CHAPTER 6

Subliminal emotion perception in brain imaging: findings, issues, and recommendations

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Abstract: Many theories of emotion propose that emotional input is processed preferentially due to its relevance for the organism. Further, because consciousness has limited capacity, these considerations imply that emotional input ought to be processed even if participants are perceptually unaware of the input (subliminal perception). Although brain imaging has studied effects of unattended, suppressed (in binocular rivalry), and visually masked emotional pictures, conclusions regarding subliminal perception have been mixed. The reason is that subliminal perception demands a concept of an awareness threshold or limen, but there is no agreement on how to define and measure this threshold. Although different threshold concepts can be identified in psychophysics (signal detection theory), none maps directly onto perceptual awareness. Whereas it may be tempting to equate unawareness with the complete absence of objective discrimination ability (d' = 0), this approach is incompatible with lessons from blindsight and denies the subjective nature of consciousness. This review argues that perceptual awareness is better viewed as a continuum of sensory states than a binary state. When levels of awareness are characterized carefully in terms of objective discrimination and subjective experience, findings can be informative regarding the relative independence of effects from awareness and the potentially moderating role of awareness in processing emotional input. Thus, because the issue of a threshold concept may never be resolved completely, the emphasis is to not prove subliminal perception but to compare effects at various levels of awareness.

Keywords: consciousness; attention; emotion; brain imaging; subliminal perception; backward masking

Because humans are complex organisms, many processes need to occur automatically to permit proper functioning and survival. Although our own experience of consciousness accepts that consciousness is clearly insufficient to mediate all of these processes (e.g., blood pressure adjustments during postural changes), it appears to us that consciousness plays a critical role in important mental processes. For example, to evaluate an external event as good or bad, or for it to affect our behavior, we would need to be consciously aware of it. That is, to evaluate a picture of another human face as threatening, and to respond to it, we would first need to become consciously aware of the facial expression.

The importance of perceptual awareness in responding to emotional events has been challenged by evolutionary considerations and theories of emotion (Öhman, 1986; Robinson, 1998; LeDoux, 2000; Dolan and Vuilleumier, 2003; Öhman and Wiens, 2003). In particular, because of their relevance to organisms, threatening situations need to be registered and handled swiftly. However, because consciousness is limited and slow (Shevrin and Dickman, 1980; Roser and Gazzaniga, 2004; Marois and Ivanoff, 2005), these considerations

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suggest that emotional input needs to be processed partly unconsciously to ensure survival.

Several research paradigms have been developed to study the role of perceptual awareness in processing of emotional pictures. The most commonly used approach is the dissociation paradigm (Holender, 1986). The goal of this approach is to present emotional pictures of which people are not consciously aware, and to study whether or not these emotional pictures have effects despite peoples’ unawareness. If so, such findings would provide evidence that emotional pictures are processed in the absence of awareness. Stated differently, because emotional effects would be obtained after elimination of perceptual awareness, awareness may not be necessary for their occurrence. Further, because people are considered either aware or unaware, perception is treated as a dichotomous state. Therefore, research on subliminal (or implicit) perception studies the degree to which visual input is processed below the threshold (“limen”) of perceptual awareness. This review summarizes main results from recent brain imaging findings on subliminal perception of emotional visual input. However, even though there has been a surge of findings on this topic, no agreement about the existence of subliminal perception has been reached. This paper reviews the main issues and presents alternative strategies for future research. Although this review focuses on subliminal perception of emotional pictures, the issues and strategies are generally applicable to research on subliminal perception.

Findings

Perceptual awareness can be manipulated in a number of ways (Frith et al., 1999; Kim and Blake, 2005). Although visual masking has been traditionally used in subliminal perception, alternative approaches such as manipulations of attention might have comparable effects on awareness (Merikle and Joordens, 1997). This review focuses on brain imaging findings with emotional pictures of which participants were unaware as a result of manipulation of attention (i.e., unattended pictures), binocular rivalry (i.e., suppressed pictures), and visual masking (i.e., masked pictures).

Participants can be instructed to attend to particular visual input, and responses to unattended input can be studied. If participants attend to some pictures but fail to notice pictures that are outside of their attentional focus, responses to the unattended pictures might qualify as subliminal perception (Merikle and Joordens, 1997). Several brain imaging studies with unattended emotional pictures suggest that unattended pictures are processed even though participants are unaware of the pictures (Vuilleumier et al., 2001; Anderson et al., 2003; Bishop et al., 2004; Williams et al., 2004). In one study, participants were shown simultaneously two houses and also two faces with either neutral or fearful expressions (Vuilleumier et al., 2001). Pictures of the same category were positioned left and right, or above and below fixation. For example, one house each was shown left and right of fixation, and one fearful face each above and below fixation. During different blocks of trials, participants were instructed to attend to either the horizontal or vertical picture pairs, and determine whether the two attended pictures were the same or different. Results showed that the amygdala responded more to fearful than neutral faces irrespective of whether or not the faces were attended. In a separate behavioral study with a surprise awareness test, participants could not report facial expression (fearful or neutral), gender, or identity of the unattended face pair from the preceding trial. These findings suggest that the amygdala differentiated between fearful and neutral expression even though participants were unaware of the faces (as these were unattended). In another study (Anderson et al., 2003), pictures of places were colored in green and superimposed with faces in red, and participants were instructed to attend to the places or faces. When attending to the places, participants rated whether it was inside or outside, and when attending to faces whether it was male or female. Results showed that the amygdala responded to fearful faces irrespective of whether or not they were attended. In another study, pairs of emotional faces were shown superimposed on houses in the periphery. Again, amygdala activation was greater to unattended than attended fearful faces (Williams et al., 2004). Taken together, these findings suggest that fearful faces elicit
amygdala activation even if participants are unaware of them because they are unattended.

However, this conclusion has been challenged by results from two studies. In one study, participants were shown a fearful, happy, or neutral face in the center of the screen together with a small bar in the left and right periphery (Pessoa et al., 2002). During different blocks, participants rated either the gender of the face or judged whether the two bars had the same orientation. Results showed that amygdala differentiated among the expressions when participants rated the faces but not when they performed the bar task. In a similar study, participants also judged bar orientation while faces were presented centrally, but task difficulty was manipulated in three levels (Pessoa et al., 2005). Results showed that amygdala differentiated between unattended fearful and neutral faces only when the bar task was simple. Based on these findings, Pessoa et al. concluded that unattended pictures are not processed outside of awareness if awareness is focused sufficiently. Although the studies did not include a manipulation check to determine that awareness of the faces was actually reduced by the bar task (cf. Williams et al., 2005), findings from these and other studies suggest that whether or not unattended faces are processed depends on how unaware participants are of them. In addition, individual differences such as state anxiety may play a moderating role (Bishop et al., 2004). Accordingly, it is a matter of debate if studies of unattended faces provide evidence for subliminal perception (Pessoa et al., 2005; Vuilleumier, 2005).

Subliminal perception can also be studied in binocular rivalry. In these studies, two pictures are presented simultaneously in different colors (e.g., red and green), and participants wear glasses with differently colored lenses on each side (e.g., red on left and green on right). Under these conditions, participants are typically aware of only one picture at a time. For example, if a red house is presented to one eye and a green face to the other eye, participants might be aware only of the house. Thus, responses to the suppressed face can be studied. Two studies support the idea that fearful faces are processed under conditions of binocular suppression (Pasley et al., 2004; Williams et al., 2005). Williams et al. (2005) showed brief pictures of fearful, happy, and neutral faces simultaneously with houses. During the experiment, participants performed a one-back task in which they had to report the repetition of the same image on consecutive trials. Although participants detected repetition of nonsuppressed pictures on most trials, they missed all repetitions of suppressed pictures. Nonetheless, amygdala differentiated between suppressed fearful and neutral faces. Similarly, Pasley et al. (2004) presented houses to one eye and suppressed fearful faces or chairs to the other eye. After excluding the small number of trials in which participants detected the presence of suppressed faces or chairs, results showed that amygdala responded more strongly to the suppressed fearful faces than the chairs. Taken together, as suppressed fearful faces were processed even though participants reported that they were unaware of the faces, these findings provide evidence for subliminal perception. However, it has been argued that mixed states of perception are possible in binocular rivalry (Kim and Blake, 2005; Pessoa, 2005). This finding suggests that the measures of awareness used in studies of binocular rivalry may not be sensitive enough to assess participants’ awareness. For example, because participants performed a one-back task and monitored repetition of the clearly visible nonsuppressed pictures, they might have been distracted from reporting the suppressed pictures. That is, although aware of the suppressed pictures, they did not report them. To conclude, as with studies of unattended emotional pictures, there is a debate as to whether or not the findings provide unequivocal evidence for subliminal perception.

Although manipulations of attention and binocular rivalry are important methods to study subliminal perception, visual masking has a long tradition in research on subliminal perception (Holender, 1986; Öhman and Soares, 1994). In visual masking, a target picture is shown briefly and typically followed by another irrelevant picture (mask). When picture parameters are adjusted carefully, people often report that they are not consciously aware of the target pictures. Thus, subliminal perception of masked target pictures can be studied. During the last few years, there has been a surge of brain imaging studies using visual masking (Morris et al., 1998; Whalen et al., 1998; Rauch et al., 2000; Sheline et al., 2001; Critchley et al., 2002; Hendler et al.,
However, because research has shown that small changes in picture parameters can have strong effects on perceptual awareness (Esteves and Öhman, 1993), it is important to use a setup that controls picture durations reliably. If picture duration cannot be held constant over repeated presentations, picture duration might vary and thus confound results (Wiens and Öhman, 2005b). For example, if a certain level of awareness is targeted but picture duration is unreliable over trials, it is difficult to maintain a particular level of awareness. Similarly, if trials are to be sorted after the experiment on the basis of individual responses, differences in responding might be due to variable picture duration rather than to differences in participants’ processing of the pictures. Although traditional (bulky-type) cathode ray tube (CRT) monitors have adequate reliability, they cannot be used in functional magnetic resonance imaging due to magnetic interference with the imaging process (Wiens et al., 2004). Also, the reliability of recent (flat-display) technologies based on liquid crystal displays (LCD) and thin-film transistors (TFT) is often poorer than assumed by researchers and claimed by manufacturers (Wiens et al., 2004). However, reliable picture presentation is possible with a setup involving two data projectors and mechanical high-speed shutters (Wiens and Öhman, 2005b). This setup permits precise control of picture durations in milliseconds rather than refresh cycles. Because many studies do not describe their setup and do not provide convincing evidence that picture presentation was reliable, it cannot be ruled out that many brain imaging results from visual masking are confounded.

Early brain imaging studies of subliminal perception used masked facial expressions and reported findings that supported subliminal perception (Morris et al., 1998; Whalen et al., 1998). In these and subsequent studies, emotional facial expressions have been mainly masked with neutral faces. Although the use of faces as both targets and masks might confound the results, faces continue to be used because it is easier to mask faces with other faces (Costen et al., 1994); this procedure is necessary with limitations in minimum picture duration for regular display devices (Wiens et al., 2004; Wiens and Öhman, 2005b). In one study (Whalen et al., 1998), participants were shown fearful and happy faces that were masked by neutral faces. After the experiment, participants were interviewed about their awareness and asked to point out the faces that they had seen during the experiment. Although participants did not report seeing any emotional expressions and pointed only at neutral faces, results showed that amygdala responded more strongly to fearful than happy faces. Similarly, in another study (Morris et al., 1998), participants were shown two angry faces and either face was fear-conditioned (i.e., paired with a loud noise). Participants were instructed that after each picture they should respond “yes” or “no” depending on whether they detected either angry face. Although participants responded yes only when the pictures were nonmasked, amygdala differentiated between the two angry faces even when masked. Findings from other studies are broadly consistent with these results for faces (Rauch et al., 2000; Sheline et al., 2001; Critchley et al., 2002; Etkin et al., 2004; Killgore and Yurgelun-Todd, 2004; Liddell et al., 2005) and other emotional pictures (Hendler et al., 2003; Carlsson et al., 2004). However, although findings in visual masking are consistent with subliminal perception, many studies have used only an indirect awareness measure (preference measure, e.g., Critchley et al., 2002), provided insufficient information about whether and how awareness was measured (Carlsson et al., 2004; Liddell et al., 2005), or reported evidence for partial awareness (Rauch et al., 2000; Sheline et al., 2001; Killgore and Yurgelun-Todd, 2004; Whalen et al., 2004). Also, other studies have not found amygdala activation to masked fearful faces (Phillips et al., 2004; Pessoa et al., 2006) and suggested a moderating role of individual differences (Etkin et al., 2004). In sum, it is a matter of debate (Pessoa, 2005) whether visual masking provides evidence for subliminal perception.

Issues

Despite these numerous approaches and findings, researchers continue to disagree on whether these
data provide convincing evidence for subliminal perception. To end this debate, researchers would have to concur on a concept of threshold (limen) to determine whether emotional processing can occur below this threshold of awareness. However, there is no threshold concept that researchers agree upon. Indeed, research on subliminal perception has often blurred the distinction between concepts of measurement and threshold (Reingold and Merikle, 1990). That is, awareness is defined only indirectly by the measure that is used. Also, although awareness measures are often distinguished in terms of objective and subjective measures, this distinction is vague and has unclear references to contemporary psychophysics (Macmillan, 1986; Macmillan and Creelman, 1991). The remainder of this paper discusses pros and cons of objective and subjective measures, and reviews potential candidates for threshold concepts that fit with contemporary psychophysics, in particular signal detection theory.

Requirements for a valid measure of awareness are that it should be exhaustive and exclusive (Reingold and Merikle, 1990; Merikle and Reingold, 1998; Wiens and Öhman, 2002). This means that it should capture all aspects of conscious processing (i.e., exhaustive) but no unconscious processes (i.e., exclusive). To illustrate, if a measure is not sensitive enough to capture conscious processes completely (i.e., it is not exhaustive), any emotional effects could be due to the conscious processes that were not captured by the measure. Similarly, if a measure is too sensitive and captures unconscious as well as conscious processes (i.e., it is not exclusive), the apparent absence of unconscious emotional effects could be due to this mislabeling of unconscious as conscious processes.

Numerous measures have been proposed as valid indexes of awareness. However, two forms of awareness thresholds are often distinguished, namely objective and subjective thresholds (Cheesman and Merikle, 1984, 1986). Cheesman and Merikle (1984) defined the subjective threshold as the “level at which subjects claim not to be able to discriminate perceptual information at better than at a chance level”, and the objective threshold as the “level at which perceptual information is actually discriminated at a chance level” (p. 391). Whereas subjective measures assess participants’ self-reported (subjective) ability to discriminate the stimuli, objective measures assess participants’ actual (objective) ability to discriminate the stimuli. In this context, the terms subjective and objective refer to the content rather than the quality of measurement. That is, if a subjective measure requires participants to report about their awareness by pressing buttons, it can be as reliable (i.e., objective in a measurement sense) as an objective measure of discrimination ability.

Objective measures are often favored over subjective measures. The most important reason is that objective measures typically allow one to separate discrimination ability from response criterion (Eriksen, 1960). That is, even though participants may not differ in their actual awareness of the pictures, they might have different notions about their level of awareness. For example, some participants might already report that they saw a face even if they noticed only a pair of eyes, whereas others might do so only if they could clearly identify eyes, nose, and mouth. If so, the latter participants would perform less well on a subjective measure than the former participants, and the subjective measure would incorrectly suggest that the participants differed in awareness. Response criteria are affected by demand characteristics (Eriksen, 1960). Also, participants tend to underestimate their performance in difficult perception tasks (Björkman et al., 1993). In support, when awareness is assessed both objectively and subjectively, objective measures often show evidence of discrimination ability in the absence of subjective awareness. Thus, subjective measures of awareness tend to be less sensitive than objective measures (Cheesman and Merikle, 1984, 1986). Further, because the experimenter has little control over the participant’s criterion, “we are in fact using as many different criteria of awareness as we have experimental subjects” (Eriksen, 1960, pp. 292–293). In contrast, objective measures typically allow one to control for differences in response criterion.

However, this is true only if performance measures are used that allow one to separate discrimination ability and response criterion. That is, even if awareness is measured with an objective task, it is possible that the performance measure might be
confounded by response bias. As such, it would not be a pure (objective) index of participants’ discrimination ability but might represent a measure of participants’ subjective awareness. For example, although yes–no detection tasks are objective measures, the commonly used measure of performance (percent correct) is affected by response bias as well as discrimination ability (Macmillan and Creelman, 1991). That is, if participants are instructed to detect whether or not a target is shown, percent correct is affected by their predisposition to respond that a target was shown. Thus, a participant with a particular discrimination ability might score anywhere from 50% to 95% correct on a yes–no detection task (see Figure 1 in Azzopardi and Cowey, 1997).

Although objective tasks can be used to assess discrimination ability, a potential problem with objective measures is the possibly confounding effect from lack of motivation. When masking parameters are chosen so that the masked pictures are barely visible, participants might have no motivation to perform a discrimination task (Duncan, 1985; Merikle, 1992) as it might be experienced as meaningless. Because participants would loose motivation, they might push buttons randomly and thus perform at chance. Hence, objective measures might not necessarily index the objective threshold but the subjective threshold (i.e., participants’ self-reported unawareness). This discussion highlights the issue of whether or not the use of objective measures guarantees that an objective threshold is assessed. Indeed, Merikle and Daneman (2000) suggested that factors such as an insufficient number of trials on the objective measure as well as insufficient motivation of the participants could explain why many reports of unconscious processes have been comparable for studies in which unawareness was assessed with an objective measure (purportedly indexing the objective threshold) or a subjective measure.

Aside from these issues, a major problem is that unawareness is commonly defined in terms of statistical deviations from chance performance instead of an absolute level of performance. For example, mean performance is measured for an individual or a group, and if the mean is not significantly different from the level of performance expected by chance, it is concluded that awareness was absent. In this view, the absolute level of performance is almost irrelevant, as long as mean performance does not differ significantly from chance. However, because unawareness is defined on the basis of results from a statistical significance test, the outcome of this test depends greatly on statistical power. In fact, this definition of unawareness based on statistical testing can result in nonsensical conclusions (for review, see Wiens and Öhman, 2005a). That is, if the absolute level of performance is constant and only the number of trials or participants changes, one would have to conclude that an individual became suddenly aware when more trials were run, or that the whole group became suddenly aware when more participants were run. To illustrate, results from a statistical test (e.g., one-sample t test) depend on the number of observations and on the variability among observations. Statistical power increases with the number of observations and decreases with the variability among observations. Thus, when the number of observations is increased and everything else is held constant, a lower observed significance value (p-value) is obtained. For example, assume that the observed mean performance is 60% and chance level is 50%. For the ease of argument, assume further that percent correct is unbiased (see above). Then, at a constant mean performance of 60%, an individual might perform significantly better than chance (by definition, become aware) when the objective measure consists of 40 trials but not when it consists of 20 trials. Similarly, a group might perform significantly better than chance (by definition, become aware) when the sample consists of 40 participants but not when it consists of 20 participants. Also, because statistical power decreases with variability among observations, heterogeneity among participants might result in nonsignificance. However, these data may not suggest that all participants were unaware of the pictures, but may indicate that there is substantial variation among participants. Thus, the mean may not be representative for the group. Although variability among participants can be evaluated in terms of confidence intervals (Cumming and Finch, 2005) and correlations with variables of interest, this is not commonly discussed in research. Further, because researchers
are mainly interested in retaining the null hypothesis (i.e., participants do not perform better than chance and are thus unaware), the commonly used \( z = 0.05 \) is probably too low. However, there is no general agreement on which \( z (0.20, 0.10) \) to use.

Another problem with objective and subjective measures is that they are often measured on different time scales. Objective measures typically require participants to respond after each picture. For example, on each trial, participants indicate if they saw a happy or a fearful face by pushing a button. In contrast, subjective measures often require participants to respond only after a series of pictures. For example, participants are interviewed at the end of the experiment if they saw any emotional facial expressions. This makes it difficult to compare results from the two tasks, as any differences might be partly due to contextual differences during measurement (Lovibond and Shanks, 2002). That is, because in subjective measures, participants are often asked about their integrated experience over trials, confounding effects of forgetting seem more problematic for subjective measures than objective measures.

Yet another problem with both objective and subjective measures is that because the definitions are rather vague, it is unclear which specific measures ought to be used to capture these thresholds. For example, Cheesman and Merikle (1986) measured objective thresholds in terms of either performance on a detection task (Experiment 2) or identification task (Experiment 3). That is, performance was indexed by participants’ ability to detect whether or not a word was presented (detection task) or which word was presented (discrimination task). However, because other research has used detection tasks as the objective measure and identification tasks as the measure of unconscious processing (Snodgrass et al., 2004b), it is unclear which measure is the correct one to index a supposed objective threshold. Indeed, dissociations among measures might be expected by chance (Eriksen, 1960) or result from subtle differences in task requirements or performance indexes (Fisk and Haase, 2005). To give a simple example, Öhman and Soares (1994) measured ability to classify masked spiders, snakes, flowers, and mushrooms. However, as Lovibond and Shanks (2002) argued, participants might be able to discriminate among the masked pictures without being able to verbally label the masked pictures. Because both measures assess different kinds of discrimination abilities, it is unclear which measure indexes the supposed objective threshold. Similarly, if participants are shown masked spiders and snakes, but they report that they did not see any spiders or snakes, it might be concluded that they were unaware (subjective threshold). However, if participants also reported that they noticed that masked pictures were shown even though they could not tell if the pictures were spiders or snakes, these findings would suggest that participants had some subjective awareness of the masked pictures. Therefore, it is unclear if it can be concluded that participants were unaware at the subjective threshold. In fact, this decision might be particularly difficult for tasks that combine subjective with objective features. For example, Kunimoto et al. (2001) described a measure that combines (objective) discrimination ability with (subjective) confidence.

Apparently, objective measures have the advantage of objectifying awareness by removing individual differences in response criteria and assessing pure discrimination ability. However, this is their greatest drawback, as they ignore the principally subjective nature of awareness. That is, because awareness refers to phenomenological experience, it may be more relevant to index what people notice subjectively rather than what they can discriminate objectively (Bowers, 1984; Wiens and Öhman, 2002). In analogy, the phenomenological experience of pain cannot be indexed in terms of whether people can discriminate stimuli objectively but whether they experience them subjectively as painful (Wiens, 2006). Because awareness is a process that is closer to the process of “noticing” than “discriminating,” a valid measure of awareness ought to capture what participants notice rather than what they can discriminate. Indeed, because research has shown that objective measures often provide evidence for discrimination ability despite subjective unawareness, objective measures might fulfill validity requirements of exhaustiveness but not exclusiveness (Merikle and Reingold, 1998). That is, objective measures might
capture not only conscious aspects but also unconscious processing, and their apparent greater sensitivity might be due to this violation of exclusiveness. Hence, objective measures might not be valid indexes of awareness.

Indeed, proponents of objective measures of awareness would have to infer that performance better than chance demonstrates necessarily that people are aware of the pictures. This reasoning is inconsistent with findings from studies of brain-damaged patients. In these studies, objective measures were used to demonstrate that people could perform a task although they are unaware of the target stimuli, as indexed by subjective measures. The most famous example is blindsight (Weiskrantz et al., 1974; Weiskrantz, 1986; Cowey and Stoerig, 1995; Cowey, 2004). Blindsight is observed in patients with damaged primary visual cortex (V1) who report that they are completely unaware of the stimuli in their damaged visual field; nonetheless, they can discriminate among them (de Gelder et al., 1999; Morris et al., 2001; for blindsight studies with emotional stimuli and brain imaging, see Anders et al., 2004; Pegna et al., 2005). Blindsight is commonly demonstrated by a dissociation of performance on two visual tasks: a localization task (objective measure) and a classification task (subjective measure). In the localization task (objective), subjects focus on the center of the screen. When they push a button to initiate a trial, a light flashes somewhere, and subjects are instructed to push the screen at that position. Typical results are that subjects can localize the flashes accurately, even in their damaged visual field. In the classification task (subjective), subjects have an additional response option to indicate when an empty trial (i.e., no light flash) was presented. Here, typical results are that subjects report blanks only when light flashes are presented in their damaged visual field. Hence, although subjects can localize the light flashes in their damaged visual field accurately when forced to point at the location, they choose the blank button when given the option to do so. Such discrepant results between tasks have been obtained for both humans and monkeys with similar lesions in V1 (Cowey and Stoerig, 1995; Stoerig et al., 2002).

In humans, similar performance on the subjective classification task is obtained irrespective of whether they are instructed to verbally report their awareness or to indicate their responses with button presses. Also, although monkeys first had to be trained on the tasks, they showed similar dissociations in task performance when compared to human blindsight patients.

These findings imply that monkeys have perceptual awareness (Cowey, 2004). Critically, they also challenge the notion of discrimination ability as a valid index of awareness. That is, because objective measures (i.e., localization task) were used to index performance outside of awareness, these data challenge the notion that above-chance performance on objective measures necessarily shows that people are aware of the target stimuli. However, because it is possible that patients are not reporting accurately about their awareness, potential alternative explanations must be considered. Regarding fellow humans, it may be tempting to trust them about their self-report. In contrast, when considering data from animal research, it is easier to remain skeptical and to think of possible confounding variables. The role of potentially confounding variables has been studied extensively in monkey models of blindsight (Cowey and Stoerig, 1995; Stoerig et al., 2002).

The main challenge to blindsight is the argument that patients are perceptually aware of the visual input in their damaged visual field, but because the pictures are perceived as weaker than in the undamaged visual field, patients report that they are unaware of them. That is, targets in the damaged visual field are classified as blanks because they appear more similar to blanks than to targets in the undamaged visual field. In signal detection terms, this argument can be conceptualized in terms of stimuli falling below the response criterion. Although signal detection will be explained below, this means that people use an arbitrary level of visibility at which they report whether or not they are aware of a target. Accordingly, targets in the damaged visual field fall below this criterion and are thus reported as blanks. However, a series of experiments have addressed this potential confound (e.g., Stoerig et al., 2002). First, when target visibility was manipulated so that target contrast was near threshold in the undamaged visual field and maximal in the damaged field, subjects reported only a small proportion of targets in the undamaged field as targets. Still, subjects continued to report targets
in the damaged field as blanks. Importantly, these findings were obtained although performance on the localization task was apparently better for targets with maximal contrast in the damaged than near-threshold contrast in the undamaged visual field. These findings are inconsistent with the argument of a decreased visibility in the damaged field, as it would have been expected that with similarly poor levels of target visibility in undamaged and damaged visual fields, differences in ratings would disappear. Second, when number of trials was greater for the damaged than undamaged visual field, subjects continued to classify targets in their damaged visual field as blanks. Importantly, even though monkeys received rewards for reporting targets correctly and did not receive a reward when they misclassified a target in the damaged field as a blank, they reported targets in the damaged field as blanks and thus did not receive any rewards on the majority of trials. These findings argue against the possibility that less visible targets in the damaged visual field were classified as blanks because they occurred less often than targets in the undamaged visual field or because they had different outcomes associated with them. Taken together, the most parsimonious explanation for these findings is that greater-than-chance performance on a task (e.g., localization) does not demonstrate awareness per se. If this conclusion is rejected, then it indicates that blindsight does not exist, as greater-than-chance performance would necessarily indicate that patients are aware of the target stimuli. In fact, this reasoning makes it logically impossible to demonstrate performance without awareness (Bowers, 1984). Accordingly, because there is no a priori reason that emotional effects might not be considered indexes of perceptual awareness, any form of discriminative responding could actually be viewed as evidence of awareness (Wiens and Öhman, 2002). However, in the absence of a convincing alternative explanation for blindsight, lessons from blindsight suggest that discrimination ability per se is not indicative of awareness.

To conclude, the distinction between objective and subjective measures makes intuitive sense because it reflects differences between actual discrimination performance and phenomenological aspects of noticing. However, underlying concepts and their measurement are rather unclear. As illustrated above, different measures are used interchangeably as indexes of the same process, and identical measures are sometimes used as indexes of either conscious or unconscious processing. As a potential solution, it has been advocated to use awareness measures based on signal detection analyses (e.g., Hannula et al., 2005). However, the theory of signal detection makes no reference to awareness (Macmillan, 1986; Macmillan and Creelman, 1991). So, how can signal detection measures be used to index something that it is not part of the theory of signal detection?

Threshold concepts in signal detection theory

Although signal detection theory (SDT) makes no reference to perceptual awareness, several concepts can be construed as thresholds (Macmillan, 1986; Macmillan and Creelman, 1991). These threshold concepts can then be evaluated for their usefulness in indexing the threshold idea in subliminal perception. From a psychophysics perspective, four thresholds might be distinguished: sensory, criterion, empirical, and energy threshold. For the ease of argument, the following discussion of these concepts is illustrated for a simple yes–no detection task. For example, in a face detection task, face and no-face trials are presented and participants decide after each trial whether or not they detected a face (yes or no).

Sensory threshold

A sensory or observer threshold is a hypothetical threshold that is internal to the participant and determines if a stimulus is sensed or not. This sensory threshold cannot be mapped directly to participants’ overt responses. Thus, responding yes or no in a detection task does not correspond directly to sensory states that fall above or below the sensory threshold, respectively. The concept of a sensory threshold is probably closest to the notion of a limen and the distinction between subliminal and supraliminal. Although this concept was included in many early theories of psychophysics, there is little evidence that supports the idea of a
sensory threshold. In fact, SDT has been introduced as an alternative model that can account for many findings without resorting to the concept of a sensory threshold (Macmillan and Creelman, 1991).

SDT argues against a sensory threshold in favor of an internal continuum of sensory states (more generally called strength of evidence; Pastore et al., 2003). According to SDT, each presentation of a stimulus (signal) occurs against a variable background of internal noise. In theory, the variability of this noise over trials can be captured by presenting no-signal trials repeatedly, measuring the values of these no-signal trials on the sensory continuum, and forming a histogram of these values. This noise distribution characterizes the mean and variability of the internal noise on the continuum of sensory states. Due to continuous background noise, a signal is then presented in the context of noise; that is, a signal is superimposed on the noise (i.e., signal plus noise). As with no-signal trials, a hypothetical distribution for signal (plus noise) trials can be plotted. Theoretically, there is no point on the continuum that allows one to determine unmistakably whether or not a signal was presented. That is, a signal can sometimes evoke a relatively weak internal response, whereas the absence of a stimulus (no-signal trial) can even evoke a relatively strong internal response. Accordingly, it is possible to make only probability statements. For example, if the point on the continuum is high relative to the mean of the noise distribution, it is likely that a signal was presented, whereas if the point is low, it is likely that no signal (noise) was presented. However, the more the signal (plus noise) and noise distributions overlap, the more difficult it is to distinguish between both types of trials. If the distributions overlap perfectly, signal and noise trials cannot be distinguished at all.

The locations of the noise and signal (plus noise) distributions cannot be measured directly. Instead, they need to be inferred. To do that, many signal and no-signal trials need to be presented, and participants are asked to make a response on each trial. For example, in the face detection task, face and no-face trials are shown and participants decide after each trial whether or not they detected a face (yes or no). According to SDT, when observers are asked to make overt responses in a detection task, they choose an arbitrary level on the sensory continuum as a cutoff score (criterion). Above this criterion, they respond yes, and below this criterion, they respond no. Based on the criterion, it is possible to distinguish among hits (responding yes on signal trials), false alarms (responding yes on no-signal trials), misses (responding no on signal trials), and correct rejections (responding no on no-signal trials). Then, probabilities for hits and false alarms can be used to compute the actual distributions to determine the relative location of signal and noise distributions. This is commonly expressed in terms of $d'$ ($d$ prime), which is the distance between the means of the signal and noise distribution in $z$ scores. Sensitivity ($d'$) is high if signal and noise distributions are far apart and low if the distributions overlap closely. Alternative indexes of sensitivity such as $Br$ and $A'$ have been proposed. However, $Br$ is based on a different threshold model, and $A'$ has been criticized for alleged claims that it is nonparametric (Snodgrass and Corwin, 1988; Macmillan and Creelman, 1990; Pastore et al., 2003). However, in practice, these indexes often give comparable results. Nonetheless, to calculate $z$ scores and thus $d'$, hit and false alarm rates must be greater than zero and less than 1. This is a potential problem when the perceptual input is degraded, as participants might never report that they detected a signal. To permit calculation of $d'$, extreme scores are often dealt with by adding 0.5 in the numerator and 1 in the denominator when calculating hit rates and false alarm rates (Snodgrass and Corwin, 1988).

A critical feature of SDT is that the observer's placement of the criterion does not affect estimation of discrimination ability, as the distance between the signal and noise distributions is unaffected by participants' placement of their criterion. Different indexes of criterion placement have been proposed (Snodgrass and Corwin, 1988; Macmillan and Creelman, 1991). The likelihood ratio $\beta$ (beta) is the ratio of the heights of the signal and noise distributions, and the criterion $C$ is the distance from the intersection point of signal and noise distributions as a $z$ score. A neutral criterion or absence of a response bias is present if participants set their criterion so that the probabilities for signal and noise are equally likely (i.e., where they cross). That is, $\beta = 1$ and $C = 0$. If participants position the
criterion more towards the lower end of the sensory continuum, then they exhibit a lax or liberal response bias (as they are more willing to respond yes); if they position it more to the higher end of the sensory continuum, then they exhibit a strict or conservative response bias (as they are less willing to respond yes). A liberal response bias results in $\beta < 1$ and $C < 0$, whereas a conservative response bias results in $\beta > 1$ and $C > 0$. Although beta is used more commonly as an index of response bias, a number of arguments favor $C$ (Macmillan and Creelman, 1990). Although the location of the criterion is chosen arbitrarily by the observer, it is often affected by the pay-off associated with different response outcomes. For example, if there is a big reward for detecting a signal, observers are more willing to respond yes (lax response bias). In contrast, if there is a punishment for false alarms, observers are less willing to respond yes (strict response bias).

**Criterion threshold**

The criterion itself might be viewed as a threshold of awareness. For example, applied to the face detection task, participants could be instructed to respond yes only if they were consciously aware of the faces. Thus, the placement of the criterion would correspond to a subjective measure of awareness. However, participants might have different notions about their awareness. In the face detection task, some might respond yes already if they noticed only eyes (lax response bias) whereas others might respond yes only if they noticed eyes, nose, and mouth (strict response bias). Indeed, in SDT the criterion is considered a pure index of response bias that says nothing about awareness. However, if participants receive clear instructions about how they should place their criterion (e.g., respond yes in the face detection task only if they can clearly see eyes, nose, and mouth), individual differences might be reduced. Of course, this requires that the experimenter has a clear and explicit definition of awareness (e.g., which experiences constitute awareness of a face). But, if these instructions are clear, the criterion might be a useful measure of the subjective aspect of awareness. Also, because a response is collected on every trial, it has an advantage over other subjective measures that are assessed only across a number of trials. But, a drawback is that it is unclear how this measure can be averaged over trials. For example, if participants report awareness on 12% of the signal trials, it is unclear if they should be considered aware or unaware. Intuitively, one might consider whether participants reported awareness of faces even when no faces were shown. However, the false alarm rate cannot be used to make inferences about participants’ subjective awareness, as this would assess merely their discrimination ability (as $d'$ is calculated from hit rates and false alarm rates).

Another approach to using the criterion as a threshold might be to sort signal trials into detected and undetected trials (i.e., above and below criterion). Then, effects of interest could be studied for undetected signals, that is, signals of which participants report to be unaware. This approach has a long tradition in experimental psychology (for review, see Merikle et al., 2001). However, SDT can account for seemingly surprising findings that undetected stimuli can be discriminated. For example, undetected faces might be discriminated in their facial expressions. The reason is that undetected signals do not necessarily indicate that discrimination ability is absent ($d' = 0$) (Macmillan, 1986; Haase et al., 1999). Because the relative location of signal and noise distributions is unaffected by the location of the criterion, discrimination ability between signal and noise might be quite high even if the signal is not detected on 95% of the signal trials (strict response bias). Hence, there would be nothing mysterious if participants can discriminate undetected faces in terms of facial expressions. However, SDT would predict that if detection ability were indeed absent ($d' = 0$), participants should be unable to discriminate among signals, as the signal and noise distributions would overlap perfectly. Although this point is debated, evidence suggests that observed effects are small and might be due to slight differences in task setup (Snodgrass, 2002; Haase and Fisk, 2004; Holender and Duscherer, 2004; Reingold, 2004; Snodgrass et al., 2004b; Snodgrass et al., 2004a; Fisk and Haase, 2005).
Further, although effects below a subjective threshold can be studied, this threshold seems arbitrary. For example, instead of asking participants to respond yes or no, they could rate level of awareness (visibility) on a continuous scale (Sergent and Dehaene, 2004). When subjective awareness is considered on a continuum, it comes at no surprise that unreported (i.e., below threshold) stimuli are processed. That is, participants may not report pictures below a particular cutoff on a continuous scale (e.g., 6 on a 10-point scale) but still be able to discriminate among these pictures.

**Empirical threshold**

An empirical threshold is defined arbitrarily as a particular level of behavioral performance. For example, different empirical thresholds might correspond to various performance levels (e.g., $d' = 1, 2$). Because there is no theory of awareness that equates particular empirical thresholds with awareness, empirical thresholds appear to have limited usefulness in indexing awareness and unawareness. However, findings of qualitative differences would provide some support for the validity of particular empirical thresholds. As discussed by Merikle and colleagues (e.g., Merikle et al., 2001), the distinction between subliminal (unconscious) and supraliminal (conscious) processes is supported if they have qualitatively different effects. In fact, the distinction between subliminal and supraliminal perception might be interesting only if they have effects that differ qualitatively rather than quantitatively. For example, Merikle and Cheesman (1987) found that reaction times in the Stroop task were in opposite directions for masked (subliminal) and nonmasked (supraliminal) words. Because awareness was indexed by whether or not participants reported awareness of the masks, these findings support this measure of awareness. However, although interesting, qualitative differences have been reported only for a few experimental conditions (Merikle et al., 2001). Also, this validation is rather indirect, as qualitative differences might indicate only that awareness is a marker or correlate of qualitative differences rather than a causal mechanism (Kunimoto et al., 2001; Wiens and Öhman, 2005a).

**Energy threshold**

The energy threshold is the level at which performance level is null, that is, $d' = 0$. Thus, it can be conceptualized as a specific empirical threshold. The energy threshold is the most common denominator among researchers in subliminal perception. That is, researchers agree that people are unaware if their performance is null ($d' = 0$). However, the debate ensues as to whether performance above null reflects awareness. Some models propose that subliminal perception ought to be studied at $d' = 0$ (Snodgrass, 2002; Haase and Fisk, 2004; Snodgrass et al., 2004a, b; Fisk and Haase, 2005). However, this approach has methodological and conceptual problems. A major problem is that it attempts to prove the null hypothesis. This endeavor is generally known to be difficult if not impossible. It requires thousands of trials to obtain a reliable estimate of $d'$, and a lax significance criterion ($\alpha = 0.20$) to guard against a type 2 error of retaining the null (i.e., participant is unaware) even though the alternative hypothesis (i.e., participant is aware) is true. Also, because signal and noise trials will be barely distinguishable, it is doubtful that participants will stay motivated during this task. Therefore, it is likely that participants will give up and start pushing buttons randomly. As a consequence, $d' = 0$ may not accurately reflect absence of discrimination ability but lack of motivation (Merikle and Daneman, 2000). Further, this approach concludes that performance above null ($d' > 0$) necessarily indicates perceptual awareness. However, it is not intuitive to conclude that any deviation from 0, however small, indicates awareness. Critically, as discussed above, it ignores the subjective nature of perceptual awareness as well as lessons from blindsight.

In sum, central aspects of contemporary psychophysics, and in particular SDT, are that there is a continuum of sensory states (i.e., there is no actual sensory threshold), and that the relationship between stimulus events and sensory states is probabilistic due to constant background noise in the sensory system. It is therefore impossible to deduce unequivocally from a given sensory activation whether it resulted from a signal or noise trial. Also, although a response (e.g., yes or no) is
obtained on each trial, it does not reflect awareness per se but the cutoff point on the continuum of sensory states that participants choose arbitrarily to separate different response alternatives (e.g., yes and no).

**Recommendations**

It is definitely an oversimplification to treat perceptual awareness as a unitary concept. Perceptual input often consists of various aspects, each with their own thresholds for awareness. For example, a face comprises aspects such as features (eyes, nose, and mouth), expression, gender, race, age and so on. Similarly, awareness of words might be differentiated in terms of awareness of individual characters and of the whole words (Kouider and Dupoux, 2004). Awareness is likely to differ for these various aspects and in their underlying mechanisms (e.g., Stoerig, 1996). Therefore, future studies ought to include measures that capture the relevant stimulus dimension of interest.

Further, several masking studies have reported that awareness was not measured at all because picture parameters were similar to other experiments (e.g., 30 ms SOA). However, reliability and luminance curves of picture parameters vary substantially for different display technologies (Wiens et al., 2004; Wiens and Öhman, 2005b), and small differences in picture parameters can have strong effects on perceptual awareness (Esteves and Öhman, 1993). Therefore, it is recommended that reliability of display equipment is demonstrated and that participants’ awareness is measured explicitly rather than assumed. In fact, to rule out potentially confounding effects from individual differences in awareness, individual performance needs to be assessed. Also, if a particular level of performance is targeted, specific stimulus parameters could be selected on the basis of an awareness test prior to the actual experiment. This approach is recommended from a psychophysics approach, but a potential drawback is that participants might habituate to the target pictures.

Most studies lack an explicit definition of awareness (Reingold and Merikle, 1990). Because nobody challenges the conclusion that participants who are completely unable to discriminate visual input are unaware, researchers might have been tempted to use this definition of unawareness. In SDT terms, this definition corresponds to the energy threshold or an empirical threshold that is set at $d = 0$. However, because this approach attempts to prove the null, any null findings on the awareness task might be challenged on the grounds of insufficient statistical power or confounding effects from lack of motivation (Merikle and Daneman, 2000). In fact, the conclusion that brain imaging studies of subliminal perception are based on $d = 0$ has been questioned (Hannula et al., 2005; Pessoa, 2005). Therefore, if researchers intend to argue that $d = 0$, they need to provide convincing evidence that participants were actually unable to discriminate the stimuli.

A possible reason why researchers tend not to be explicit about their definition of awareness may be that they actually feel uncomfortable about equating unawareness with $d = 0$. Indeed, if $d > 0$ is inevitably equated with awareness, then this approach denies the subjective nature of awareness (Bowers, 1984). Also, it tends to make it logically impossible to demonstrate subliminal perception, and implies that findings from blindsight patients are invalid (Wiens, 2006). Although many researchers might agree with this conclusion, they might be unsure about which measure to use to capture subjective experience. Participants might be instructed to make a yes–no decision about their own awareness (i.e., placement of criterion). If participants are not instructed where to place this criterion, there will probably be as many definitions of awareness as there are participants (Eriksen, 1960). However, if participants are presented with an explicit definition of subjective awareness, participants will probably use this definition accurately. Thus, subjective experience can be assessed objectively.

Despite methodological difficulties, awareness needs to be treated and assessed as a subjective state. Indeed, shortcomings in dichotomizing performance on subjective measures do not argue against subjective measures in general but against a conceptualization of awareness that assumes it to be a binary state. Hence, conclusions about awareness may be more realistic and informative in
terms of relative awareness rather than as awareness as present or absent.

Because awareness might be treated more accurately as a continuum, a psychophysics approach lends itself to study stimulus-response relationships between awareness and effects of interest. First, participants might be asked to rate their perceptual awareness on a continuous scale to determine if awareness changes gradually or dichotomously. For example, Sergent and Dehaene (2004) propose that participants experience the attentional blink as dichotomous. In general, when series of pictures are presented briefly and participants have to detect two target pictures, participants often fail to detect the second target if it follows about 200–500 ms after the first target (i.e., attentional blink). In their study, participants were instructed to rate visibility of the second target on a 21-point scale. Results showed a bimodal distribution of visibility ratings for the second target. This bimodal distribution was probably not due to response biases, as participants gave gradually higher visibility ratings for detected targets when the duration of the target was lengthened. Second, a psychophysics approach allows studying how perceptual input is processed at different levels of awareness. For example, in a follow-up study on the attentional blink, Sergent et al. (2005) sorted trials based on visibility ratings to study their neural correlates. This example illustrates that continuous measures of awareness can be powerful tools to index different levels of awareness and to study their neural correlates. Therefore, if facial expressions compared to other pictures were processed similarly at various levels of awareness, such results would suggest that awareness does not play a critical role in processing facial expressions. Alternatively, if emotional input can be shown to have (qualitatively) different effects at different levels of awareness, this would suggest that awareness (as indexed by a particular measure) plays a moderating role in emotion face perception. A similar approach might be useful for studying the role of attention in processing of emotional input (Pessoa et al., 2005; Vuilleumier, 2005).

So, even though findings for unattended, suppressed, and masked emotional pictures may not permit absolute statements about subliminal perception, findings that suggest a relative independence of effects from awareness or yield different effects depending on awareness are informative. However, in order to characterize particular effects in terms of awareness, it is necessary to document awareness carefully.

To conclude, because the debate in defining and measuring awareness is conceptual, results from brain imaging cannot solve this issue. Nonetheless, by adopting an eclectic approach using subjective and objective measures, and treating awareness as a continuum, brain imaging can provide informative insights on how the brain processes emotional input at various levels of awareness. Thus, past and future findings from brain imaging studies should not be evaluated in terms of whether or not they demonstrate subliminal perception but instead in terms of if and how effects differ at different levels of awareness.

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References


