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Signal detection measures cannot distinguish perceptual biases from response biases

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Abstract. A common conceptualization of signal detection theory (SDT) holds that if the effect of an experimental manipulation is truly perceptual, then it will necessarily be reflected in a change in d' rather than a change in the measure of response bias. Thus, if an experimental manipulation affects the measure of bias, but not d', then it is safe to conclude that the manipulation in question did not affect perception but instead affected the placement of the internal decision criterion. However, the opposite may be true: an effect on perception may affect measured bias while having no effect on d'. To illustrate this point, we expound how signal detection measures are calculated and show how all biases—including perceptual biases—can exert their effects on the criterion measure rather than on d'. While d' can provide evidence for a perceptual effect, an effect solely on the criterion measure can also arise from a perceptual effect. We further support this conclusion using simulations to demonstrate that the Müller-Lyer illusion, which is a classic visual illusion that creates a powerful perceptual effect on the apparent length of a line, influences the criterion measure without influencing d'. For discrimination experiments, SDT is effective at discriminating between sensitivity and bias but cannot by itself determine the underlying source of the bias, be it perceptual or response based.

Keywords: signal detection theory, Müller-Lyer illusion, perceptual biases, response biases

1 Introduction

Many researchers assume that effects on the criterion measure necessarily reflect decision-based processes, and if an effect is truly perceptual, then it will necessarily exert its influence on d'. Consequently, when researchers observe an effect of an experimental manipulation on the criterion measure, they frequently conclude that the effect must be due to decision-based processes. The purpose of this paper is to explain why that conclusion does not follow from the signal detection measures. Specifically, it is because an effect on perception (one that has no effect on the location of the internal decision criterion) can influence the criterion measure without affecting d'.

While it is true that a change in decision processes will, all else being equal, affect a criterion measure (such as c or β), it is not true that a change in the criterion measure necessarily implies a change in decision processes. Similarly, while a change in d' can imply an effect on perception, it is not true that the absence of an effect on d' implies the absence of a perceptual effect. Even when d' remains constant, a perceptual effect can be quite large and show up as a large (and selective) change in the criterion measure across conditions.

The idea that a change in measured criterion in the absence of an effect on d' reflects an effect on decision processes (and the absence of an effect on perception) is widespread. This misconceptualization is especially surprising given that articles have already proven this idea wrong (eg Morgan, Hole, & Glennerster, 1990; Raslear, 1985). Yet, several recent empirical pieces have made this error of interpreting bias effects as necessarily response based. For example, the stream/bounce effect for which two objects moving towards each other are more likely to be perceived as bouncing than as streaming if a sound is presented at the moment the objects meet (Sekuler, Sekuler, & Lau, 1997) has recently been attributable to decisional processes because an effect was observed in *c* and not in *d′* (Grove, Ashton, Kawachi, & Sakurai, 2012; see below for other examples). Even in studies that report an effect on *d′*, the idea that signal detection parameters can, in and of themselves, distinguish between a perceptual effect and an effect on decision processes is commonly expressed (Cardoso-Leite, Mamassian, Schutz-Bosbach, & Waszak, 2010; Lippert, Logothetis, & Kayser, 2007; Liu, Mercado, & Church, 2011; McDonald, Teder-Salejarvi, & Hillyard, 2000; Meteyard, Bahrami, & Vigliocco, 2007; Shams & Kim, 2010). This misunderstanding of the claims that can be made based on signal detection measures has led to many potentially incorrect conclusions, and it is conceivable that some stimulating and intriguing findings might not have been submitted or accepted for publication due to the misinterpretation that effects on the criterion necessarily reflected decision-based processes and not perceptual processes.

Signal detection theory (SDT) techniques are well designed to do what they were created to do—namely, provide separate measures of sensitivity and bias (Green & Swets, 1966; Tanner & Swets, 1954). Yet, just as sensitivity measures can reflect perceptual sensitivity, memory sensitivity, or any other type of sensitivity, bias measures can also reflect perceptual bias, memory bias, or response bias. However, this latter point has often been misstated, including in tutorials designed to make signal detection techniques more accessible. For example, in his guide, Abdi (2007) explains that "the sign of *C* reveals the participant's strategy" (page 5). In other cases, bias measures are accurately described as reflecting an observable behavioral tendency, but such descriptions can easily be misunderstood to mean that the measures capture an internal response strategy and not another kind of bias. For example, in their classic handbook on SDT, Macmillan and Creelman (2008) describe the criterion measure as "a tendency to *say* 'no' or a tendency to *say* 'yes' " (page 29, emphasis added). Similarly, in their widely used and incredibly useful tutorial, Stanislaw and Todorov (1999) state "negative values of *c* signify a bias toward responding *yes* … whereas positive values signify bias toward the *no* response" (page 140, emphasis as in original). To the extent that one interprets phrases such as 'a tendency to say' or 'or a bias towards responding' as referring to an internal strategy, any change in measured bias across conditions will be misinterpreted to necessarily reflect a change in the participant's decision strategy.

The measure of *c* is sensitive to the participant's strategy and will change as the participant's bias towards making a yes or no response changes across conditions (ie as their strategy changes), but that is *not the only bias* that is captured by *c*. This is the key point. Yet, as shown by the examples discussed below, *c* is often directly linked to response biases without consideration of other types of biases. The fact that the criterion does not necessarily reflect a response-based bias has already been established and accepted with respect to perceptual biases (Morgan et al., 1990) and, more recently, with respect to memory biases (Wixted & Stretch, 2000). However, this message continues to be overlooked as errors in interpreting effects in *c* still occur.

1.1 *Example 1: the stream/bounce or ABE effect*

A recent example of incorrect conclusions based on signal detection measures comes from the stream/bounce effect. The stream/bounce effect (also known as audiovisual bounce effect, or ABE) is the perception of two objects as bouncing off of each other, as opposed to streaming through each other, when a sound coincides with the moment the objects meet (Sekuler et al., 1997). Two objects move towards and then through each other, and participants indicate if they perceived the objects as continuing along the original path (streaming) or if the objects bounced off of each other and reversed paths (bouncing). The stimuli can be made more ambiguous by using identical objects, or less ambiguous by using objects with visible differences. The critical manipulation is the inclusion of a sound at the moment the objects meet, which has been shown to increase the number of 'bounce' responses. The question of interest is whether the sound leads to the perception that the objects bounce, or if the sound influences decisional processes.

To address this question, Grove and colleagues state that "a standard approach to independently characterize perceptual and decisional processes in perception is signal detection theory" (Grove et al., 2012, page 2). In their experiment participants judged whether two objects bounced or streamed in the presence or absence of a sound. Hits were classified as correctly identifying bouncing objects as bouncing, and false alarms were classified as incorrectly identifying streaming objects as bouncing. They found no differences in d' as a function of the presence of a sound, but significant differences in the criterion measure c. This pattern of results led the authors to conclude that their "results clearly demonstrate a strong decisional component but failed to reveal a perceptual component when discriminating between object streaming and bouncing motion sequences" (page 8). The basis for their conclusion comes from the assumption that only d' can capture perceptual changes, and only c can capture decisional processes. As we illustrate below, this assumption does not hold.

1.2 *Example 2: sound-induced flash illusion*

The sound-induced flash illusion is the illusion that a single visual flash of light is perceived as being two flashes when accompanied by two auditory beeps (Shams, Kamitani, & Shimojo, 2000). In order to determine if the auditory information produces a perceptual change or a decisional effect, the authors used signal detection measures to compare across conditions (Rosenthal, Shimojo, & Shams, 2009; Watkins, Shams, Tanaka, Haynes, & Rees, 2006). However, instead of comparing the one-beep condition with a two-beep condition, as was done when looking at accuracy scores, the authors compared d' in the two-beep condition with the no-beep condition. For example, Rosenthal et al. (2009) found that d' was lower when two beeps were present than in the baseline no-beeps condition. From this significant effect in d', it was concluded that this effect is due to perceptual processes, specifically multisensory integration (Rosenthal et al., 2009; Shams & Kim, 2010; Watkins et al., 2006).

However, the d' for the one-beep condition was very similar to the d' for the two-beep condition (approximately 0.83 and 0.73, respectively, based on reported accuracy scores). Should this be interpreted to mean that *perception* in the one-beep condition is not different from perception in the two-beep condition? Furthermore, when we computed c, there was a large difference between these two conditions (approximately -1.24 and 2.08, respectively). Does this mean that the sound-induced flash illusion that two beeps leads to the visual perception of two flashes is due to response bias when compared with a condition with one beep but due to perception when compared with a condition with no beeps? The authors did not provide a reason why d' or c in the one-beep condition was not presented, but they clearly find this condition to be of value as it is frequently included in the procedure, and the accuracy results from this condition are usually reported (Rosenthal et al., 2009; Watkins et al., 2006).

Theoretically, the sound-induced flash illusion is an example of a perceptual bias, and therefore the illusion should present itself in the measure of c (or β), and not in d'. The number of beeps is theorized to bias perception to detect the same number of flashes, not to make perception more sensitive per se. The finding that c differs between the one-beep and two-beep conditions is exactly what should be predicted if the effect were a perceptual bias. We will make the case that signal detection measures cannot be used to determine if a bias is perceptual or decisional; instead, other considerations must be made. Researchers studying the sound-induced flash illusion have used a wide variety of clever, elegant techniques that have made a convincing case that the illusion is perceptual (see Shams & Kim, 2010, for review).

So the finding that it is *c*, and not *d*′, that differs between the two critical conditions should serve as a good illustration that *c* does not necessarily imply a decisional bias.

Two other examples of this kind of interpretation error have been found with the ventriloquist effect (Choe, Welch, Gilford, & Joula, 1975) and in audiovisual interactions (Sanabria, Spence, & Soto-Faraco, 2007). Given that the error of interpreting effects in the criterion as necessarily response based persists despite reports to the contrary (eg Morgan et al., 1990), we hope it will be useful to provide a simple illustration and demonstration to counter this error. The goal of this paper is to demonstrate that perceptual biases can and will exert their influence on the criterion measure rather than on *d*′.

2 The Müller-Lyer illusion

Typically, the underlying processes of a given effect are unknown, and signal detection measures are calculated to differentiate between different underlying components. In contrast, here we will start with an effect whose underlying processes are both widely thought to be perceptual and were modeled as perceptual. We illustrate how such a perceptual effect would influence signal detection measures. The purpose is to demonstrate the correspondence between signal detection measures and underlying processes, which requires that the underlying processes are known. The effect we selected is the Müller-Lyer illusion, which is the illusion that a line presented with tails oriented out looks longer than when the tails are oriented in.

2.1 *Simulated data from the Müller-Lyer illusion*

We simulated data that would be obtained from an experiment using the Müller-Lyer illusion. We performed this simulation to demonstrate, in a concrete and simple way, what happens when standard methods of analysis (namely, computing *d*′ and *c*) are applied to data that arise from a known perceptual bias. The modeled task was to indicate if a line was a long line or a short line, and the line had either tails oriented inwards or tails oriented outwards. The same results would apply if the task were to respond whether a long line was present or absent, and left/right decisions tasks (or any kind of A/B decisional tasks) are analyzed the same way as yes/no tasks (Macmillan & Creelman, 2008, page 1). On any given trial, the simulated participant responded ‘long’ if the perceived line length exceeded the internal criterion for long lines, and responded ‘short’ if the perceived line length did not exceed this internal criterion.

Perceived line length was coded as a Gaussian distribution in order to account for noise in the system. The Müller-Lyer illusion creates a bias to see lines as shorter (for tails in) or longer (for tails out). This was modeled by shifting the mean of the Gaussian distribution to be shorter for the tails-in condition and longer for the tails-out condition. Thus, on each trial the perceived line length was drawn from a Gaussian distribution with the mean set to the sum of the actual line length plus the theorized influence of the tails (13% for tails out, −13% for tails in). The standard deviation of the Gaussian distribution was set to 1.2 cm and was the same regardless of tail orientation. One could speculate whether tail orientation would influence standard deviation. Perhaps, for example, the tails-in orientation would make lines look shorter, and perception of shorter lines might be less variable. This is an open empirical question that could be tested using receiver-operating characteristics (ROC) analysis. A pilot study did not reveal differences in the just-noticeable differences (JNDs) across tails-in and tails-out lines, suggesting that tail orientation does not influence standard deviation (see also Morgan, Dillenburger, Raphael, & Solomon, 2012; Morgan et al., 1990). Furthermore, a difference in JNDs is not the main effect of the Müller-Lyer illusion, which is what we wish to model. The internal criterion was positioned at the midway point between the two lines (6 cm) to model that there was no response bias.

On each trial a short (5 cm) or a long (7 cm) line was presented, and the line had either tails in or tails out. Ten simulated observers completed 1000 trials each (250 repetitions of 4 trial types). Hits were classified as correctly indicating the long line was long, and false alarms were classified as incorrectly indicating that the short line was long. From hits and false alarms, d' and c were computed using the following equations. The results are presented in figure 1.

$$d' = z(\text{hits}) - z(\text{false alarms}) \; ; \tag{1}$$

$$c = z(\text{hits}) + z(\text{false alarms}) \; . \tag{2}$$

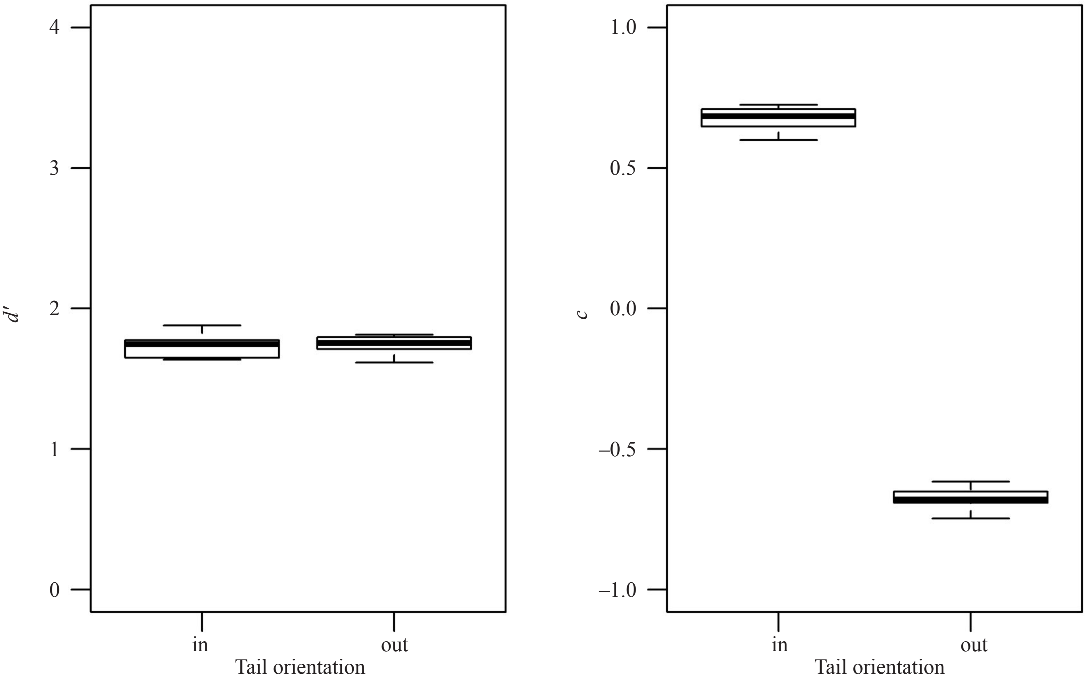

Figure 1. Boxplot graphs of the results from simulated data with the Müller-Lyer illusion modeled as a perceptual bias. Tail orientation does not influence d' (left) but does influence c (right). Even though the effect is perceptual, it is revealed in c not d'.

As can be seen, the Müller-Lyer influenced c and did not influence d'. Does this mean that we should conclude that the Müller-Lyer is due to decisional, not perceptual, processes? Does tail orientation influence the internal criterion of what participants deem is a long line? Because the Müller-Lyer illusion is (or was modeled as) a visual illusion, it would seem that we have made some mistake. Surely a visual effect such as the Müller-Lyer illusion should influence d' and not c. Perhaps our experimental conditions were not designed correctly. This, we argue, is not the case. Rather, readers who are perplexed by the finding that the Müller-Lyer illusion does not influence d' are making the mistake of assuming that d' is the only signal detection measure that will reveal a perceptual effect. As shown in the examples above, this mistake continues to occur in the literature. Next, we illustrate signal detection measures and explain how a visual effect can exert its influence on c.

3 Illustrated overview of SDT measures

Figure 2 illustrates the alternative signal detection models as they would apply to the Müller-Lyer illusion. The models presented in figure 2 can be used to make predictions to compare with empirical (or simulated) data. The stimuli are short (5 cm) and long (7 cm) lines that either have tails oriented inwards or outwards. The figure shows how both perceptual changes in line length (as is assumed to occur in the Müller-Lyer illusion) and response-based changes in line length (as is assumed to occur when observers shift their criterion) would affect measures of d' and the criterion measure c.

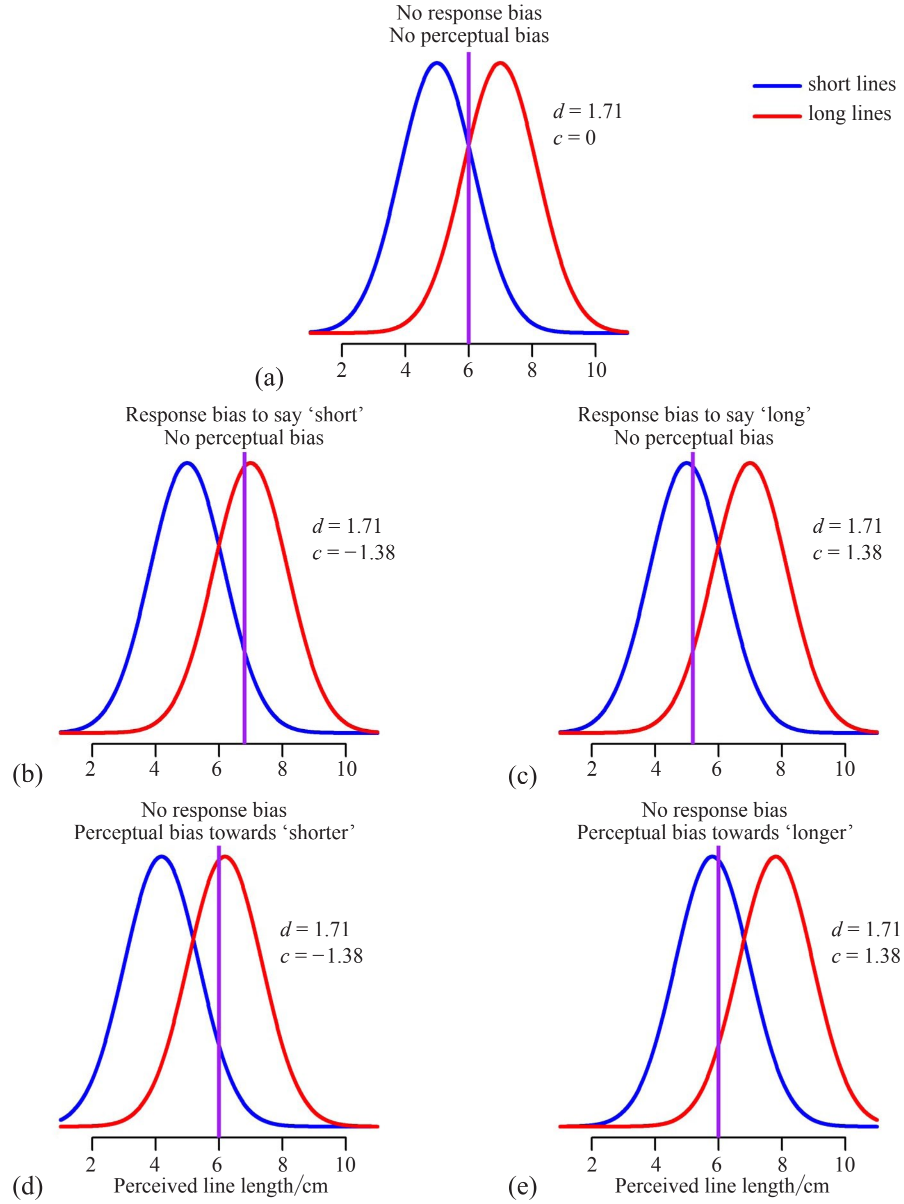

Figure 2. The figures represent hypothetical distributions of perceived line length for short (blue curves) and long (red curves) lines. The vertical purple line represents the criterion location for classifying a line as long. Panel (a) shows distributions when there is no perceptual or response-based bias. Panels (b) and (c) show distributions when there are only response-based biases. Panels (d) and (e) show distributions when there are only perceptual biases. A perceptual bias towards shorter means that there is a perceptual bias to see the lines as shorter. The left column shows hypothetical effects on response bias (b) and perceptual bias (d) for the tails-out condition. The right column shows hypothetical effects on response bias (c) and perceptual bias (e) for the tails-in condition. Note that both the response bias and the perceptual bias in each column lead to the exact same distribution of hits and false alarms as each other. For the tails-out condition both lead to increased hits and false alarms relative to the baseline condition; for the tails-in condition both lead to decreased hits and false alarms relative to the baseline condition. In other words, both types of biases would lead to the same effect on c. Consequently, an effect in c cannot, in and of itself, differentiate between a perceptual bias and a response-based bias.

The top panel represents the baseline signal detection model that applies before taking into account any effect of the tails' manipulation. The perceived length of the line (the *x*-axis variable) is assumed to be normally distributed. On trials in which the line is long, the average perceived length is longer than on trials in which the line is short. The point halfway between the two lines represents the point of subjective equality; it is the point at which the two lines are perceived to be of equal length. The criterion is placed at this point (ie responding is unbiased) for the sake of simplicity.

In the Müller-Lyer illusion there are two tail manipulations: tails in and tails out. In this example, on each trial the line is set to one type of tails condition. The middle and lower rows depict two alternative interpretations for each of the tail manipulations. The middle row illustrates the classic case of a *response bias* where there is a shift in the decision-based criterion location due, in this case, to the addition of the tails. Note that the criterion location (the vertical line) is no longer at 6 cm (panels b and c). In these cases the measured bias would change because the subject's decision strategy changed from responding 'long' when the percept exceeds 6 cm (as in panel a) to responding 'long' when the percept exceeds 6.8 cm (panel b) or when the percept exceeds 5.2 cm (panel c). Under the condition depicted in panel c, whenever the perceived line length falls between 5.2 cm and 6 cm, the participant will *respond* 'long' even though the line is actually *perceived* to be shorter. Note that this is the interpretation that typically follows from the signal detection measures themselves (ie only the response bias measure changed, so the theoretical analysis assumes that, in fact, response bias changed). However, this is not the only interpretation of an observed effect in the criterion measure.

The bottom row illustrates the anticipated result of a *perceptual bias* due to the addition of inward tails (panel d) and outward tails (panel e) on the test line. In the case of a perceptual bias there would be a shift in the means of both distributions (note the lateral displacement of the curves in panels d and e relative to the other panels). In other words, the point of subjective equality is changed by the addition of the tails (to 5.2 cm in panel d, and to 6.8 cm in panel e). Here, we have depicted the case where there is no shift in the criterion location (the vertical line remains at 6 cm). Thus, the subject's decision strategy is to choose 'long' whenever the test line is perceived to be longer than 6 cm. In other words, the internal decision rule is exactly the same in panels (a), (d), and (e). But the *measured* criterion would be different in each because of the effect of the tails on perception (and the subsequent shifts in the distributions). In other words, even though the internal decision rule did *not* change, the measure of *c* would change.

The criterion measure changes when a perceptual effect consists of an equivalent shift of both distributions because the criterion measure is a relative measure. It reflects the location of the decision criterion *relative* to the point of intersection between the two distributions. Even if a participant does not change his or her strategy (ie even if the location of a decision criterion on a perceptual dimension remains constant, as shown in panels d and e, a selective effect on the criterion will still emerge if there is an equivalent *perceptual* shift of both distributions because the location of the (fixed) criterion changes with respect to the (shifted) point of intersection between the perceptual distributions.

Indeed, this is the main effect of the Müller-Lyer illusion: when the tails are oriented inwards, this creates a perceptual shift to see both short and long lines as shorter than they would otherwise be perceived; and when the tails are oriented outwards, this creates a perceptual shift to see both short and long lines as longer than they would otherwise be perceived. Given this perceptual shift, it is to be expected that this illusion would produce effects in the criterion. Similarly, any perceptual effect that causes a shift to both distributions will lead to a significant effect in the criterion without necessarily influencing *d'*. In other words, *perceptual biases will influence c, not d'*.

When we reran the simulation of the Müller-Lyer illusion, but modeled a response bias instead of a perceptual bias, similar values for d' and c were observed as when we modeled the perceptual bias. This highlights our key point: the effect in c, by itself, could not differentiate whether we modeled a perceptual bias or a response bias.

4 Revisiting the previous examples

In the examples described above the authors concluded that their effect was due to decisional processes because the experimental manipulation affected c, not d'. However, if the effects had been perceptual biases, the exact same results would have been obtained. The implication is that the pattern of results obtained in each of those papers was ambiguous as to the underlying processes, and the authors did not have sufficient information to make claims about decisional versus perceptual processes. One could even simulate data from each experiment and model a perceptual bias and a response-based bias to prove that each type of bias would produce equivalent results by simply substituting the conditions in each of those examples for the conditions that were modeled above for the Müller-Lyer illusion (see table 1).

Table 1. Analogy between the four examples described as 'decisional' effects to the Müller-Lyer illusion.

Illusion	Category A	Category B	Manipulation that increases A responses[a]	Manipulation that increases B responses[a]	Effect of perceptual bias on c[b]	Effect of decisional bias on c[c]
Müller-Lyer illusion	long lines	short lines	tails out	tails in	change	change
Stream/bounce effect	stream	bounce	sound absent	sound present	change	change
Sound-induced flash illusion[d]	2 flashes	1 flash	2 beeps	1 beep	change	change
Ventriloquist effect[e]	same location	different location	synchronous	asynchronous	change	change
Audiovisual effect[f]	leftward sound	rightward sound	leftward light	rightward light	change	change

[a] Descriptor of behavior that is purposefully ambiguous of underlying process (eg decisional vs perceptual).

[b] Determination of whether c would change or stay the same if the manipulation were to cause a perceptual bias (and only a perceptual bias).

[c] Determination of whether c would change or stay the same if the manipulation were to cause a decisional bias (and only a decisional bias).

[d] The authors claimed their effect was perceptual based on a significant effect in d', but had they analyzed d' and c across two critical conditions, they likely would have concluded the effect was decisional (see example 2).

[e] Descriptors refer to relative location (same or different) and timing (synchronous or asynchronous) of a tone and a light.

[f] Descriptors refer to movement direction, not location.

Table 2 expresses what process is reflected by SDT measures in each of the examples. The intent is to show that the predictions for each effect better align with anticipated changes in c rather than in d'. If we reject the notion that d' is the only measure of perception, and instead recognize that d' is a measure of discriminability, it is easy to see that none of these theorized effects should produce a significant effect in d'. One could produce an effect in d' for each example by pairing the manipulations with the conditions such that discriminability will be increased. For example, bouncing balls could be paired with sounds and streaming balls could be paired with no sound. This would increase discriminability between bouncing balls and streaming balls (whereas the reverse pairings would decrease discriminability). However, this

Table 2. A description of the process that is captured by each signal detection theory measure for the examples described above.

Illusion	What d' measures	What c measures in the case of a perceptual bias
Müller-Lyer illusion	ability to discriminate long and short lines	perceptual bias to see lines as longer (tails-out condition)
Stream/bounce effect	ability to discriminate when the two objects stream versus when they bounce	perceptual bias to see two objects as bouncing (sound-present condition)
Sound-induced flash illusion	ability to discriminate the number of times a light flashes	perceptual bias to see two flashes (two-beep condition)
Ventriloquist effect	ability to discriminate when sound and flash are at the same location from when they are at different locations	perceptual bias to see sound and visual object as in the same location (synchronous presentation condition)
Audiovisual effect	ability to discriminate when a sound moves left versus when it moves right	perceptual bias to see a sound as moving left (leftward-moving light condition)

would not shed light on whether the underlying processes are perceptual or decisional in nature as the exact same pattern of results on d' would emerge if one were to mix-and-match stimuli with manipulations that influenced response bias (eg pairing high payoff for bouncing balls with the presentation of bouncing balls and high payoff for streaming balls with the presentation of streaming balls). An example of making unsupported claims about an effect in d' demonstrating a perceptual effect after doing this kind of mix and matching can be found in Sanabria and colleagues (2007).

5 General discussion

While it is widely known that changes in decision-based processes will affect the criterion measure, some also assume the reverse is true: that changes in the criterion measure are due only to decision-based processes. Several published papers made this very error, claiming that a given effect is or is not perceptual based solely on the patterns of effects in d' and c (Choe et al., 1975; Grove et al., 2012; Rosenthal et al., 2009; Sanabria et al., 2007; Watkins et al., 2006), and even some SDT tutorials encourage this error (eg Abdi, 2007). To help dispel this misunderstanding, we have provided a simple illustration and demonstration with the Müller-Lyer illusion. We hope that, by showing that a visual illusion influences c and not d', this will send a clear message that c does not just measure decision-based processes and that c can also measure perceptual biases.

5.1 *Discrimination versus sensitivity experiments*

The claim that c can measure perceptual biases applies only when the manipulation causes a shift in both distributions. If the manipulation shifts only one distribution, then a perceptual bias should reveal itself in d', and c will reflect decisional processes alone. In sensitivity experiments for which trials consist of signal present or absent, a perceptual bias will influence only the distribution for the signal, and not the distribution for noise alone. In this case a perceptual bias will lead to a change in d' rather than in c (for example, see McDonald et al., 2000). This kind of experiment has the advantage that changes in c can be interpreted in terms of decisional processes because only a change in the internal criterion will influence c. This single-shift requirement is unlikely to be the case in the bounce/stream illusion, the audiovisual interactions described above, or the Müller-Lyer illusion. In the case of such discrimination experiments for which participants discriminate between two classes of stimuli, *c* does not just reflect decisional processes.

Although sensitivity experiments and discrimination experiments are analyzed in the same way (Macmillan & Creelman, 2008), the theoretical implications of results with each SDT measure are different. For sensitivity experiments, perceptual effects will reveal themselves only in d'. However, d' will not be able to determine if an effect is due to a change in sensitivity (defined here as a change in the standard deviation of the response to the signal) or to a perceptual bias (defined here as a shift in the mean response to the signal). To distinguish between these two types of perceptual effects, ROC analyses will be necessary. Thus, d' can be interpreted as a perceptual effect and *c* can be interpreted as a response-bias effect, although the nature of any perceptual effect will require further examination. For discrimination experiments, d' can be interpreted as a perceptual effect related to changes in sensitivity, but *c* can be interpreted only as a bias without the ability to distinguish between perceptual bias and response-based bias.

It is important to note that the ability to interpret SDT measures in this way applies only when the signal-absent condition is a true signal-absent condition, and not when the observer's task is configured to treat presented stimuli as absent (as would be the case if participants viewed long and short lines and were told to respond 'present' in the presence of a long line and 'absent' in the presence of a short line). Only when a manipulation causes a perceptual bias that shifts one distribution (eg the signal) and not the other distribution (eg noise) that *c* corresponds to only a response bias and can be interpreted as such. If the manipulation causes a perceptual bias that shifts both distributions, *c* cannot be used to determine if the underlying effect is perceptual or due to response bias.

6 Conclusion

SDT is effective for distinguishing between discriminability and bias (Green & Swets, 1966; Tanner & Swets, 1954). However, in discrimination experiments SDT cannot distinguish between biases caused by shifts in perception from biases caused from decision-based processes. Although this point has already been made with respect to visual illusions (Morgan et al., 1990, 2012), memory biases (Wixted & Stretch, 2000), and multidimensional extensions of SDT (Mack, Richler, Gauthier, & Palmeri, 2011), the point bears repeating because errors continue to be made (eg Choe et al., 1975; Grove et al., 2012; Rosenthal et al., 2009; Sanabria et al., 2007; Watkins et al., 2006). The goal of this paper is to address this problem head on with a simple illustration and demonstration in order to help make this critical point accessible to a wide audience.

There are many cases of these kinds of perceptual shifts. Visual illusions like the Müller-Lyer illusion and the Ponzo illusion are such cases. These illusions are generally accepted as being perceptual, but other kinds of purported perceptual shifts are controversial with respect to whether the shifts are perceptual. Examples include the effects of attention on perceptual judgments of contrast (eg Carrasco, 2011), effects of a person's ability to act on judgments of spatial perception (eg Witt, 2011), effects of planned actions on perceptual detection of features (eg Musseler & Hommel, 1997), and crossmodal effects of vision on audition and vice versa (eg Shams et al., 2000). SDT can be used to determine if these effects are perceptual but only if the experiments can be designed to compare signal present versus signal absent. In cases such as the stream/bounce effect it is not clear that such an experiment could be constructed. Otherwise, determining if these effects are perceptual will require additional techniques because SDT alone cannot distinguish perceptual and decision-based biases in cases for which two sets of stimuli are presented. Potentially effective techniques include methodological designs that reduce the possibility of decision-based biases, the use of converging measures such as indirect and action-based measures, and the use of neuroimaging techniques.

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7 Summary

In discrimination experiments SDT techniques cannot, by themselves, determine if the locus of a bias is perceptual or decision based. As shown above, both perceptual biases and decision-based biases exert their influence on the criterion measure of c. This is why the Müller-Lyer illusion resulted in a significant effect in c rather than in d'. The measure of c provides a measure of bias, but the underlying process cannot be determined based solely on a given value of c. An influence on c implies a bias, but the nature of this bias—be it a perceptual bias, a memory bias, a social bias, or a response-based bias—is not specified by current SDT techniques.

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