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Subjective and objective approaches in the study of conscious perception

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Abstract

Science requires objective measurements to be able to falsify predictions, whereas consciousness is thought to be intrinsically personal and subjective. Consequently, behavioral measures of consciousness are often designated as "objective" or "subjective". Surprisingly however, the exact meaning of the terms objective and subjective is typically not clearly defined. Moreover, applying this label to a given behavioral measure is misleading, as the same measure can often be analyzed within a "subjective" or "objective" framework. Thus, the objective-subjective designation is not only relevant to the measure that is used, but to several other dimensions as well. In this chapter we provide a brief overview of dichotomies along which one might conceptualize the difference between objective and subjective approaches, such as the empirico-analytical method (manipulation vs trial-by-trial sorting), the mode of stimulus presentation (forced-choice vs nonforced-choice), the response type (Type 1 vs Type 2), and the adoption of a ground truth when computing the outcome measure (performance vs appearance). Although these dichotomies often overlap, the correspondence between them is typically only partial. Problems and pitfalls are discussed. Finally, advice is formulated to always explicitly outline how one's stimulus presentation, task, response measure, and analysis approach score on these dichotomies, requiring further explicit justification when claiming to capture "consciousness" as a construct.

Intro

It is difficult to say when the scientific study of consciousness started. Some may align this with the foundation of the first psychophysics labs, as the first experimental psychologists set out to determine the relationship between physical stimulation and mental experience [1]. Others may set it at the second half of the 20th century with the advent of research on patients that show dissociations between conscious and unconscious processing [2]. Still others may place it in the early nineties of the 20th century, when an explicit research program for identifying the neural correlates of consciousness was put forward [3]. Regardless of one's view, a common denominator has been the need to experimentally establish whether an observer has a conscious experience of a stimulus or not.

This need can come in various forms, depending on the research program. The dominant experimental approach has been to follow a variation of standard methodology in cognitive (neuro)science. In this approach, one isolates some process that is relevant to the phenomenon one wants to understand by isolating the difference between two conditions that only differ in the relevant aspect, but which are otherwise identical [4]. In consciousness science this method has been branded "contrastive analysis" [5]. For example, in research on perceptual awareness, one attempts to contrast the processes involved in consciously perceiving a stimulus with the processes that occur when the stimulus remains unconscious. Conscious and unconscious conditions can be experimentally established in many ways [6] , such as masking [7–11], the attentional blink [9,12,13], continuous flash suppression [14,15], binocular rivalry / dichoptic fusion [16–19] and so forth.

To isolate behaviors or processes that are thought to reflect consciousness, an "unconscious condition" is subtracted from a "conscious condition" [20,21]. Importantly, to be meaningful this approach requires that there is some residual processing even in the unconscious condition, or else the procedure does not isolate anything that is unique to consciousness. To establish unconscious processing in the unconscious condition, an awareness measure needs to demonstrate that an observer has zero awareness of a stimulus, also called the zero-awareness criterion [22–25]. Having established that a person is unaware of the stimulus, the researcher determines the degree to which there is residual processing through a secondary behavioral [26], physiological [27] or neural processing measure [28]. An alternative approach involves establishing 'relative' unconscious processing. One approach is to demonstrate that residual unconscious processing exceeds awareness when both measures are compared directly on the same scale [29–33]. Another approach is to match conditions in terms of objective performance and test whether they differ on a secondary measure [34]. In these approaches awareness does not have to be zero, but merely smaller than in a second condition [34], but see [35–38].

All these approaches require a measurement tool that reflects the relationship between physical stimulation and what is consciously experienced. This was also what the first experimental psychologists tasked themselves with when they started the field of psychophysics. The field of psychophysics has given rise to a large toolbox of procedures and measurement approaches that allow one to determine the relationship between stimuli (physical input) and the sensations and perceptions they produce (mental phenomena) [39]. In today's consciousness research, specific measurement tools reflect a specific amalgam of the studied aspect of consciousness (e.g., awareness of presence of a stimulus vs subjective experience of its spatial orientation), the observer's task (e.g., detecting a stimulus vs indicating one's confidence in one's orientation judgment), and analysis choices (e.g., average performance calculated over many trials vs sorting individual trials into "conscious" and "unconscious" categories). Interestingly, choice preferences for different measurement approaches vary substantially across the community of consciousness researchers [40]. Given that the results of empirical research on the constituents of consciousness depend on the specific measurement approach, it is important to contextualize results by providing rationale for and being explicit about the selected approach, using consistent terminology.

Characterizing approaches: objective vs subjective

In the contrastive approach, empirical results on the constituents of consciousness depend on the measurement approach used to establish the contrasted conscious and unconscious conditions. An important distinction is between "objective" and "subjective" approaches [28,41–43]. Importantly however, "objective" and "subjective" are loosely defined terms and can mean different things to different people and their meaning may depend on context. In consciousness research, objective approaches often refer to measurement strategies in which questions are asked that can be evaluated in terms of performance, i.e. questions that impose a ground truth against which the responses of the observer are evaluated. Subjective approaches on the other hand typically refer to strategies that gauge subjective experiences that are intrinsic/personal to the observer and thus cannot be falsified or evaluated in terms of a ground truth, i.e. for which the report of the observer is accepted as-is. However, this characterization is not watertight and can be open to interpretation. Although these terms are often used to characterize different measures of consciousness (i.e. response measures, such as giving a yes/no response or a confidence response), their meaning encompasses much more, just as the operationalization of consciousness as a construct involves much more than just using one or the other measure [39]. Thus, at a high level the terms can be used to indicate that consciousness is operationalized in a certain way on theoretical grounds (e.g., objective: evaluating responses against a ground truth, subjective: reported phenomenology), but at a lower level they can mean that a certain task and/or stimulus presentation mode is used (e.g., objective: forced-choice between two stimuli, subjective: nonforced-choice), that a certain response measure is used (e.g. objective: reporting presence or absence, subjective: reporting how strong the experience of a stimulus is), or that a certain analysis approach is adopted (e.g., objective: average performance across trials, subjective: trial sorting). Although these aspects are often interrelated, the terms objective and subjective may refer to any specific combination of construct, task, mode of presentation, response measure and analysis approach (Figure 1). To help navigate the plethora of awareness measures and measurement approaches, we outline several dichotomies in the sections below that often come up in consciousness research and relate these to the objective vs subjective distinction. Notably, the validity of none of the operationalizations of consciousness has been firmly established, partially because there is no agreed upon theoretical grounding to support such a validation [44,45].

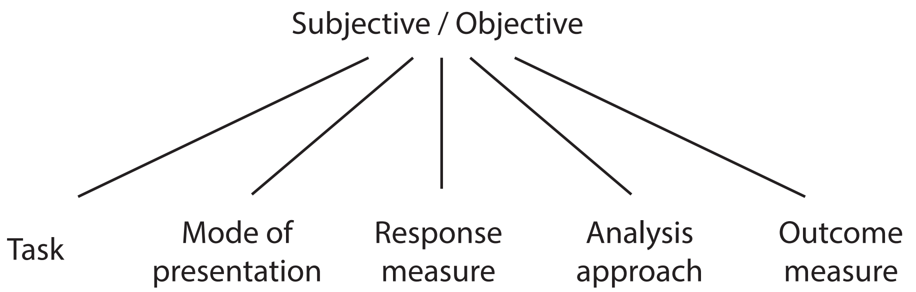


Figure 1. *Taxonomizing approaches in the study of consciousness. The terms objective and subjective may refer to any specific combination of task, mode of presentation, response measure, analysis approach and outcome measure.*

Analysis approaches: performance vs trial-by-trial sorting

Before treating dichotomies related to task, stimulus presentation and response, we first characterize the two main analysis approaches. The common distinction between objective, falsifiable performance metrics vs. subjective, non-falsifiable subjective reports illustrates how tasks and analysis choices are closely intertwined. In what is typically referred to as objective approaches, an experimental manipulation (e.g., strong vs weak masking) is used to create an "unconscious" condition where performance, calculated across all trials of this condition, is around chance level, and a "conscious" condition where average performance is high. Thus, objective, performance-based tasks are analyzed by calculating summary statistics reflecting behavioral performance across many trials of an unconscious and conscious condition, respectively. In contrast, in what we refer to as subjective approaches, an experimental manipulation is often titrated (e.g., masking of intermediate strength) so that an observer reports conscious experience in some trials but no conscious experience in other trials. These subjective reports are subsequently used to sort trials into "conscious" and "unconscious" categories. In other words, objective approaches manipulate consciousness directly (consciousness being an independent variable), whereas subjective approaches use consciousness as a dependent variable, dependent on an observer's non-falsifiable introspective report (see Figure 2). Note that response metrics can often be used for both purposes, and approaches are sometimes even combined. It can be hard for non-experimentally trained readers to see the difference, but it is important to realize these approaches are fundamentally different, and that each has its own set of theoretical and methodological problems.

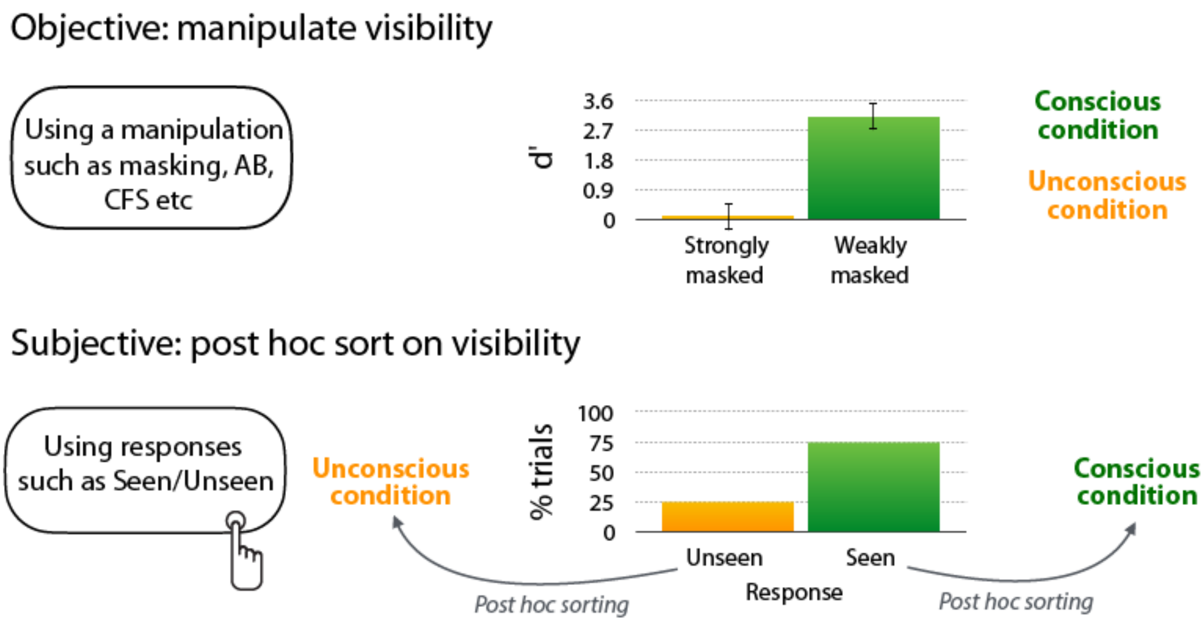


Figure 2. *Illustration of different analysis approaches and their effects. In the objective approach, consciousness is manipulated using techniques such as masking, the AB, or CFS. This leads to a*

conscious condition, in which performance (e.g., expressed as d') is high and an unconscious condition in which performance is low and/or (close to) at chance level. In the subjective approach, consciousness is not manipulated but trials are sorted based on a subjective response of the observer about stimulus perceptibility (e.g., seen vs. unseen). Often performance is titrated to be around 75% correct to have sufficient trials in both post-hoc created conditions.

Mode of stimulus presentation: Forced-choice vs Nonforced-choice

Some may refer to objective as forced-choice and subjective as non-forced choice. Although the term forced-choice is commonplace in the literature, its precise meaning is seldom made explicit, and thus the label is used inconsistently. In the classic psychophysics framework of signal detection theory (SDT), forced-choice refers to tasks in which an observer chooses from two or more stimuli presented on every trial, while nonforced-choice refers to tasks in which the participant evaluates only a single stimulus per trial (see Figure 3) [46]. Another meaning often adopted in consciousness research is that a participant has two (or more) response options to choose from after seeing a single stimulus, especially when applied to discrimination tasks. Under that definition, virtually any empirical study would be “forced choice”, given that in almost any study participants respond using a limited set of options, thus stripping the term of its meaning. We therefore recommend using the designation “forced-choice” only for tasks in which a participant chooses from a limited set of stimuli presented on every trial. Thus, “two alternative forced choice” means that a participant is presented two stimuli on every trial (for example on the left and on the right side of the screen) and makes a forced choice to indicate whether the left or the right stimulus is the pre-defined target. The temporal version of the 2AFC is the two-interval forced choice (2IFC) in which two stimuli are presented in succession, and the participant indicates whether the target was present in the first or in the second interval (see Figure 3a).

Using the term forced-choice to refer to the number of stimuli presented on every trial is important because only when defined in this way can a forced-choice task considered to be “criterion-free” (when performance is evaluated over all trials), whereas a non-forced choice task is intrinsically susceptible to the observer’s response criterion, as we discuss in the next paragraph. In a non-forced choice task, such as the “yes/no” task, only a single stimulus, which might either contain the target or not, is presented on every trial, while a pre-defined number of response options is available to respond to this stimulus (see Figure 3b). Although the distinction between forced-choice and nonforced-choice is sometimes thought to map onto the subjective-objective dimension, neither of these tasks can be said to be inherently “objective” or “subjective.” Importantly, the classification as objective or subjective also depends on how data from these tasks are analyzed, e.g. whether performance across all trials is evaluated against a ground truth (objective), or whether individual trials are sorted into conscious vs unconscious conditions and/or used to indicate a shift in the point of subjective equality (subjective). For example, a yes/no task in which an observer indicates target presence vs absence would yield a subjective measure when trials are sorted according to the observer’s response, but the same task would yield an objective measure when a summary statistic reflecting the observer’s ability to distinguish between target presence vs absence is calculated across many trials.

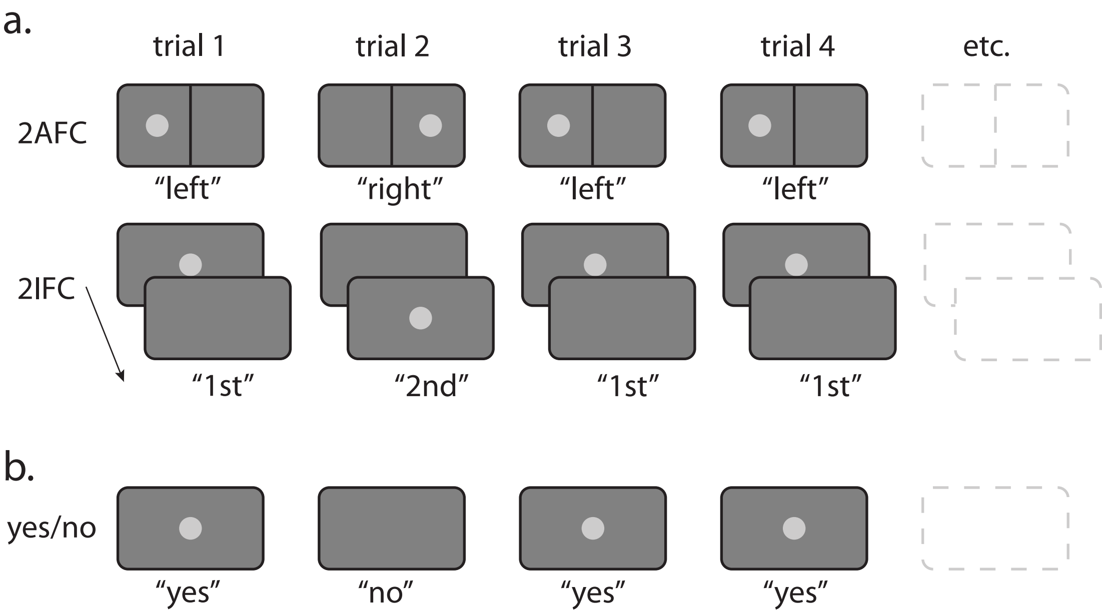


Figure 3. *(a) In forced-choice tasks the observer chooses from two or more stimuli presented on every trial. For example, in the 2AFC task illustrated here, two stimuli are presented on every trial, one containing the target and one without the target. The observer must indicate which of these stimuli contained the target, the left or the right portion of the screen (thus being able to directly compare both sides). In the 2IFC task illustrated here, the observer indicates whether the target is presented in the first or second interval. (b) In nonforced-choice tasks, the observer only evaluates a single stimulus on every trial. In the yes/no task illustrated here, trials either contain a target or not and the observer indicates presence (yes response) or absence (no response).*

Criterion-free vs criterion-dependent

Some might also choose to refer to objective as “criterion-free” and subjective as “criterion-dependent”. This dichotomy maps onto the degree to which a measure can be influenced by criterion shifts / biases, which depends on the nature of the task and the way the data are analyzed. Forced-choice tasks such as the 2AFC/2IFC task are considered criterion-free because the participant does not need to maintain an internal criterion to perform the task. Rather, the participant can concurrently evaluate both stimuli and use the difference between the two as a natural criterion to choose between left and right or between the first and the second interval. Thus criterion-free does not mean that no criterion is involved, but rather that the criterion is likely to be neutral with respect to the relevant stimulus dimension. Thus, criterion-free in this context refers to the fact that the observer is not likely to exhibit a bias for one stimulus category over the other. Importantly, this does not preclude a bias for the first or the second interval (2IFC), or for left and right (2AFC). Such biases might always occur and cannot be prevented, but they would not impact the prior probability of designating stimuli as either one or the other stimulus category in a 2AFC/2IFC, because a biased preference for a location or interval is orthogonal to the relevant stimulus dimension. In contrast, in the yes/no task the observer needs to set and maintain a criterion throughout the task for deciding whether the single presented stimulus contained the target or not, and in such a task there is no natural criterion that can be adopted to make a choice. Rather, the observer must arbitrarily decide which signal strengths count as noise (target absent) and which ones count as signal (target present), thus becoming a criterion-dependent choice.

In consciousness research it is commonplace to use responses on a criterion-dependent yes/no task to sort individual trials into categories reflecting the degree of conscious experience, either based on a simple seen-unseen response, or using a more fine-grained measures like the Perceptual Awareness Scale (PAS) or a confidence evaluation, as discussed further down [12,28,47–51]. This seems to naturally and intuitively allow participants to express their subjective experience, potentially even incorporating different criteria when using more fine-grained response options. However, it also means that the observer’s criterion for any given response effectively marks a discrete boundary between conditions such as “unconscious” and “conscious”. Unfortunately, this boundary is known to be easily confounded by internal and external factors that may not reflect changes in subjective experience [30,38].

As a potential solution to the criterion problem, one may collect yes/no responses across a series of trials containing targets and non-targets to separate out the influence of the criterion. Using this approach, the arbitrary response criterion can be estimated independently from the observer’s objective ability (sensitivity) to distinguish between target presence and absence, for example by applying signal detection theory to calculate d’ (sensitivity) and the criterion (SDT, see Figure 4). In this analysis approach, sensitivity can be said to represent an objective, criterion-free awareness measure derived from a yes/no task. Indeed, using SDT sensitivities from 2AFC (or 2IFC) tasks can be directly related to sensitivities from yes/no tasks. Alternative approaches involve computing criterion-free metacognitive metrics to estimate the degree of metacognitive efficiency of an observer (see Type 1 vs Type 2 section below) [52–54].

Although it might seem appealing to adopt such a criterion-free approach, either by using forced-choice stimulus-presentations and/or by computing criterion-free performance metrics such as d’, the disadvantage is that these inescapably require the researcher to set a ground truth, which may disregard the observer’s actual phenomenology [55].

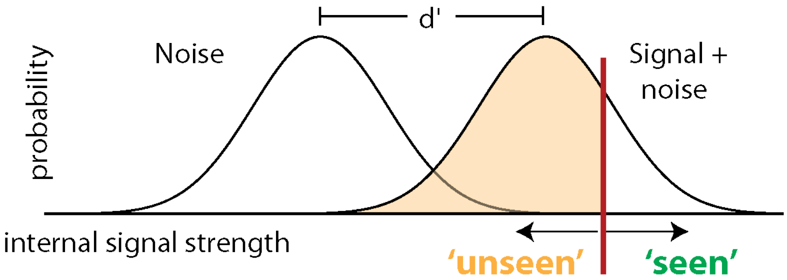


Figure 4. *Illustration of criterion shifts in the SDT framework. Internal signal strength is plotted for noise-only trials (left distribution) and signal + noise trials (right distribution). d' reflects the distance between the means of the distributions (how well an observer can distinguish between signal and noise). The observer must set an internal criterion (red vertical line) to indicate whether a stimulus was present or not. This criterion can be liberal (more to the left), leading to more “seen” responses (when the internal signal strength is relatively weak), or the criterion can be conservative (more to the right), leading to less “seen” responses (only when the internal signal strength is relatively strong). Thus, the designation “seen” or “unseen” arbitrarily depends on the criterion that is adopted by the observer.*

Response types: Type 1 vs Type 2

Another dichotomy that often comes up in consciousness research and that is often mapped onto objective and subjective is the distinction between Type 1 and Type 2 responses. Type 1 responses are first-order judgments about stimuli, such as detecting or categorizing a stimulus (e.g., in a 2AFC or yes/no task), whereas Type 2 responses are second-order judgments on a Type 1 response, involving reflection on one's own percepts, cognitive processes or a confidence in one’s own judgments [56]. A primary difference between the two is the notion that Type 2 decisions involve some metacognitive judgment about a Type 1 response. An alternative definition for a Type 2 decision that is sometimes adopted is that it involves any decision for which the correctness cannot be evaluated on objective grounds [e.g. see 39,57]. This is arguably a slightly more inclusive definition than one that involves the presence of a metacognitive judgement. Consequently, one might debate about whether a certain measure is a ‘true’ Type 2 measure or not depending on which exact definition of Type 2 one adopts.

Typical examples of Type 2 measures that can be used in consciousness research are post-decision wagering, confidence measures and the Perceptual Awareness Scale (PAS) (as compared in [58]). In post-decision wagering, observers place a bet on the correctness of their decision, thereby revealing whether their decision was informed by consciously available information [59], but see [60] . Similarly, confidence responses reflect how much confidence observers place in their decision, typically without a monetary incentive for doing so [52], but see [61]. In the PAS, observers indicate the strength of their percept using a four-point scale (e.g. ‘No experience’, ‘Brief glimpse’, ‘Almost clear experience’, ‘Clear experience’), reflecting an assessment of the degree of clearness of their percept, rather than a direct detection of the stimulus itself [62].

Type 1 and Type 2 responses can either be executed sequentially (see example in Figure 5A), or concurrently (see example in Figure 5B). The advantage of the concurrent response is that the second order judgement is not based on an evidence accumulation process that may have continued after giving the Type 1 response, which could create a potential mismatch between the two [63,64]. As discussed in the previous paragraphs, Type 1 responses can either be considered objective or subjective, depending on whether they analyzed within an objective or subjective framework (i.e. whether these responses are evaluated against a ground truth or whether they are sorted into categories as-is). Similarly, when considering the Type 2 response in isolation, it yields a subjective measure because it cannot be evaluated on correctness (there is no “right” or “wrong”) [50,65,66]. Thus, when confidence judgments are used to sort individual trials into conscious (high confidence) and unconscious (low confidence) conditions, or when trials with certain confidence levels are matched against each other, its use is essentially subjective, because without a ground truth the observer’s subjective response criterion cannot be distinguished from objective performance (sensitivity).

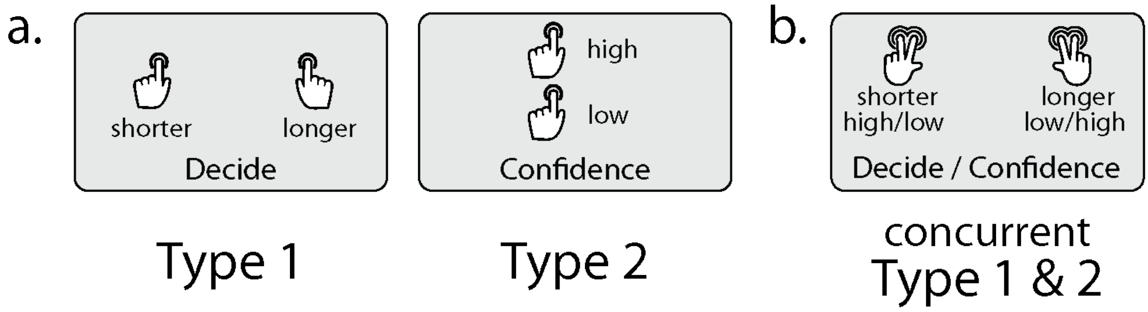


Figure 5. *Examples of collecting Type 1 and Type 2 responses. Type 1 responses are first-order judgements about stimuli (e.g., presence/absence) and can be correct or incorrect. Type 2 responses can either be defined as reflecting a metacognitive judgement about a Type 1 response (e.g., confidence in its correctness) or be thought of as responses reflecting the subjective experience of a stimulus, so that the correctness of the response cannot be evaluated on objective grounds (as it reflects subjective experience). When combined in a task, Type 1 and Type 2 responses can be given (a) separately, i.e. serially or (b) concurrently, e.g. see* [67] .

However, by evaluating the relationship between Type 2 responses such as confidence and Type 1 accuracy, one can calculate metacognitive measures that potentially disentangle metacognitive sensitivity from an observer’s criterion. Such measures of metacognitive sensitivity introduce a ground truth against which the Type 2 response are evaluated: trials with correct Type 1 responses and high confidence are considered “correct”, whereas trials with incorrect Type 1 responses and low confidence are considered “incorrect.” Metacognitive sensitivity thus reflects how well an observer’s Type 2 responses distinguish between an observer’s own correct and incorrect Type 1 responses. However, in its initial inception this metric was known to be affected by Type 1 sensitivity, response bias and confidence bias, prompting the development of the meta-d’ model. This measure of metacognitive sensitivity potentially corrects for these confounds [54].

The meta-d’ model was subsequently further extended by computing the ratio between meta-d’ and d’, an outcome metric of the metacognitive efficiency by which an observer converts their first order ability into confidence responses [52,53,68]. Calculated as a summary statistic over a series of trials, measures of metacognitive sensitivity and metacognitive efficiency can be said to have a hybrid objective-subjective nature. By analyzing participants’ introspective insight into their own performance, a “subjective” aspect of consciousness is studied. At the same time, by considering these insights to be “correct” or “incorrect”, the response is evaluated “objectively” against a ground truth. Therefore, it is important to realize that a given response metric such as confidence can be considered subjective when considered in isolation (there is no intrinsic ground truth against which it can be compared), but as soon as a metric based on this measure utilizes a ground truth to evaluate it, the outcome metric carries the hallmarks of the objective approach. Thus, response measures like post-decision wagering, confidence, or even the PAS can be converted into outcome metrics that are not purely subjective.

Performance vs Appearance

A final dichotomy related to the objective vs subjective distinction is that of performance vs appearance. As discussed above, performance reflects how good one is at a task relative to a ground truth, whereas appearance reflects the perceived magnitude of some stimulus dimension. Examples of appearance measures are those in which an observer indicates the strength of their percept, as in the PAS [62], those in which one either indicates which of two stimuli is perceived as stronger in some dimension, such as brightness [69], or one which one reproduces a stimulus dimension [70,71], see Figure 6. These examples also illustrate the tension between what constitutes a subjective "measure" and what constitutes an objective "measure". When responses on a reproduction task are considered regardless of how they relate to the presented stimulus, the approach is best characterized as subjective; but when reproduction accuracy is evaluated with reference to the presented stimulus, the approach is best characterized as objective. Thus, even an intrinsically subjective scale like the PAS can be used within an objective framework by incorporating an external ground truth into the analysis, even though this is not how it was originally intended to be used. Similar intricacies arise when considering a forced-choice decision between two alternatives based on the subjective appearance of a stimulus. Although such a 2AFC decision may be regarded as criterion-free, and although responses could be analyzed across a series of trials, it can also be used in a subjective framework if one abolishes the use of "correct" or "incorrect" answers during analysis.

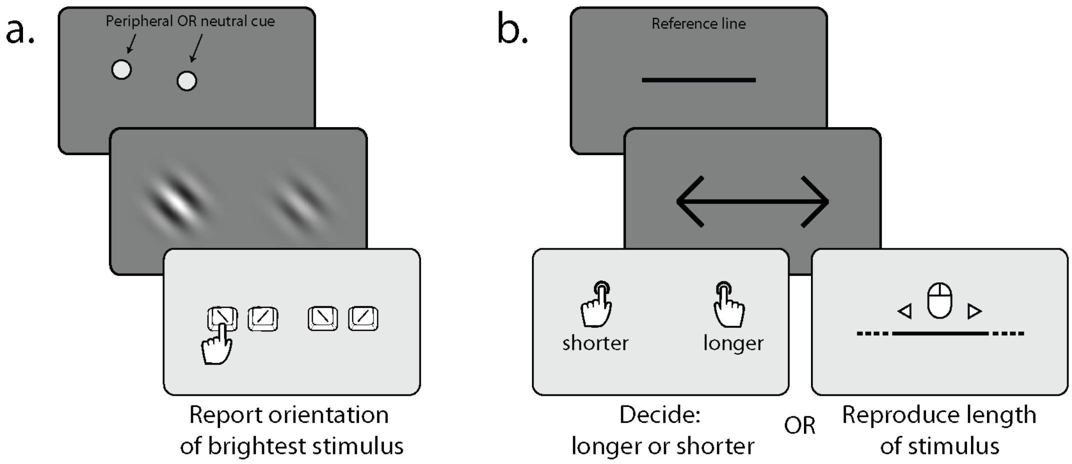


Figure 6. *Examples of appearance paradigms. (a) Depiction of Carrasco's 2AFC paradigm. The response is based on which patch appears brighter, the dependent measure is not the performance of the participant but how the stimulus appears to the observer. It is therefore a subjective, and not an objective approach, despite the usage of a 2AFC task (cf.* [69]*). (b) Example of decision (performance) and controlled reproduction (appearance) tasks, indicating appearance by reproducing the experience of a target length in a nonforced-choice design (cf.* [70] *).*

Summarizing, there are several dichotomies which are sometimes considered to loosely map onto the subjective-objective distinction, but the way they are used together and how the data are eventually analyzed is more informative for the objective-subjective distinction than any one of them in isolation. In Table 1, we provide a selective overview of tasks, modes of presentation, response measures, analysis choices, and outcome measures, which we relate to the abovementioned dichotomies, as well as the core objective/subjective distinction. This table is far from complete. It merely provides an overview of typically encountered combinations of tasks in consciousness research and attempts to provide some conceptual clarity regarding what constitutes an objective or subjective approach. [28,41]

Table 1 *Overview of common combinations of tasks, modes of presentation, response measures, analysis choices, and outcome measures, and how they correspond to the objective/subjective distinction and the related dichotomies discussed in this chapter.*

Task	Mode of stimulus presentation	Response measure	Analysis	Outcome measure	Outcome measure requires ground truth?	Forced-choice	Criterion-free outcome measure	Type 1 / Type 2	Objective / Subjective *
Detection	Multiple stimuli per trial (e.g. 2IFC/2AFC)	Identify presence (1st/2nd | L/R)	Performance	Sensitivity (d', AUC etc.)	✓	✓	✓ **	Type 1	Objective
		Confidence (about decision) / post decision wagering	Summarize	Summary statistic (mean etc.)	✗	✓	✗	Type 2	Subjective
			Performance	Metacognitive sensitivity	✓	✓	✗ ***	Type 2	Hybrid
			Performance	Metacognitive efficiency	✓	✓	✓ theoretically	Type 2	Hybrid
	Single stimulus per trial	Yes/no	Performance	Sensitivity (d', AUC etc.)	✓	✗	✓ **	Type 1	Objective
			Post-hoc sorting	Defines conditions	✗	✗	✗	Type 1 / 2 ****	Subjective
		Confidence (about decision) / post decision wagering	Summarize	Summary statistic (mean etc.)	✗	✗	✗	Type 2	Subjective
			Post-hoc sorting	Defines/matches conditions	✗	✗	✗	Type 2	Subjective
			Performance	Metacognitive sensitivity	✓	✗	✗ ***	Type 2	Hybrid
			Performance	Metacognitive efficiency	✓	✗	✓ theoretically	Type 2	Hybrid
		PAS	Performance	Sensitivity (d', AUC etc.)	✓	✗	✓ **	Type 1	Objective
			Post-hoc sorting	Defines conditions	✗	✗	✗	Type 1 / 2 ****	Subjective
		Reproduction (e.g. intensity, contrast)	Performance	Sensitivity (e.g. deviation)	✓	✗	✓ **	Type 1	Objective
			Summarize	Summary statistic (mean etc.)	✗	✗	✗	Type 1 / 2 ****	Subjective
Discrimination	Multiple stimuli per trial (e.g. 2IFC/2AFC)	Identify feature (1st/2nd | L/R)	Performance	Sensitivity (d', AUC etc.)	✓	✓	✓ **	Type 1	Objective
			Summarize	Point of Subjective Equality	✗	✓	✗	Type 1 / 2 ****	Subjective
		Confidence (about decision) / post decision wagering	Summarize	Summary statistic (mean etc.)	✗	✓	✗	Type 2	Subjective
			Performance	Metacognitive sensitivity	✓	✓	✗ ***	Type 2	Hybrid
			Performance	Metacognitive efficiency	✓	✓	✓ theoretically	Type 2	Hybrid
	Single stimulus per trial	Yes/no (e.g. whether CW tilted)	Performance	Sensitivity (d', AUC etc.)	✓	✗	✓ **	Type 1	Objective
		Confidence (about stimulus or decision)	Summarize	Summary statistic (mean etc.)	✗	✗	✗	Type 2	Subjective
		Reproduction (e.g. tilt, length)	Performance	Sensitivity (e.g. deviation)	✓	✗	✓ **	Type 1	Objective
			Summarize	Summary statistic (mean etc.)	✗	✗	✗	Type 1 / 2 ****	Subjective

* The objective / subjective distinction is not always clear-cut, here we provide a tentative division that is open to discussion depending on the definition that one adopts.

** Responses in tasks that yield a criterion-free outcome measure can still be prone to response biases (e.g., for the first or second interval, the left or the right image, history effects, etc.). These response biases can be computed separately, e.g., using the SDT framework.

*** These outcome measures are influenced by first order performance.

**** This could be conceived of as either Type 1 or Type 2, depending on the exact definition one adopts for Type 2 (either referring to a metacognitive judgement about a Type 1 assesment, or referring to any response/metric for which the correctness cannot be evaluated, see main text).

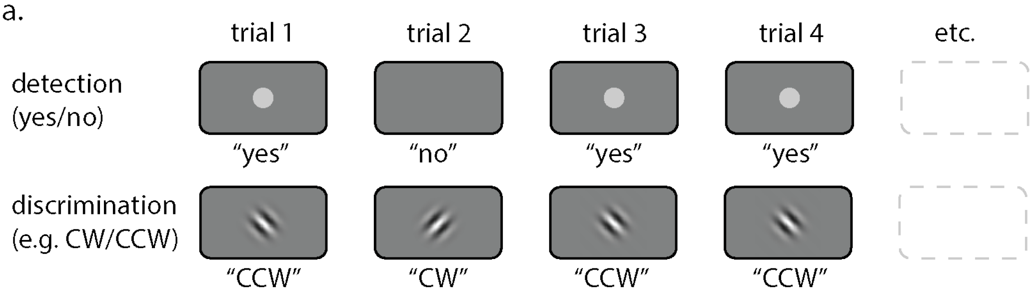
Characterizing tasks: detection vs discrimination

A not yet discussed distinction that is often made in consciousness science is between detection tasks (detect presence vs. absence of one specific target stimulus) and discrimination or categorization tasks (discriminate between several possible target stimuli), also see Table 1. Detection and discrimination can both be measured using forced-choice tasks or nonforced-choice tasks such as yes/no tasks. For example, a forced-choice detection task may present a target in the first interval, and “nothing” (noise) in the second interval (Figure 3a). A more common task is the nonforced-choice yes/no detection task, where a target is present or absent in a single observation interval (see 7a, top row). Similarly, discrimination is often assessed with a nonforced-choice yes/no task, for example by presenting either a left- or a right-tilted stimulus (see Figure 7a, bottom row). Note again that single stimulus discrimination tasks are often incorrectly labeled forced-choice, even though they only contain a single stimulus. Indeed, in psychophysics, the terms detection and discrimination are often considered interchangeable, as detection can be seen as a variant of discrimination in which one has to discriminate between target and non-target (noise). However, an important difference between the two is that in detection tasks the observer must accumulate evidence for absence in target absent trials. Despite the superficial similarity in task design, the brain tackles this problem differently from accumulating evidence for one of two alternatives [72–75]. Relatedly, detection tasks have an asymmetrical confusion matrix and are naturally prone to bias, whereas discrimination tasks have a symmetrical confusion matrix and are naturally less prone (but not immune) to bias (see Figure 7b). Traditionally, consciousness science has put a lot of emphasis on the distinction between detection and discrimination when contrasting conscious vs unconscious processing.

Detection is often thought to have a more direct relation to consciousness than discrimination. When measured subjectively, a stimulus is considered conscious when it is "detected", i.e., given a "present" label by the observer. Detection appears consistent with our intuitions about perceptual awareness: when we are conscious of a stimulus, we can report its presence. When we fail to report the presence of any visual stimulus, we are considered blind. Accordingly, the phenomenon of "blindsight" involves demonstrating that patients with visual cortex lesions fail to report the presence of stimuli in their defective portions of the visual field (this is the "blind" part of the phenomenon), while still being able to discriminate some aspect of the stimulus with above-chance accuracy (this is the "sight" part of the phenomenon).

However, when detection and discrimination are compared as in the case of blindsight, detection is a criterion-dependent subjective measure involving sorting of trials into "conscious" and "unconscious" categories, while discrimination is an objective (and often criterion-free) measure calculated across all "unconscious" trials. Dissociations between these measures may therefore reflect the fact that subjective thresholds are substantially higher than objective thresholds (resulting in the objective discrimination measure having higher sensitivity than the subjective detection measure), as well as their differential susceptibility to criterion effects. A convincing demonstration of blindsight would need to show that discrimination exceeds detection when detection is at chance and both tasks are measured using comparable approaches (e.g. forced-choice, no correlation between detection and discrimination, criterion-free) [76,77]. There seem to be few studies that attempt to achieve this, and those that do typically find no proof of blindsight, at least in normal subjects [78–80].

a.



b.

Stimulus detection

		Present	Absent
Response	Yes	Hit	False alarm
	No	Miss	Correct rejection

Stimulus discrimination

	CW	CCW
CW	Correct	Incorrect
CCW	Incorrect	Correct

Figure 7. *Illustration of the difference between detection and discrimination. (a) In detection (top row), some trials contain a stimulus, whereas others do not. In discrimination (bottom row), every trial contains a stimulus, and the task is to detect a certain feature like location or orientation (CW: clockwise oriented or CCW: counterclockwise oriented). Note that a nonforced-choice discrimination task like the one depicted here can also be thought of as a yes/no task in which the participant has to detect a certain feature like clockwise orientation (press "CW" if present, press "CCW" if absent). (b) Nevertheless, the two tasks have different confusion matrices, stimulus detection being asymmetrical and discrimination being symmetrical.*

Interestingly, above-chance discrimination is sometimes used as a measure of unconscious processing – as in the case of blindsight - but sometimes also used to evaluate consciousness. While the mapping of detection on consciousness appears well aligned with a folk psychological understanding of consciousness, in many cases the goal is to measure awareness of a particular stimulus property like location, orientation, color, shape, motion direction, emotion, object category, and so on. For example, when measuring the extent to which a secondary measure of residual unconscious processing (e.g., fMRI response in visual cortex) is influenced by a specific stimulus property (e.g., images of faces vs houses), the awareness measure should capture that particular stimulus property, and this typically requires a discrimination task (e.g., discrimination of faces vs houses) [25] . While chance-level discrimination performance is generally seen as evidence that awareness of the to-be-discriminated stimulus property was absent, associating awareness with above-chance discriminability is controversial, even when performance is close to 100% correct, as in certain cases of blindsight. However, one may argue that when evaluating conscious experience, we tend to categorize specific contents relative to other potential contents, which may be considered more discrimination- than detection-like. Given these divergent perspectives, it is important for researchers to make explicit their assumptions and logic for implementing different tasks to quantify conscious vs unconscious processing.

Problems and pitfalls

In this chapter, we outlined several dichotomies that overlap with the objective-subjective distinction in different ways. An important point is that measuring consciousness involves a cascade of decisions that impact the outcome and conclusion of a study. Thus, measuring consciousness is more complicated than simply choosing an “objective” or “subjective” measure. Rather, the high-level choice to operationalize consciousness within a certain framework impacts the task, the way in which one presents stimuli, the response measure, the analysis approach, the outcome measure, all of which together have a large impact on the outcome and conclusions of a study. Consequently, one might think that it should be obvious whether a certain experiment has adopted an objective or subjective framework, but a complicating factor is that superficially similar tasks, manipulations and measures (like making a present-absent judgement) can be analyzed in fundamentally different ways, using fundamentally different assumptions, leading to fundamentally different outcomes. Thus, what might look superficially similar might involve a very different approach. The practice of combining approaches can add another layer of complexity, for example when computing performance metrics (objective framework) based on post-hoc sorted conditions (subjective framework) [81–83].

Nevertheless, it is also difficult to claim with authority that one approach is intrinsically superior to another approach. Both approaches have their own problems associated with them. For example, using the contrastive approach within an objective framework typically involves experimentally creating conscious and unconscious conditions using experimental techniques. The advantage of this approach is that the researcher has experimental control, which is the bedrock of scientific inquiry. However, critics may point out that these techniques also introduce a difference between conditions by either changing the physical stimulation (e.g. masking, the attentional blink, CFS) or by directly interfering with neural processing (e.g. using TMS). As a result, some may question whether the difference that was introduced isolates the relevant difference between conscious and unconscious processing. For example, one may ask whether the observed difference between weakly and strongly masked stimuli indeed uncovers the difference between conscious and unconscious processing, or whether the difference in physical stimulation instead represents a confound rather than an explanation for the observed changes in conscious experience.

Relatedly, the objective approach requires setting a ground truth for which responses are “correct”, and which are “incorrect”. This disregards the fact that consciousness is about the subjective experience of the observer, so that in fact there is no ground truth to be had other than what the observer experiences [55]. To give some examples, an observer may experience stimuli as larger (Ebbinghaus illusion), longer (Ponzo and Müller-Lyer illusion) [70,84], brighter [69], bouncing [85], multiplying [86] and so forth due to contextual influences and/or due to influences intrinsic to the participant. These may diverge from the physical characteristics of those stimuli when measured using the “ground truth” that the experimenter chooses to adopt. Thus, when analyzing the data in an objective SDT framework, the response of the participant may express itself as a “bias” (criterion shift), but this bias could either reflect a “true” perceptual shift, but it could also reflect a non-perceptual bias that has no effect on conscious experience. Objective frameworks are not able to resolve such ambiguities because they – by their nature - require setting a ground truth, and these frameworks cannot disentangle whether a behavioral departure from the experimenter’s ground truth is due to perceptual or non-perceptual reasons [70,84].

The subjective approach has its advantages and disadvantages too. It aims to take experience of the observer seriously by letting go of a ground truth, and thus by letting the response of the observer take center stage. It tackles the potentially confounding influence of physical stimulation by taking the response of the participant as a starting point to create conditions. As a side note, it may be somewhat confusing that in a subjective approach too, researchers often manipulate consciousness using methods like masking, the attentional blink and CFS. However, rather than using this manipulation to create experimental conditions, the manipulation is used to titrate performance to a fixed level somewhere between chance and perfect[1]. Once this is achieved, physical stimulation can be kept identical, and the responses of the participant can be used to sort trials into conscious and unconscious conditions. An advantage of this approach is that differences in stimulation cannot themselves be a source of confounds. However, the experimental control that researchers maintain in the objective approach is now handed over to the participant, who through response selection determines to which condition a given trial belongs. Consequently, the potential source of confounds no longer comes from differences in physical stimulation, but rather from the response of the participant itself. For example, a well-known confound is that the response of the participant does not just reflect the experience of the observer but may also reflect a plethora of non-perceptual influences. This has been shown to confound neural measures of consciousness based on trial sorting, both on theoretical and on empirical grounds [38] (see Figure 8).

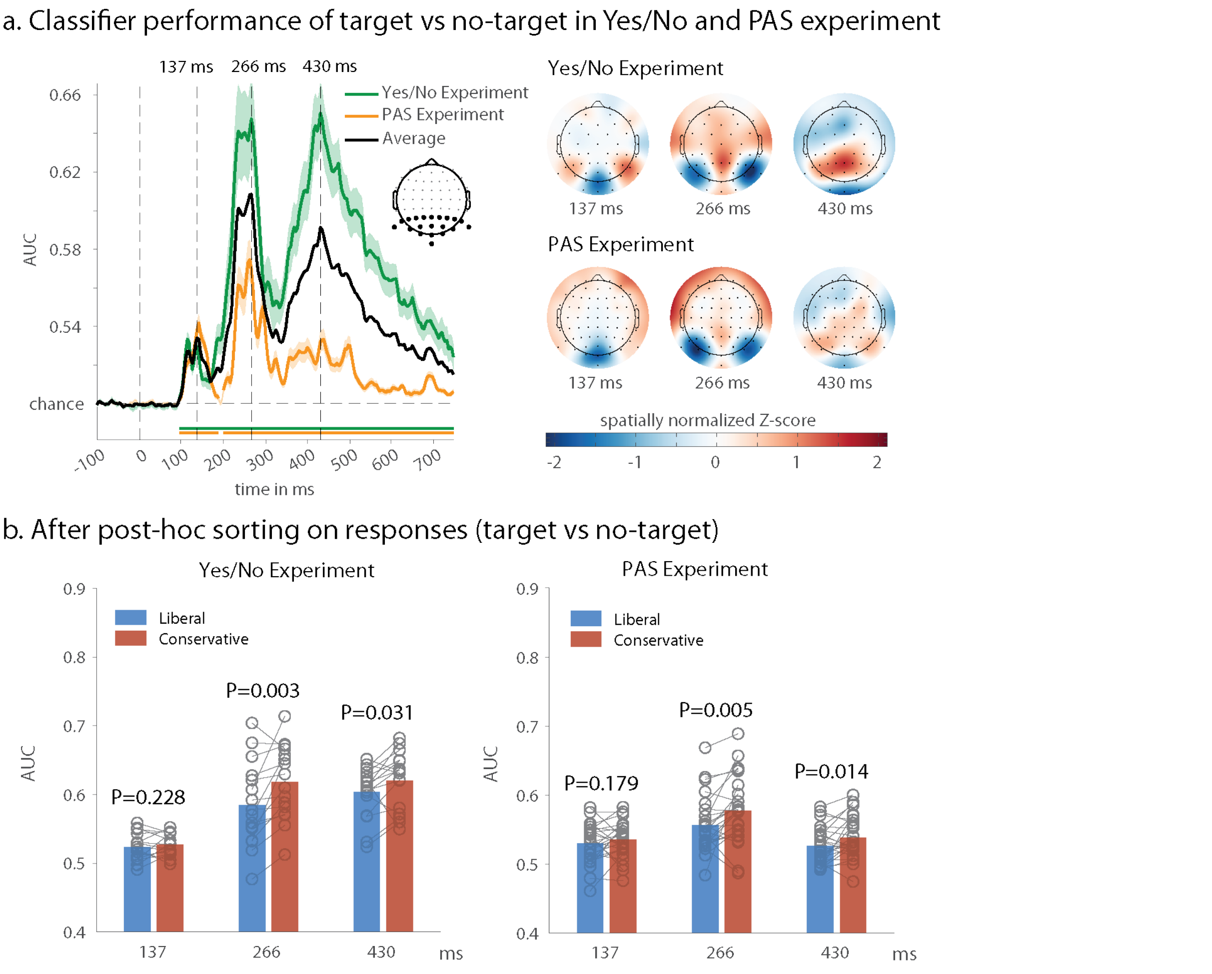


Figure 8. *(a) EEG decoding from a nonforced-choice yes/no task in which the observer indicates the visibility of a stimulus on every trial using seen/unseen responses or the PAS (four levels of subjective awareness). Decoding target presence vs. absence revealed three neural events of interest peaking at 137, 266 and 430 ms (based on the average decoding from both tasks). The spatial topography of these events is shown on the right. (b) In the experiment observers are nudged towards employing a more liberal or conservative response criterion using negative feedback on either misses or on false alarms.*

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[1] Or by creating conditions in which the percept of an observer switches back and forth, as in binocular rivalry.

Consequently, the number of seen and unseen trials (or the awareness judgements on the PAS) changes as a factor of this criterion manipulation (while d' remained similar). Note that the average signal strength of both unseen and seen trials is greater under a conservative response criterion than under a liberal response criterion (see also Fig 4). When criterion shifts are combined with post-hoc sorting of trials based on visibility (e.g., seen vs. unseen), this affected the decoding accuracy of the second and third neural events, but not the first neural event. In combination with simulations (data not shown), these results revealed that the neural correlate associated perceptual awareness is affected by criterion confounds, threatening the validity of using contrastive approaches (e.g., seen vs unseen) based on (criterion sensitive) subjective measures to reveal the neural correlates of consciousness (reproduced with permission from [38]*, published under a CC BY 4.0 license).*

This is problematic, because criterion shifts can arise due to many factors, both internal and external to the observer. Internal factors might be endogenous attention, or the fact that participants are intrinsically conservative or liberal. External sources of variation across experiments may be contextual effects such as the ratio of targets to non-targets, the perceived utility of certain response-outcome mappings, or the relative strength of the stimulus compared to other stimuli in close temporal proximity [38,67,70,87]. These factors and more are known to shift the response criterion, thereby confounding the outcome with aspects that are not related to subjective experience.

Furthermore, it has become increasingly clear that the choice of the overall framework strongly impacts the results one obtains. For example, the threshold marking the transition from unconscious to conscious conditions is typically substantially higher when measured subjectively, so that under subjective measurement approaches estimates of unconscious processing are greater, and the functional role of consciousness is diminished, compared to objective measurement approaches (see Figure 9). Similarly, detection and discrimination approaches may naturally yield different results, as detection tasks are naturally more prone to bias than discrimination tasks. Unfortunately, there is no gold standard for measuring consciousness, so that the measurement approach depends on the researcher's convictions and intuitions.

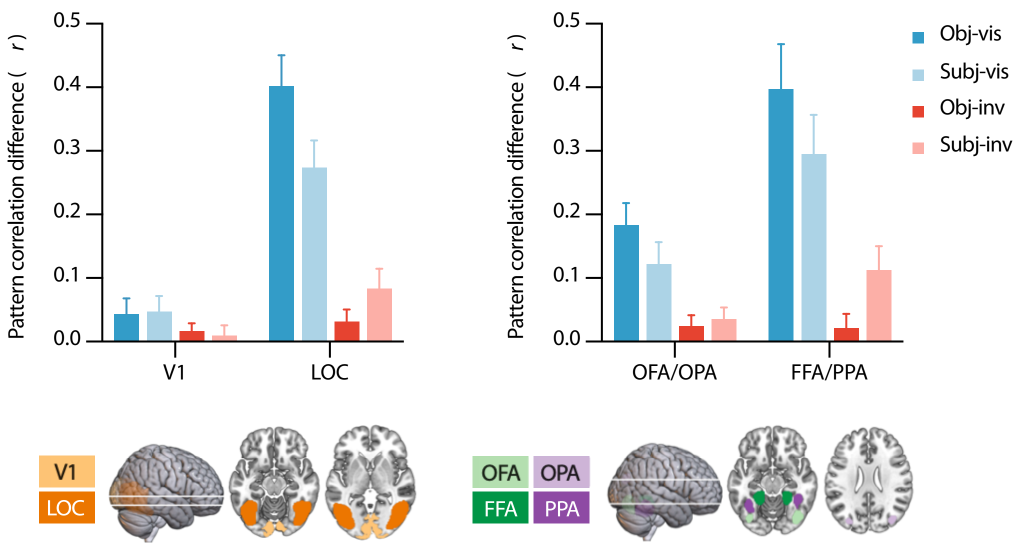

Figure 9. *Illustration of results from a study comparing subjective and objective analysis approaches. The results show that decoding of subjectively "invisible" categories in object selective areas (LOC, OFA/OPA, FFA/PPA) is much better than for objectively "invisible" categories, whereas for "visible" categories the reverse holds (reproduced with permission from* [28]*, published under a CC BY 4.0 license).*

Some may see relief in the use of hybrid approaches, such as measures of metacognitive efficiency across trials [52,88]. These may carry hallmarks from both subjective and objective measurement strategies, depending on how the outcome metric is computed. This can be seen as a strength, but also as a weakness. From a strength perspective, when the outcome metric of these approaches is computed over many trials, and if this computation successfully models or corrects for confounds related to first order performance as well as response and confidence biases, they could resolve some of the methodological issues that plague subjective and objective measures, while retaining a core aspect of the subjective approach by interrogating the experience of the observer. However, even state-of-the art metacognitive measures do not resolve all problems [52,89]. Thus, one might also argue the reverse, that despite their adoption of a subjective measure like confidence, hybrid outcome metrics like metacognitive efficiency will always require a ground truth, which is inconsistent with the intrinsic nature of conscious experience. As such, the remaining problems in hybrid approaches may be a consequence of the fickle influence of projecting a ground truth in experiments that investigate subjective experience.

Whatever approach one favors, the measurement and analysis strategy one adopts greatly influences the outcome and conclusions. Plausibly, this also partially explains the heterogeneity of results in the empirical literature and precludes drawing definitive conclusion based on the wealth of data that has already been collected. For this reason, we strongly advise that researchers are explicit about the approach that they prefer to adopt and provide a rationale for doing so. In addition, we hope that researchers are not just explicit about their general framework but also defend in more detail how these choices map onto the dichotomies that we put forward in this chapter (see Table 1). Although this step may not resolve the issues, it at least provides a starting point for having constructive discussions regarding the meaning and interpretation of empirical results.

References

[1] Fechner GT. Elemente der Psychophysik [Elements of psychophysics]. Leipzig: Breitkopf und Härtel; 1860.

[2] LeDoux JE, Michel M, Lau HC. A little history goes a long way toward understanding why we study consciousness the way we do today. PNAS 2020;117:6976–84. https://doi.org/10.1073/pnas.1921623117.

[3] Crick F, Koch C. Towards a neurobiological theory of consciousness. Seminars in the Neurosciences 1990;2:263–75.

[4] Donders FC. Over de snelheid van psychische processen [On the speed of mental processes]. Onderzoekingen Gedaan in Het Physiologisch Laboratorium Der Utrechtsche Hoogeschool: 1868-1869 1868;Tweede Reeks, 2:92–120.

[5] Baars BJ. A Cognitive Theory of Consciousness. Cambridge University Press; 1988.

[6] Kim C-Y, Blake R. Psychophysical magic: rendering the visible 'invisible.' Trends Cogn Sci 2005;9:381–8. https://doi.org/10.1016/j.tics.2005.06.012.

[7] Breitmeyer BG. Visual masking: An integrative approach. Oxford/Clarendon Press/Oxford University Press; 1984.

[8] Fahrenfort JJ, Scholte HS, Lamme VAF. Masking disrupts reentrant processing in human visual cortex. J Cognitive Neurosci 2007;19:1488–97. https://doi.org/10.1162/jocn.2007.19.9.1488.

[9] Fahrenfort JJ, Leeuwen J van, Olivers CNL, Hogendoorn H. Perceptual integration without conscious access. Proceedings of the National Academy of Sciences 2017;114:3744–9. https://doi.org/10.1073/pnas.1617268114.

[10] Dehaene S, Naccache L, Cohen L, Bihan DL, Mangin JF, Poline JB, Riviere D. Cerebral mechanisms of word masking and unconscious repetition priming. Nat Neurosci 2001;4:752–8.

[11] Dehaene S, Naccache L, Clec'H GL, Koechlin E, Mueller M, Dehaene-Lambertz G, Moortele P-F van de, Bihan DL. Imaging unconscious semantic priming. Nature 1998;395:597–600. https://doi.org/10.1038/26967.

[12] Sergent C, Baillet S, Dehaene S. Timing of the brain events underlying access to consciousness during the attentional blink. Nat Neurosci 2005;8:1391–400. https://doi.org/10.1038/nn1549.

[13] Raymond JE, Shapiro KL, Arnell KM. Temporary suppression of visual processing in an RSVP task: an attentional blink? . J Exp Psychol Human 1992;18:849–60.

[14] Tsuchiya N, Koch C. Continuous flash suppression reduces negative afterimages. Nat Neurosci 2005;8:1096–101. https://doi.org/10.1038/nn1500.

[15] Stein T, Hebart MN, Sterzer P. Breaking Continuous Flash Suppression: A New Measure of Unconscious Processing during Interocular Suppression? Front Hum Neurosci 2011;5:167. https://doi.org/10.3389/fnhum.2011.00167.

[16] Tong F, Nakayama K, Vaughan JT, Kanwisher N. Binocular Rivalry and Visual Awareness in Human Extrastriate Cortex. Neuron 1998;21:753–9. https://doi.org/10.1016/s0896-6273(00)80592-9.

[17] Tong F, Meng M, Blake R. Neural bases of binocular rivalry. Trends Cogn Sci 2006;10:502–11. https://doi.org/10.1016/j.tics.2006.09.003.

[18] Moutoussis K, Zeki S. The relationship between cortical activation and perception investigated with invisible stimuli. P Natl Acad Sci USA 2002;99:9527–32. https://doi.org/10.1073/pnas.142305699.

[19] Fahrenfort JJ, Snijders TM, Heinen K, Gaal S van, Scholte HS, Lamme VAF. Neuronal integration in visual cortex elevates face category tuning to conscious face perception. P Natl Acad Sci USA 2012;109:21504–9. https://doi.org/10.1073/pnas.1207414110.

[20] Baars BJ. Contrastive Phenomenology: A Thoroughly Empirical Approach to Consciousness. In: Ğuzeldere"] ["Ned Block and Owen Flanagan and Güven, editor. The Nature of Consciousness: Philosophical Debates, MIT Press; 1994, p. 187–202.

[21] Aru J, Bachmann T, Singer W, Melloni L. Distilling the neural correlates of consciousness. Neurosci Biobehav Rev 2012;36:737–46. https://doi.org/10.1016/j.neubiorev.2011.12.003.

[22] Holender D, Duscherer K. Unconscious perception: The need for a paradigm shift. Percept Psychophys 2004;66:872–81. https://doi.org/10.3758/bf03194980.

[23] Cheesman J, Merikle PM. Distinguishing conscious from unconscious perceptual processes. Can J Psychol 1986;40:343–67. https://doi.org/10.1037/h0080103.

[24] Greenwald AG, Draine SC, Abrams RL. Three Cognitive Markers of Unconscious Semantic Activation. Science 1996;273:1699–702. https://doi.org/10.1126/science.273.5282.1699.

[25] Schmidt T, Vorberg D. Criteria for unconscious cognition: Three types of dissociation. Percept Psychophys 2006;68:489–504. https://doi.org/10.3758/bf03193692.

[26] WEISKRANTZ L, WARRINGTON EK, SANDERS MD, MARSHALL J. VISUAL CAPACITY IN THE HEMIANOPIC FIELD FOLLOWING A RESTRICTED OCCIPITAL ABLATION. Brain 1974;97:709–28. https://doi.org/10.1093/brain/97.1.709.

[27] Weiskrantz L. Pupillary Responses With and Without Awareness in Blindsight. Conscious Cogn 1998;7:324–6. https://doi.org/10.1006/ccog.1998.0360.

[28] Stein T, Kaiser D, Fahrenfort JJ, Gaal S van. The human visual system differentially represents subjectively and objectively invisible stimuli. PLoS Biol 2021;19:e3001241. https://doi.org/10.1371/journal.pbio.3001241.

[29] Meyen S, Zerweck IA, Amado C, Luxburg U von, Franz VH. Advancing Research on Unconscious Priming: When Can Scientists Claim an Indirect Task Advantage? J Exp Psychol: Gen 2022;151:65–81. https://doi.org/10.1037/xge0001065.

[30] Schmidt T. Invisible Stimuli, Implicit Thresholds: Why Invisibility Judgments Cannot be Interpreted in Isolation. Adv Cogn Psychol 2015;11:31–41. https://doi.org/10.5709/acp-0169-3.

[31] Merikle PM, Reingold EM. Measuring unconscious perceptual processes. In: R.F.Bornstein, T.S.Pittman, editors. Perception without awareness: Cognitive, clinical, and social perspectives, Guilford Press; 1992, p. 55–80.

[32] Stein T, Gaal S van, Fahrenfort JJ. How (not) to demonstrate unconscious priming: Overcoming issues with post-hoc data selection, low power, and frequentist statistics. Conscious Cogn 2024;119:103669. https://doi.org/10.1016/j.concog.2024.103669.

[33] Schmidt T. The Finger in Flight: Real-Time Motor Control by Visually Masked Color Stimuli. Psychol Sci 2001;13:112–8. https://doi.org/10.1111/1467-9280.00421.

[34] Lau HC, Passingham RE. Relative blindsight in normal observers and the neural correlate of visual consciousness. P Natl Acad Sci USA 2006;103:18763–8. https://doi.org/10.1073/pnas.0607716103.

[35] Azzopardi P, Cowey A. Blindsight and Visual Awareness,. Consciousness and Cognition 1998;7:292–311.

[36] Balsdon T, Azzopardi P. Absolute and relative blindsight. Conscious Cogn 2015;32:79–91. https://doi.org/10.1016/j.concog.2014.09.010.

[37] Peters MAK, Ro T, Lau H. Who's afraid of response bias? Neurosci Conscious 2016;2016:niw001. https://doi.org/10.1093/nc/niw001.

[38] Fahrenfort JJ, Johnson PA, Kloosterman NA, Stein T, Gaal S van. OLD Criterion placement threatens the construct validity of neural measures of consciousness. ELife 2024. https://doi.org/10.7554/elife.102335.1.

[39] Kingdom FrederickAA, Prins N. Psychophysics: A Practical Introduction. Second Edition. Academic Press; 2016. https://doi.org/10.1016/c2012-0-01278-1.

[40] Francken JC, Beerendonk L, Molenaar D, Fahrenfort JJ, Kiverstein JD, Seth AK, Gaal S van. An academic survey on theoretical foundations, common assumptions and the current state of consciousness science. Neurosci Conscious 2022;2022:niac011. https://doi.org/10.1093/nc/niac011.

[41] Merikle PM. Perception without awareness. Critical issues. Am Psychol 1992;47:792–5.

[42] Snodgrass M, Shevrin H. Unconscious inhibition and facilitation at the objective detection threshold: Replicable and qualitatively different unconscious perceptual effects. Cognition 2006;101:43–79. https://doi.org/10.1016/j.cognition.2005.06.006.

[43] Kunimoto C, Miller J, Pashler H. Confidence and Accuracy of Near-Threshold Discrimination Responses. Conscious Cogn 2001;10:294–340. https://doi.org/10.1006/ccog.2000.0494.

[44] Michel M. The Mismeasure of Consciousness: A Problem of Coordination for the Perceptual Awareness Scale. Philos Sci 2019;86:1239–49. https://doi.org/10.1086/705509.

[45] Skóra Z, Pin SHD, Derda M, Koculak M, Rutiku R, Wierzchoń M. No validity without a theory—a critical look at subjective measures of consciousness. Neurosci Conscious 2021;2021:niab009. https://doi.org/10.1093/nc/niab009.

[46] Green DM, Swets JA. Signal Detection Theory and Psychophysics. Peninsula Publishing; 1966.

[47] Andersen LM, Pedersen MN, Sandberg K, Overgaard M. Occipital MEG Activity in the Early Time Range (<300 ms) Predicts Graded Changes in Perceptual Consciousness. Cereb Cortex 2016;26:2677–88. https://doi.org/10.1093/cercor/bhv108.

[48] Sandberg K, Bahrami B, Kanai R, Barnes GR, Overgaard M, Rees G. Early visual responses predict conscious face perception within and between subjects during binocular rivalry. J Cognitive Neurosci 2013;25:969–85. https://doi.org/10.1162/jocn_a_00353.

[49] King J-R, Pescetelli N, Dehaene S. Brain Mechanisms Underlying the Brief Maintenance of Seen and Unseen Sensory Information. Neuron 2016;92:1122–34. https://doi.org/10.1016/j.neuron.2016.10.051.

[50] Mazor M, Dijkstra N, Fleming SM. Dissociating the Neural Correlates of Subjective Visibility from Those of Decision Confidence. J Neurosci 2022;42:2562–9. https://doi.org/10.1523/jneurosci.1220-21.2022.

[51] Lamy D, Salti M, Bar-Haim Y. Neural Correlates of Subjective Awareness and Unconscious Processing: An ERP Study. J Cognitive Neurosci 2009;21:1435–46. https://doi.org/10.1162/jocn.2009.21064.

[52] Michel M. Confidence in consciousness research. Wiley Interdiscip Rev: Cogn Sci 2023;14:e1628. https://doi.org/10.1002/wcs.1628.

[53] Fleming SM. HMeta-d: hierarchical Bayesian estimation of metacognitive efficiency from confidence ratings. Neurosci Conscious 2017;2017:nix007. https://doi.org/10.1093/nc/nix007.

[54] Maniscalco B, Lau HC. A signal detection theoretic approach for estimating metacognitive sensitivity from confidence ratings. Consciousness and Cognition 2012;21:422–30. https://doi.org/10.1016/j.concog.2011.09.021.

[55] Koenderink J. The all seeing eye? Perception 2014;43:1–6. https://doi.org/10.1068/p4301ed.

[56] Galvin SJ, Podd JV, Drga V, Whitmore J. Type 2 tasks in the theory of signal detectability: Discrimination between correct and incorrect decisions. Psychon B Rev 2003;10:843–76. https://doi.org/10.3758/bf03196546.

[57] Sperling G. Type 1 and Type 2 Experiments 2008. http://www.cogsci.uci.edu/~whipl/Type_1_and_Type_2_Expts.pdf.

[58] Sandberg K, Timmermans B, Overgaard M, Cleeremans A. Measuring consciousness: is one measure better than the other? Consciousness and Cognition 2010;19:1069–78. https://doi.org/10.1016/j.concog.2009.12.013.

[59] Persaud N, McLeod P, Cowey A. Post-decision wagering objectively measures awareness. Nat Neurosci 2007;10:257–61. https://doi.org/10.1038/nn1840.

[60] Fleming SM, Dolan RJ. Effects of loss aversion on post-decision wagering: Implications for measures of awareness. Conscious Cogn 2010;19:352–63. https://doi.org/10.1016/j.concog.2009.11.002.

[61] Lebreton M, Langdon S, Slieker MJ, Nooitgedacht JS, Goudriaan AE, Denys D, Holst RJ van, Luigjes J. Two sides of the same coin: Monetary incentives concurrently improve and bias confidence judgments. Sci Adv 2018;4:eaaq0668. https://doi.org/10.1126/sciadv.aaq0668.

[62] Ramsøy TZ, Overgaard M. Introspection and subliminal perception. Phenom Cogn Sci 2004;3:1–23. https://doi.org/10.1023/b:phen.0000041900.30172.e8.

[63] Desender K, Vermeylen L, Verguts T. Dynamic influences on static measures of metacognition. Nat Commun 2022;13:4208. https://doi.org/10.1038/s41467-022-31727-0.

[64] Pleskac TJ, Busemeyer JR. Two-stage dynamic signal detection: A theory of choice, decision time, and confidence. Psychol Rev 2010;117:864–901. https://doi.org/10.1037/a0019737.

[65] Peirce CS, Jastrow J. On small differences in sensation. Memoirs of the National Academy of Sciences 1884;3:75–83.

[66] Dienes Z. Subjective measures of unconscious knowledge. Prog Brain Res 2007;168:49–269. https://doi.org/10.1016/s0079-6123(07)68005-4.

[67] Sánchez-Fuenzalida N, Gaal S van, Fleming SM, Haaf JM, Fahrenfort JJ. Confidence reports during perceptual decision making dissociate from changes in subjective experience. Commun Psychol 2025;3:81. https://doi.org/10.1038/s44271-025-00257-y.

[68] Maniscalco B, Lau HC. Signal detection theory analysis of type 1 and type 2 data: Meta-d′, response-specific meta-d′, and the unequal variance SDT model. The Cognitive Neuroscience of Metacognition, vol. 9783642451904, The Cognitive Neuroscience of Metacognition; 2014, p. 25–66. https://doi.org/10.1007/978-3-642-45190-4_3.

[69] Carrasco M, Ling S, Read S. Attention alters appearance. Nat Neurosci 2004;7:308–13. https://doi.org/10.1038/nn1194.

[70] Sánchez-Fuenzalida N, Gaal S van, Fleming SM, Haaf JM, Fahrenfort JJ. Predictions and rewards affect decision-making but not subjective experience. Proc Natl Acad Sci 2023;120:e2220749120. https://doi.org/10.1073/pnas.2220749120.

[71] Fritsche M, Mostert P, Lange FP de. Opposite Effects of Recent History on Perception and Decision. Curr Biol 2017;27:590–5. https://doi.org/10.1016/j.cub.2017.01.006.

[72] Meuwese JDI, Loon AM van, Lamme VAF, Fahrenfort JJ. The subjective experience of object recognition: comparing metacognition for object detection and object categorization. Attention Perception & Psychophysics 2014;76:1057–68. https://doi.org/10.3758/s13414-014-0643-1.

[73] Mazor M, Friston KJ, Fleming SM. Distinct neural contributions to metacognition for detecting, but not discriminating visual stimuli. Elife 2020;9:e53900. https://doi.org/10.7554/elife.53900.

[74] Kanai R, Walsh V, Tseng C. Subjective discriminability of invisibility: A framework for distinguishing perceptual and attentional failures of awareness. Consciousness and Cognition 2010;19:1045–57. https://doi.org/10.1016/j.concog.2010.06.003.

[75] Bowers JS, Jones KW. Detecting objects is easier than categorizing them. Q J Exp Psychol 2008;61:552–7. https://doi.org/10.1080/17470210701798290.

[76] Phillips I. Consciousness and Criterion: On Block's Case for Unconscious Seeing. Philosophy and Phenomenological Research 2016;93:419–51. https://doi.org/10.1111/phpr.12224.

[77] Phillips I. Blindsight is qualitatively degraded conscious vision. Psychol Rev 2020. https://doi.org/10.1037/rev0000254.

[78] Peters MAK, Lau HC. Human observers have optimal introspective access to perceptual processes even for visually masked stimuli. ELife Sciences 2015;4:e09651. https://doi.org/10.7554/elife.09651.

[79] Robichaud L, Stelmach LB. Inducing blindsight in normal observers. Psychon B Rev 2003;10:206–9. https://doi.org/10.1093/brain/97.1.709.

[80] Morgan MJ, Mason AJS, Solomon JA. Blindsight in normal subjects? Nature 1997;385:401–2. https://doi.org/10.1038/385401b0.

[81] Salti M, Monto S, Charles L, King J-R, Parkkonen L, Dehaene S, Johansen-Berg H. Distinct cortical codes and temporal dynamics for conscious and unconscious percepts. ELife Sciences 2015;4:e05652. https://doi.org/10.7554/elife.05652.

[82] Hsieh P-J, Colas JT, Kanwisher N. Pop-out without awareness: unseen feature singletons capture attention only when top-down attention is available. Psychol Sci 2011;22:1220–6. https://doi.org/10.1177/0956797611419302.

[83] Soto D, Mäntylä T, Silvanto J. Working memory without consciousness. Curr Biol 2011;21:R912–3. https://doi.org/10.1016/j.cub.2011.09.049.

[84] Witt JK, Taylor JET, Sugovic M, Wixted JT. Signal Detection Measures Cannot Distinguish Perceptual Biases from Response Biases. Perception 2015;44:289–300. https://doi.org/10.1068/p7908.

[85] Grove PM, Ashton J, Kawachi Y, Sakurai K. Auditory transients do not affect visual sensitivity in discriminating between objective streaming and bouncing events. J Vis 2012;12:5–5. https://doi.org/10.1167/12.8.5.

[86] Rosenthal O, Shimojo S, Shams L. Sound-Induced Flash Illusion is Resistant to Feedback Training. Brain Topogr 2009;21:185–92. https://doi.org/10.1007/s10548-009-0090-9.

[87] Lebreton M, Bacily K, Palminteri S, Engelmann JB. Contextual influence on confidence judgments in human reinforcement learning. PLoS Comp Biol 2019;15:e1006973 EP-. https://doi.org/10.1371/journal.pcbi.1006973.

[88] Peters MAK. Introspective psychophysics for the study of subjective experience. Cereb Cortex 2024:bhae455. https://doi.org/10.1093/cercor/bhae455.

[89] Guggenmos M. Measuring metacognitive performance: type 1 performance dependence and test-retest reliability. Neurosci Conscious 2021;2021:niab040. https://doi.org/10.1093/nc/niab040.