processing between parieto-frontal and posterior regions (“ignition”) at the moment a stimulus becomes visible (Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006; Dehaene, Kerszberg, & Changeux, 1998).

Here, we propose that the contradictory perspectives offered by the graded and dichotomous accounts may be unified by considering which experimental stimuli and tasks have been used in each. Indeed, experiments that support the graded account have typically used low-level stimuli and tasks, whereas studies that support the dichotomous account have generally used high-level stimuli and tasks. Crucially, studies reporting evidence for the graded or dichotomous account have also shown more graded and more non-linear psychophysical curves, respectively. It is important to emphasize that these curves as such cannot be used to claim either gradedness or dichotomy (see also the discussion). However, in previous research, evidence for the graded (dichotomous) account seems to have been consistently associated with low-level (high-level) tasks and more linear (non-linear) psychophysical curves. Therefore, we propose to test level of processing as a first step towards integration of the graded and dichotomous accounts. To compare the two accounts, we asked participants to express either low-level or high-level judgements on the very same briefly presented and masked colored number stimuli. They had to be categorized along the color (i.e., low-level task) or the number dimension (i.e., high-level task). We predicted and observed a modulation of the steepness of the curves, with a more non-linear curve in the high-level condition (in line with GWT) than in the low-level condition (in line with RPH).

2. Methods

2.1. Participants

Twenty naive participants (4 male, 16 female) took part in the experiment (mean age 21.6 years, $SD = 2.22$), and were paid €10 or received an equivalent amount of course credits.

2.2. Apparatus

Participants were seated in front of a 17 inch CRT monitor (Philips 107S) with a refresh rate of 100 Hz, a screen resolution of 800×600, and a color depth of 16 bit. The experiment was programmed in Eprime 2 Professional (Psychology Software Tools Inc., Pittsburgh, USA; http://www.pstnet.com/eprime.cfm).

2.3. Stimuli

Four different numbers (1, 3, 7, 9) in four different colors (RGB-values of red 1 = 255, 0, 0; red 2 = 255, 100, 100; blue 1 = 0, 0, 255; blue 2 = 100, 100, 255) served as stimuli. These were preceded and followed by a mask consisting of a 25 by 25 grid of small colored squares. Eight different masks were randomly generated before the experiment, using the same four colors as the stimuli (the two reds and two blues; see Fig. 1). Every stimulus-mask combination was presented equally frequently. Two black (RGB-values 0, 0, 0) hash marks were superimposed centrally on the coloredgrids.

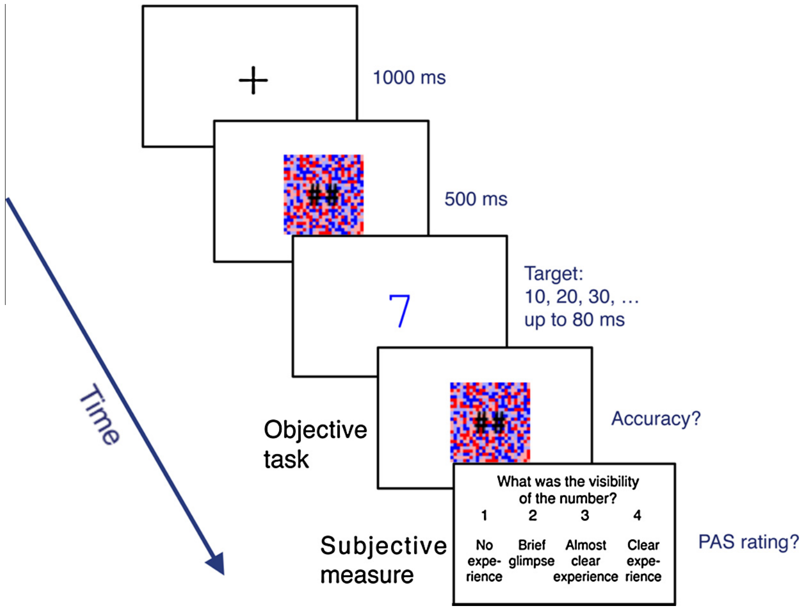

Fig. 1. Trial sequence during the experiment.

2.4. Procedure

Two different tasks constituted the two conditions in this experiment. Both conditions involved exactly the same sequences of stimuli. The following sequence took place on each trial (Fig. 1). After a central fixation cross, a premask appeared (for 1000 ms and 500 ms, respectively), and was immediately followed by a colored number stimulus (for either 10, 20, 30, 40, 50, 60, 70 or 80 ms) and the post-mask (the same image as the premask, presented until response). The stimulus duration manipulation allowed for the computation of psychophysical detection curves. In one condition, participants judged the color of the stimulus ("red or blue?", i.e. the low-level task). In the other condition, they judged the numerical value ("smaller or larger than 5?", i.e. the high-level task). In both, they pressed the S and L keys to respond. Note that in each condition, four stimulus variants (four colors, four numbers) were mapped onto two response categories, to ensure maximal comparability between both tasks. Following this measure of objective performance, participants were asked to use the Perceptual Awareness Scale (Overgaard et al., 2006) to express their subjective visual experience of the stimulus. They scored the extent to which the colored number was visible to them by means of a rating from 1 to 4 (no experience, brief glimpse, almost clear experience, and clear experience, respectively).

Responses were recorded through key presses (the R, T, Y and U keys, since the middle and index fingers were conveniently located over these keys due to the use of the S and L key with the small fingers). In the beginning of each condition, participants performed 8 practice trials so as to familiarize themselves with the procedure. Two blocks were administered per task, consisting of 4 presentations per color and 4 per number for each stimulus duration, which after crossing results in 32 trials per duration per task. Task order was counterbalanced. A break was given between the two tasks, and also between the two blocks in each task. The experiment lasted approximately 50 min.

2.5. Non-linear models

Four-parameter non-linear models were fitted to the accuracy and subjective visibility data, for each condition apart (Sandberg et al., 2011).

$$f(x) = a + \frac{b - a}{1 + e^{\frac{c-x}{d}}} \qquad (1)$$

Parameters a and b reflect the lower and upper boundary of the fitted curve, and were fixed at 0 and 1, respectively (for the accuracy data), and 1 and 4 (for the subjective data). Parameter c reflects the inflexion point, and d represents the steepness of the curve.

3. Results and discussion

We expected to observe a more non-linear psychophysical curve in the number task (in line with GWT) than in the color task (in line with RPH). After the non-linear models were fitted to the accuracy and visibility data for each condition separately, paired t-tests were carried out on the d-parameters of the non-linear curves. The d-parameter represents the steepness of the functions and thus corresponds to the extent to which they are (non-) linear (lower d values are associated with more non-linear functions). This made it possible to directly compare the (non-) linearity of the psychophysical functions observed in the low-level task with those observed in the high-level task, while keeping the number of parameters equal for each

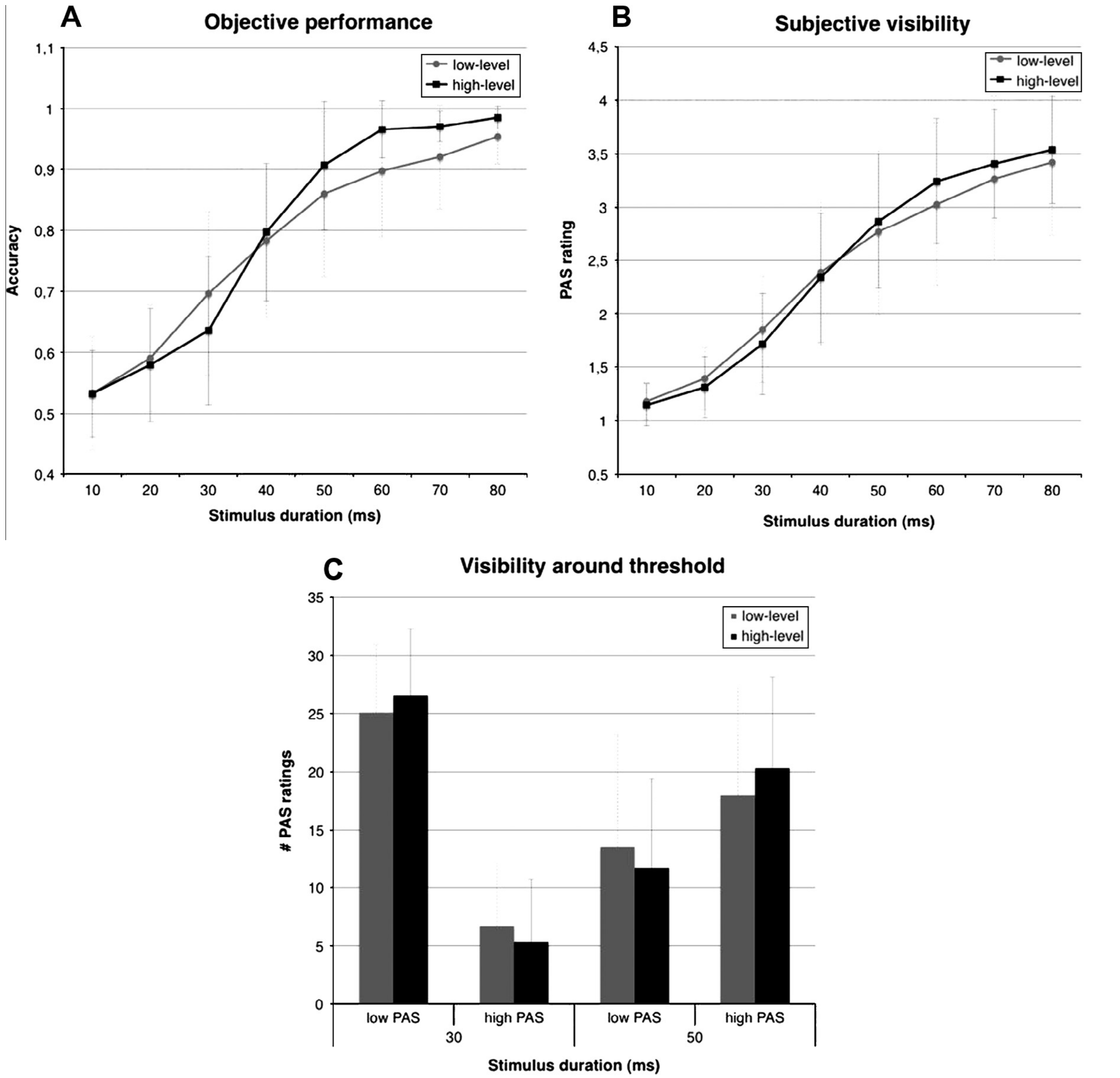

Fig. 2. Performance on the low-level and high-level tasks, and the corresponding subjective visibility ratings. A. Mean accuracy for each presentation duration (10 up to 80 ms), for both the low-level and the high-level condition. B. Mean subjective visibility rating for each presentation duration and condition. C. Number of low subjective visibility ratings (1 and 2 ratings) and high visibility ratings (3 and 4 ratings) for 30 ms and 50 ms presentation durations. Error bars represent one standard deviation.

model. Analyses confirmed that for accuracy, d was significantly higher in the low-level condition than in the high-level condition: $d_{low} = 2.401$ (SE = 0.174), $d_{high} = 1.969$ (SE = 0.122), $t(19) = 2.033$, $p = 0.028$ (Fig. 2A). The same effect was observed for the PAS ratings: $d_{low} = 1.797$ (SE = 0.164), $d_{high} = 1.451$ (SE = 0.106), $t(19) = 1.772$, $p = 0.046$ (Fig. 2B). Highly similar results were observed when the same non-linear models were fitted to the curves of the bright colors (red 1 and blue 1) and the light colors (red 2 and blue 2) separately. Note that there were no significant differences in average performance for the color (mean correct = 78%) compared to the number task (mean correct = 80%), $t(19) = -1.969$, p = 0.064, nor in average stimulus visibility (mean visibility color task = 2.28; mean visibility number task = 2.30), $t(19) = -0.404$, $p = 0.691$. This reveals that our varying task instructions manipulate the level of processing of the stimuli, without being accompanied by differences in general task difficulty.

These results show that the psychophysical functions observed in the high-level number task were significantly more non-linear than the low-level color condition functions, which exhibited a more gradual increase even around threshold, despite the stimuli being exactly identical to each other in both tasks. Our results reflect the psychophysical curves from data used to support the graded or the dichotomous account.

Additionally, to further explore modulation by level of processing, we carried out a repeated-measures ANOVA with PAS rating counts as the dependent variable. The ratings 1 and 2 (3 and 4), were pooled into the ''low PAS'' (''high PAS'') category, respectively, to facilitate interpretation. The analysis showed that high-level stimuli were reported as being significantly less visible prethreshold (more low and fewer high visibility ratings), but more visible post-threshold (fewer low and more high visibility ratings) than low-level stimuli, $F(1, 19) = 11.026$, $p = 0.004$ (Fig. 2C). This lends additional evidence to the idea that for longer stimulus durations, the high-level percept is dominant, whereas for short durations, the low-level percept is dominant, in accordance with the steeper non-linearity in the high-level task.

Overall, the psychophysical curves reported here reflect the pattern of results previously reported in experiments supporting either the graded or the dichotomous account. Across different conditions, stimuli were kept constant in this experiment, thus, both objective conscious access and subjective visibility appear to depend on the level of stimulus processing necessary to respond to task instructions (it is also conceivable that participants were giving confidence judgments rather than visibility judgments, as also mentioned by Sandberg et al., 2010. Future comparative studies using confidence measures while manipulating level of processing would be informative in this respect). The modulation of conscious access and subjective experience by level of processing unifies existing contradictory findings. In light of our own findings, they appear to stem from a biased selection of stimuli and tasks associated with either low or high level processing in the processing hierarchy. As mentioned in the introduction however, the present design does not make it possible to establish that visual perception in general is both graded and dichotomous because the data points used to generate the psychophysical curves are averages over many trials. Indeed, such functions fail to distinguish between different underlying distributions of subjective visibilityratings for each duration, which could be unimodal (i.e., ''graded'') or bimodal (i.e., ''dichotomous''). However, more linear curves have been consistently reported in studies used to support the graded account (Overgaard et al., 2004; Overgaard et al., 2006; Sandberg et al., 2010), and conversely more non-linear curves in studies that supported the dichotomous account (showing bimodal distributions, Del Cul et al., 2006; Del Cul et al., 2007; Sergent & Dehaene, 2004). Our results mirror this pattern of curves, and crucially show that a different level of processing of identical stimuli can lead to either more linear or more non-linear curves. We therefore propose level of processing as a good candidate for integrating evidence supporting either the graded or dichotomous account. At a theoretical level, this could lead to the integration of the RPH, as a graded account, and GWT as a dichotomous account, when controlling for level of processing. We could speculate that more posterior recurrent processing is sufficient for visual awareness of low-level non-semantic stimuli to arise, whereas global recurrent interactions with non-linear dynamics could be necessary for high-level semantic awareness of visual stimuli. A compatible reasoning has been proposed by Koivisto and Silvanto (2011), Koivisto and Silvanto (2012). In their research, local recurrent processing enables features to be phenomenally experienced (cf. low-level visual awareness), whereas attention-modulated recurrent processing at a later stage underlies the experience of stimuli after feature-binding (cf. high-level awareness).

Our results are also in line with a study by Fei-Fei, Iyer, Koch, and Perona (2007). They presented photos of natural scenes for different durations, and participants were asked to freely report on what they had seen. For very short priming-like durations, they mostly reported very low-level aspects, such as shape, contour and contrast information. For longer durations, participants mainly reported high-level aspects of the scene, such as whether it was indoors or outdoors and whether there were people or animals. This is in accordance with our results: at short stimulus presentation durations, participants show a better performance and report better visibility in the low-level task. When stimulation becomes sufficiently rich, the high-level percept becomes dominant. Our findings therefore fit with the framework of Crick and Koch (2003), and Hochstein and Ahissar (2002): the highest hierarchical level is assumed to access consciousness first when the stimulation is sufficiently long (here the number level). When strong constraints on stimulus presentation prevent the system from reaching these higher hierarchical semantic levels (as with the strongly masked stimuli here), subordinate stimulus information at the feature level can still be accessed. We then only have access to the highest level possible for a given amount of stimulus strength. According to Crick and Koch (2003), what level can be reached might depend on attention, but in our experiment signal strength played an important role due to the stimulus duration manipulation (see Dehaene et al., 2006).

In this study, we showed how taking level of processing into account can integrate conflicting psychophysical results. Integration of the graded and the dichotomous account of visual awareness crucially depends on identifying the factors that generate either a graded or a dichotomous visual experience. Here we propose a promising candidate to bring these two major but seemingly contradictory theories of visual awareness together. Future studies using for example a continuous visibility scale allowing for a detailed analysis of the distribution of subjective visibility ratings can verify whether the specific stimuli and tasks that are used modulate our visual experience.

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