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Review Article

SIGNAL DETECTION THEORY MEASUREMENT OF PAIN: A REVIEW AND CRITIQUE *

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INTRODUCTION

Pain is a subjective experience. Therefore, attempts to measure its extent face the same difficulties which have long plagued experimenters hoping to scale other human sensations, but they are compounded further by complex emotional reactions and cognitive interpretations [41]. Nonetheless, the need for improved methods of pain control mandates continued research on pain and its possible modulation by chemical, surgical, physiological, or psychological procedures.

Laboratory studies with normal rather than clinical subjects allow parametric variations in the level of an experimentally induced pain, rather than reliance upon some unknown endogenous one. It is possible, as well, that some of the emotional variability associated with a pain of internal origin is thus eliminated, leading to more stable estimates of the magnitude of the pain sensation itself.

The ability to vary the level of a potentially nociceptive stimulus has raised the hope that psychophysical procedures [39], well-developed for studies of vision, audition, and the other senses, might also increase our understanding of human suffering. Although some notable advances have been made in the scaling of intense discomfort [1,26,34,51], many pain investigations have concentrated on the traditional "threshold" as the dependent variable, sometimes attempting to distinguish separate thresholds for sensation, mild pain, strong pain, and maximal tolerance.

The threshold appears, at first, to be easy to measure and easy to interpret. Its value can be obtained by noting the level of some uncomfortable stimulus such as radiant heat or electric shock necessary to elicit a report of pain. In those instances where no manipulation is involved, thresholds have been compared across groups (e.g. the variables of age, sex, race, or ethnic group). In other instances, where the nature of an adequate control is still

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* Dr. Chapman and Dr. Crawford-Clark have been invited to submit critical reviews of Dr. Rollman's review and these will appear in the next issue of *Pain*.

subject to debate, thresholds have been compared before and after presentation of a potential analgesic (e.g. acupuncture).

However, it has long been recognized that non-sensory factors can also affect the responses of an individual, leading to a profound concern with placebos and other controls [2]. As well, differences in thresholds across individuals could arise from variations in anxiety and other personality traits [50]. It has been impossible to separate the physiological and the emotional aspects of the pain response.

In recent years, the development of a new psychophysical model, the theory of signal detectability (TSD) [30], has raised considerable excitement among pain researchers because of its potential for allowing just such a distinction — an independent evaluation of the physiological and emotional components of pain [6]. TSD has had a major influence on psychophysical theory, methodology, data, and applications [52]. Although it was first extended to studies of the basic senses, it has also strongly directed the interpretation of findings in attention, perception, memory, medical diagnosis, animal learning, reaction time, and other areas where ambiguity about the nature of the stimulus requires a decision involving some element of uncertainty [53].

This paper will summarize the basic assumptions of signal detection theory and review studies which have applied it to the study of pain. It will then offer a critique of these experiments, suggesting that their extension of the model is inappropriate and that the results obtained are subject to multiple interpretations. Two prominent proponents of the use of TSD for studying pain and its modulation will provide a response to these criticisms, arguing for the validity of the model.

THE THEORY OF SIGNAL DETECTABILITY

TSD presents a means by which one can independently measure two aspects of an observer's performance when he attempts to detect a stimulus or discriminate between two different ones: his sensitivity and his response bias [30]. Therefore, it separates the sensory and cognitive factors responsible for his responses, implying that a threshold, in the traditional sense, simply does not exist.

In order to understand the basic model, imagine a subject who attempts to detect a weak stimulus presented on half of a series of trials, mixed randomly with temporally defined trials containing no stimulus. The observer must report whether he believes that a stimulus had, in fact, occurred. Weak signals produce constant uncertainty because the stimuli are superimposed upon a background of noise arising from spontaneous neural activity at some critical, but unspecified portion of the nervous system. Therefore, a discrimination and decision process is involved: the observer must measure the level of activity on each trial and decide whether it was more likely to come from internal noise alone or from the neural effect of the stimulus added to the noise.

The decision can never be made with certainty, since the level of the noise itself fluctuates constantly. A particular level of activity might result from a high level of momentary noise or from a signal added to a low noise level. At best, one can make a statistical decision as to the relative likelihood of the two possible events: noise alone or signal plus noise.

Fig. 1 outlines the model, presenting two overlapping normal or Gaussian distributions. The one on the left reflects the moment to moment variability of the internal noise. The right distribution, representing the effects of a signal presented against the noise, has, in the simplest case, the same variance as the noise function but a larger mean. The abscissa, labelled "sensation continuum", could represent either the physiological activity at this critical neural region (such as the number of action potentials per unit time), the magnitude of the resulting sensory experience, or a dimensionless statistical measure, the likelihood ratio (the ratio of the *a posteriori* probability that a specific amount of activity arose from signal plus noise divided by such a conditional probability for noise alone).

Since the subject must report a decision on each trial, TSD proposes that he establishes a criterion at some point along the abscissa such as that represented in Fig. 1 by the vertical line. Values below it are most often, but not always, produced by noise alone. Higher levels are most often, but not always, produced by stimulus presentations. Uncertainty always exists.

Two types of events are possible (noise or signal plus noise) and two responses can occur (yes, it was a signal or no, it was not), yielding four possible outcomes on any trial. The observer can have a hit (correctly reporting a signal), a miss (failing to report it), a correct rejection (reporting no signal on a noise trial), or a false alarm (indicating a signal when none was presented). Psychophysicists have concentrated their attention on two outcomes: the incidence of hits and the incidence of false alarms. The propor-

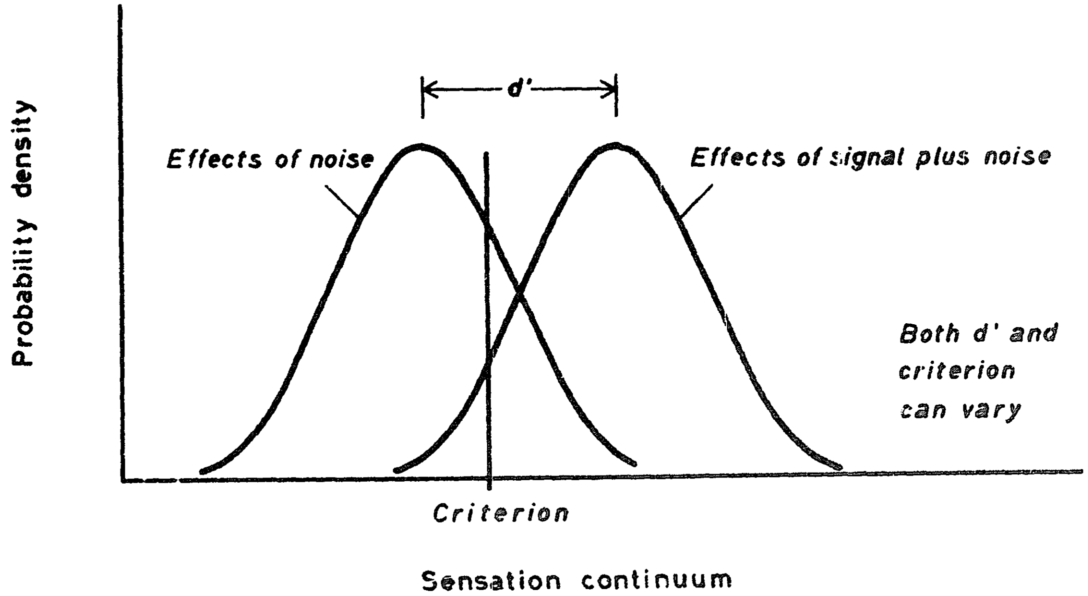

Fig. 1. Representation of the overlapping effects of internal noise and signal plus noise assumed by the signal detection model.

tions of misses and correct rejections are simply the complements of these two critical response indices.

The observer is assumed to say "yes" each time his criterion is exceeded, producing some hits and some false alarms. He could raise the hit rate by establishing a lower criterion, but at the cost of increased false positives. Likewise, false alarms can be reduced at the expense of a lowered proportion of hits, if the criterion is moved to the right.

Thus, such traditional measures of performance as the probability of reporting, "Yes, I detected the stimulus", are potentially misleading. They include true detections plus false alarms. The use of correction factors is inappropriate, because false alarms are not simply a result of guessing. They may reflect real instances of intense activity in the nervous system. A threshold, sometimes exceeded by a stimulus but never surpassed by noise, does not exist.

It has been shown possible to greatly vary how often a subject says yes without altering the stimulus level. Changes in his motivational state, his instructions, the rewards and penalties associated with various judgmental outcomes, and the ratio of signal to non-signal trials, produce predictably linked increases or decreases in hits and false alarms due to shifts in the subject's criterion or response bias. A variety of parameters, given labels such as β, L_x, or C, can be calculated to reflect the criterion location along the sensation continuum of the model.

The reader can note, in Fig. 1, that shifts in the criterion which alter the rates of hits and false alarms leave one important parameter unaffected — the distance between the means of the two normal distributions. The signal plus noise distribution will shift towards the right of the fixed noise distribution if the mean level of neural activity on stimulus trials is raised by an increase in signal intensity. It will not move, however, when motivational or cognitive factor influence the criterion.

This implies that the two factors which underlie detection performance, sensitivity and decision-making, can be separated. Sensitivity is reflected in the distance between the two distributions to be discriminated. It is represented by a parameter, extractable from the hit and false alarm rate data, which is generally called d′. The criterion location, C, which determines the verbal response evoked by a specified level of internal activity, is calculable separately. A given change in performance, such as a decrease in the probability of a correct detection, could be caused by a shift in either sensitivity or response bias. Mathematical and graphical procedures are now available to assess which of these factors has been altered. An excellent review of TSD in the pain laboratory, which includes computational examples, can be found in a paper by Clark [15].

A considerable body of data has been amassed in the sensory literature to suggest that a theory like TSD can describe human detection behavior better than traditional threshold models which confound observer sensitivity and response bias [52]. Several recent publications demonstrate the wide applicability of the signal detection methodology and conceptualization [36,43, 44,53]. Its emphasis on sensory and motivational factors underlying performance, and its ability to extract independent parameters to measure the contribution of each, has had obvious appeal for the pain researcher attempting to assess a state in which both sensory and emotional factors play evident, but heretofore indeterminable, roles. Thus, investigations of pain and its modulation, within the TSD framework, have become increasingly frequent, stemming primarily from the laboratories of W. Crawford Clark at the New York State Psychiatric Institute and Columbia University, and C. Richard Chapman of the Anesthesia Research Center at the University of Washington.

Modifications required for pain studies

In order to study pain, some alterations in the methodology outlined above become necessary. The detection task requires that the stimulus be very weak, causing confusion between signal and noise. Pain studies, however, require intense stimulus levels, clearly detected by the subject. The clinician does not ask whether the signal is there, but whether it is strong enough to be labelled painful or to reach a level of maximum tolerance.

The "pain threshold" is at least as likely as the "absolute threshold" to be affected by both sensory and cognitive factors, but the presentation of intense signals mixed with blank trials would not create the uncertainty necessary to extract the sensitivity and criterion measures. Thus, pain researchers such as Hilgard [33] and Taub [54] have expressed reservations about the applicability of a theory which has typically dealt with barely detectable signals to a situation requiring powerful ones. TSD procedures can be used at suprathreshold levels, but the question changes from one of detection or stimulus effect to one of discrimination between two or more strong but confusable stimuli, each of which is added to the internal noise. A typical psychophysical discrimination experiment might involve a large number of signal A trials and signal B trials, with the observer asked to report which stimulus occurred. If the stimuli are easily confused, the TSD calculations will yield a low value of the discriminability parameter, d'. Separate calculations will indicate if the observer's criterion favors a response of A or of B for various degrees of uncertainty. After some manipulation, the measurements can be repeated, providing, according to the proponents of this approach, evidence for possible changes in sensitivity, response bias, or both.

Instead of asking their subjects to reply A or B, pain investigators have used rating scales. Ratings have been widely employed in TSD studies, since they are assumed to provide information based upon a number of simultaneously held criteria rather than upon a single one. A sensory researcher might have a 5-point scale established so that "5" means, "I am fairly certain that the stimulus was A", while "1" means, "I am fairly certain that the stimulus was B". A rating of "3" would indicate a state of ambiguity. Pain researchers, however, have turned away from ratings about stimulus likelihood and have focused instead upon subjective descriptions of sensations.

Thus, in an experiment with radiant heat, "5" might represent, "I feel strong pain", "1" might denote, "I feel nothing", and "3" would be assigned when the subject feels warmth. The ability to partition responses to each of several stimuli into several classes still makes it possible to use a cumulating procedure to plot the data in the form of "receiver operating characteristics" and to calculate d′ and C.

PAIN STUDIES EMPLOYING SIGNAL DETECTION METHODOLOGY

Experimenters have used TSD to investigate whether changes in pain responses produced by placebos, drugs, subject characteristics, social influences, acupuncture, transcutaneous stimulation, and dorsal column stimulation could be ascribed to sensory or cognitive alterations. A review of their findings is presented below. Table I summarizes the salient information. The next section will argue that the underlying premise of these studies is incorrect. On logical grounds, a clear distinction between sensory changes and motivational ones cannot be made when investigating pain modulation with TSD procedures.

Effects of placebos and drugs

An oral placebo (described as a potent analgesic) was administered by Clark [14] to a group of volunteer subjects who then rated the thermal experience produced by several intensities of heat from a Hardy-Wolff-Goodell dolorimeter. A control group received no treatment. Traditional analysis of the data would indicate that the placebo raised the pain threshold, since the stronger stimuli elicited fewer pain reports after placebo presentation. Calculations based upon TSD methods, which examine, as well, the changes in response patterns to less intense stimulus levels, showed that a discriminability parameter was not affected. Only the criterion indices for reporting pain were increased. Thus, Clark concluded that under the placebo instructions the sensory effects of the radiant heat stimuli did not change. The decreased proportion of pain reports arose because the observers increased their criterion for indicating pain. Similar conclusions were reached by Feather et al. [29], who found that d′ for discrimination of radiant heat was uninfluenced by an oral placebo, while the criterion was shifted in a more conservative direction.

Chapman et al. [12] found that 33% nitrous oxide gas reduced d′ for 3 levels of radiant heat when calculated against the responses given to blank trials. The discriminability of adjacent levels was, however, unaffected. Combined with the assumed sensory effect was a change in response bias, with subjects less willing to report pain under the influence of gas than under a room-air control.

An orally administered tranquilizer, 10 mg diazepam, which significantly increased tolerance time to tourniquet-induced ischemia compared to both aspirin and a placebo, failed to affect either d′ for the discrimination of adjacent values of radiant heat or the location of the criterion. Chapman and

TABLE I

MAJOR CHARACTERISTICS OF TSD PAIN STUDIES

Author(s)	Modulation	Noxious stimulus	Reported results
Paceebos and drugs			
Clark [14]	Oral placebo	Radiant heat	No change in d'; Increased criterion
Feather et al. [29]	Oral placebo	Radiant heat	No change in d'; Increased criterion
Chapman et al. [12]	33% nitrous oxide	Radiant heat	Reduced d' between stimuli and blank; No change in d' between adjacent stimuli; Increased criterion
Chapman et al. [10]	33% nitrous oxide	Electrical stimulation of tooth pulp	Reduced d'; Increased criterion
Chapman and Feather [9]	10 mg diazepam	Radiant heat	No change in d' or criterion
Subject characteristics and social influences			
Clark and Mehl [19]	Age, sex	Radiant heat	Older women: reduced d'; Increased criterion Older men: no change in d'; Increased criterion
Harkins and Chapman [31]	Age	Electrical stimulation of tooth pulp	Older men: reduced d'; Some criteria increased, some decreased, some unchanged
Clark and Goodman [17]	Verbal suggestion of increased tolerance	Radiant heat	No change in d'; Increased criterion
	Verbal suggestion of decreased tolerance	Radiant heat	No change in d'; Decreased criterion
Craig and Coren [24]	Exposure to tolerant model	Electric shock	No change in d'
	Exposure to intolerant model	Electric shock	Increased d'
Craig and Ward [25]	Exposure to tolerant model	Electric shock	Reduced d'; No change in criterion
Acupuncture, transcutaneous stimulation, and dorsal column stimulation			
Clark and Yang [21] Clark et al. [18]	Acupuncture at traditional point	Radiant heat	No change in d'; Increased criterion

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TABLE I (continued)

Chapman et al. [10] Chapman et al. [13]	Acupuncture at traditional point	Electrical stimulation of tooth pulp	Reduced d′; Increased criterion
Chapman et al. [13]	Acupuncture at "placebo" point	Electrical stimulation of tooth pulp	No change in d′ or criterion
Lloyd and Wagner [35]	Acupuncture at traditional point	Radiant heat	Reduced d′ between weak stimulus and blank; No change in d′ at stronger levels; Increased criterion at weak levels
Bloedel et al. [4] Bloedel et al. [5]	Dorsal column, anterior cord, and sciatic nerve stimulation	Radiant heat	Reduced d′; Increased criterion
Bloedel et al. [4] Bloedel et al. [5]	Transcutaneous stimulation	Radiant heat	No change in d′; Increased criterion
Chapman et al. [13]	Transcutaneous stimulation at acupuncture site on arm	Electrical stimulation of dental pulp	Reduced d′; Increased criterion
Clark et al. [18]	Transcutaneous stimulation	Radiant heat	Reduced d′; Increased criterion

Feather [9], who conducted the study, concluded that neither the sensory-discriminative component of Melzack and Wall's [42] gate control model nor the central decision process were affected by diazepam. Instead, they suggested, a motivational-emotional component was influenced, extending pain tolerance by diminishing anxiety and normally potent drives to reduce continuing pain.

Effects of subject characteristics and social influences

Clark and Mehl [19] used the TSD approach to clarify some of the earlier inconsistencies in age and sex differences in pain thresholds. Some experiments had reported elevated thresholds in elderly and male subjects. Were such changes due to sensory alterations or increased pain criteria? Based on the results of a study with radiant heat, Clark and Mehl suggested that advancing age raised the criterion for pain. Their observed threshold elevation, then, might not be due simply to alterations in neural or dermal structures. The findings and interactions in Clark and Mehl's data were complex, but the authors concluded that older women showed a reduction in sensitivity (d′) coupled with a high pain criterion. Older men had the same sensitivity as younger ones, but a criterion elevated even higher than that of the older women.

Somewhat different conclusions were reached by Harkins and Chapman [31] when the stimulus was a train of electrical pulses at the incisors. Their groups of younger and older men showed no differences in detection thresholds, but the d′ between two levels of more intense current was significantly lower for the elderly group. A complex pattern of criterion differences was observed. Older subjects seemed to be more cautious than the younger ones when making a judgment of "very faint pain" (as noted by Clark and Mehl [19]), but they were less conservative about judging other signals as "mildly painful". No differences in criterion existed for ratings of "faint pain". Harkins and Chapman drew no conclusions about the pain experienced by younger and older males. The decrease in d′ with advancing age indicated a loss in discriminatory ability for stimuli at noxious intensities which might be attributable to a deficit in central nervous system structures.

Clark and Goodman [17] used TSD to investigate another ambiguous area of pain research — the nature of threshold increments produced by verbal suggestions of altered pain tolerance. Was it the experience or the report of pain which was modified in previous studies? After providing suggestions intended to increase or decrease pain and tolerance thresholds, the authors found the incidence of pain reports and withdrawals changing in the predicted manner. The discriminability index, d′, changed, but not significantly, while the sensory magnitude criterion they calculated showed a complex, but significant, interaction. Clark and Goodman concluded that verbal suggestions (and perhaps such manipulations as redirecting the focus of attention, hypnosis, and counterirritation) do not decrease pain sensitivity. Instead, they force subjects to alter the level of sensory activity required before they verbally report pain, though their sensations are unchanged.

Social influences on pain mediated through the behavior of a colleague, rather than through verbal influences, were studied within the TSD framework by Craig, who had conducted an earlier series of elegant experiments to demonstrate that pain thresholds can be dramatically influenced by exposure to human models simulating different levels of discomfort and pain susceptibility [23]. Craig and Coren [24] had subjects use a 10-point scale to describe the effects of 5 levels of electric current presented after exposure to a tolerant, intolerant, or control model who was a paid confederate of the experimenter. An index related to d′, for the discriminability of adjacent pairs of stimuli, indicated that discrimination was increased for the subjects exposed to the intolerant model but not for those in the tolerant modelling group, even though the pattern of ratings for both differed significantly from the control groups. Thus, they suggested that exposure to an intolerant model produced a change in the sensory experience of pain while exposure to a tolerant one possibly yielded a reduced willingness to issue a pain report.

In a subsequent study, in which more attention was given to the influence procedure, Craig and Ward [23,25] found that a tolerant model reduced the sensory discriminability index for adjacent pairs of shocks (although such a model had no effect on discriminability in the first experiment). The criterion showed no statistically significant changes. The authors concluded that their social intervention left unaffected the bias to report pain, changing instead the degree of discomfort experienced after presentation of intense shocks.

Effect of acupuncture, transcutaneous stimulation, and dorsal column stimulation

Several recent papers have applied TSD to the study of acupuncture analgesia. In the first of these, Clark and Yang [21] had a group of 12 subjects rate the subjective intensity of several levels of radiant heat by means of a 12-category scale before, during, and after a 15—20 min period of electrical stimulation through 3 pairs of acupuncture needles along Chinese medicine meridians of the arm and hand. The authors reported no significant differences in d′ for the discrimination of intense stimuli between an acupunctured and control arm or between the periods before, during, or after acupuncture. The criterion parameter was significantly higher in the needled arm during acupuncture compared to the control arm, and higher during stimulation than before, though not significantly. For their parameters, Clark and Yang concluded, pain experiences were not affected by acupuncture. "The sole effect of acupuncture", they claimed, "was to cause the subjects to raise their pain criterion in response to the expectation that acupuncture works".

Contrary conclusions were reached by Chapman et al. [10]. Their subjects used a 7-point scale to rate the sensations produced by 3 electrical currents and a blank applied to the dental pulp after bilateral needle stimulation at the Hoku points between the thumb and first finger of the hand. Two other comparison groups were tested for discriminatory sensitivity and criterion as well. One received 33% nitrous oxide, the other received no treatment.

According to the authors, the pain-attenuating effects of both acupuncture and nitrous oxide were weak, but significant declines in d′ occurred for both treatments. Acupuncture, which reduced the discriminability of all 3 adjacent stimulus pairs, also reduced the criterion for describing the most intense stimulus as painful. Thus, they concluded that acupuncture produced a real sensory loss in addition to a change in response bias, and suggested some procedural differences which may have mitigated against Clark and Yang finding a d′ difference after acupuncture induction [21]. Recently, Clark et al. [22] have replied to these comments.

Chapman et al. [13] compared d′ and criterion changes for acupuncture stimulation at both the traditional Hoku point and at a "placebo" point on the dorsal surface of the hand. As in their earlier study, both the sensitivity and bias parameters changed significantly for the first group, but only criterion changed for the placebo group.

Studies by Clark and Dillon [16] and Clark and Mehl [20] compared values of d′ and criterion obtained by both binary decisions ("the stimulus was the low or high one") and rating scales ("the stimulus was warm, hot, painful, etc."). Since d′ was significantly lower when only a single criterion was required, they recommended that binary decisions rather than ratings be used to compute the sensitivity measure. Nonetheless, only one TSD experiment has avoided ratings, a recent one on acupuncture by Lloyd and Wagner [35]. They hypothesized that the differences between the results of Clark and Yang [21] and Chapman et al. [10] might arise from variability in the d′ estimate obtained by the first authors. Following a baseline period without acupuncture, Lloyd and Wagner inserted 7 needles (6 of which were stimulated electrically) into the hand and forearm of their subjects. Three levels of radiant heat or a blank were presented at the hand's dorsal surface. Rather than using the usual rating procedure or the "high-low" task noted earlier, they employed another TSD method, that of a "forced-choice" decision [20,30]. Stimuli were presented in pairs (S_1 then S_3, S_2 then S_1, etc.) and subjects indicated which temporal interval, the first or the second, contained the stronger stimulus. By pooling the data obtained within a period, pairs of "hit" and "false" alarm rates could be obtained, a hit being a judgment that the less intense stimulus came in the first interval when, in fact, it did; a false alarm being a judgement that the less intense stimulus came in the first interval when, in fact, it came in the second. Lloyd and Wagner present no indication of the changes in these values or overall correct percentage, but report a reduction in d′ between a weak stimulus and a blank — subjects were less able to discriminate the two during the acupuncture session (Clark et al.'s [18] data suggest the same). However, no change was noted in the discriminability of even mildly painful stimuli.

Bloedel et al. [4,5] examined the modulating effects of peripheral nerve and spinal cord stimulation, using thermal pain and a 6-point rating scale of subjective experience. Stimulation at the dorsal column, anterior cord, or sciatic nerve yielded both a lower d′ and a shift to a more conservative criterion, while transcutaneous stimulation primarily affected the bias parameter and had no significant effect on d′.

However, Chapman et al. [13] reported a significant decrease in d′ after transcutaneous stimulation at the Hoku site for painful stimulation at the teeth (coupled with an increase in criterion), and Clark et al. [18], who stimulated the median nerve transcutaneously while asking observers to discriminate the noxious effects of radiant heat on the arm, also noted a decrease in d′ and an increase in the bias parameter.

CRITICAL COMMENTS

The reader may, at this point, find himself confused. Some of the results reported above have a certain intuitive appeal, while others seem contradictory. Individual studies indicate, for example, that transcutaneous stimulation changes only criterion [4,5], social influence changes only sensitivity [25], and diazepam increases pain tolerance time but changes neither

TSD index [9]. Bloedel et al.'s [4,5] findings with transcutaneous stimulation are in disagreement with those of Chapman et al. [13] and Clark et al. [18]. Clark and Yang's [21] and Lloyd and Wagner's [35] results with acupuncture conflict with those of Chapman et al. [10]. Harkins and Chapman [31] show a decrease in d′ with advancing age in male subjects. Clark and Mehl [19] find that only criterion is affected. Craig and Coren [24] report that tolerant pain models do not alter discrimination sensitivity. Craig and Ward [25] suggest that they do. Thirty-three percent nitrous oxide has critically different effects on discrimination in experiments by Chapman et al. [12] and by Chapman et al. [10], altering d′ between adjacent nonzero stimuli only in the latter.

The hallmarks of any useful measurement system are consistency and validity. The utility of laboratory studies of analgesia diminishes if their results are not applicable to clinical experience. We should expect that the conclusions drawn by those using TSD provide critical insight into the underlying mechanisms of pain relief. At best, one must conclude that sensitivity and criterion are greatly influenced, in yet unknown ways, by methodological differences in the presentation of the noxious stimulus and the modulating treatment and by the psychophysical methods used to determine the TSD parameters. At worst, one must question both the validity of the TSD model when applied to pain studies and the interpretations offered to date [32,37,48].

With regard to the first of these suggestions, it may be that reduction of experimentally induced pain depends not only on the modulation procedure but also on the nature of the nociceptive stimulus. Chapman et al. [10,13] used electrical stimulation of the tooth pulp while Clark et al. [18,21] presented radiant heat on the arm. Chapman found that acupuncture lowered d′; Clark found that only the criterion was shifted. If stimulation of the incisors affects Aδ or C fibers, while heat excites large A fibers as well, one might attribute the above effects of acupuncture to different physiological mechanisms. But since narrow diameter fibers are recruited by both tooth and arm stimulation, the differences in discrimination ability might relate to the presence or absence of the large A fibers. Under these and other conditions, the observer's judgment may have nothing at all to do with pain; it could reflect simply his ability to differentiate between two stimuli, independent of their noxiousness. This argument will be developed further below.

Suppose that the differences truly arise because shock and heat produce meaningful different forms of pain. Certainly the quality of discomfort produced by a number of pain induction methods seems to vary considerably. It is necessary, then, to investigate the modulation of different experimental pains, and to limit, for the moment, the generalizations drawn from any one technique.

It has been suggested that the differences between Clark et al.'s [18,21] and Chapman et al.'s [10,13] results with acupuncture arise from variables such as length of the induction period, testing site, or number of trials.

Similar concerns could be raised with respect to the experiment by Lloyd and Wagner [35] who tested only 8 subjects, seemingly had no induction period, always presented the acupuncture trials following the no-treatment ones, and employed no control groups. More deliberate attention to these and to other psychophysical variables seems clearly necessary, so that the effects of the modulation rather than deficiencies in experimental design determine the outcomes. The present paper will not deal extensively with these deficiencies. A later section will, however, examine the TSD complexities which face those convinced that an unequivocal distinction between sensory and motivational alterations can, in fact, be made.

Is signal detection theory applicable to the study of pain?

The observer reports upon his subjective impressions, but the experimenter wants to know the underlying mechanisms. When an individual proclaims relief from pain, has the treatment modulated some sensory process or is the patient more comfortable because his criterion for reporting pain has been altered? The proponents of TSD have indicated that this question can be answered.

To judge the validity of this assertion, consider again some of the basic assumptions of TSD. In simple detection, d′ represents the distance between the signal plus noise and the noise distributions. Decreases in d′ will occur if the stimulus is made weaker. The distribution of spontaneous, internal neural activity would not be influenced by manipulations of the stimulus, so alterations in d′ can be interpreted without ambiguity.

In a sensory discrimination experiment, a reduction in d′ indicates simply that the two stimuli are more easily confused. Attenuation of the stronger stimulus or amplification of the weaker one might produce such an effect, though reduction of d′ by itself would not provide information as to which manipulation had been carried out.

The proponents of TSD make a further statement, however. They claim that discrimination ability, as reflected in the d′, provides information about pain. Chapman et al. [13] assume that "decreases in d′ for a subject perceiving normally painful stimulation in a properly structured experiment are indicative of a loss of pain sensibility, and hence they reflect analgesia". The generally accepted mechanism of this action is described by Clark and Yang [21]: "a decrease in d′ after administration of an analgesic would suggest that the drug had attenuated neural activity in the sensory system".

Thus, several assumptions underlie all TSD studies of pain: (1) a reduction in neural activity can produce a reduction in experienced pain; (2) a reduction in neural activity will produce a reduction in d′; (3) a reduction in d′ indicates a reduction in experienced pain; (4) a reduction in experienced pain will be reflected in a reduction in d′.

Let us consider a discrimination task during a pain modulation procedure. Assume that the treatment truly functions as an analgesic by modulating, at the peripheral nerve, spinal cord, brain stem, or cortex, the neural activity which follows nociceptive stimulation (assumption 1). Assumption 2 need not follow. If two different, but intense, stimuli are presented during treatment, the activity due to *both* of them will be reduced, as in Fig. 2, shifting the distributions of the effects of the two signals to the left. The relationship between such a reduction in neural activity and an alteration in d′ can be considerably more complex than the simple statement of assumption 2. It requires first an indication of whether modulation reduces activity by a specified proportion (a multiplicative relationship) or a specified sum (an additive relationship). If two discriminable stimuli have distributions with means of 50 and 75 arbitrary units, will they be changed to 5 and 7.5 or 5 and 30?

In the additive relationship, as illustrated in Fig. 2, the means of the distributions change, but their variance remains constant. Weber's law, which states that the difference limen or just noticeable difference is directly proportional to the intensity of the stimulus, would predict that a constant difference in the level of neural activity should cause d′ for the discrimination of adjacent stimuli to increase with neural attenuation, not to decrease.

But experimental data, from several sensory modalities, show that Weber's law fails to hold at low intensities. There, internal noise causes the difference threshold to be independent of stimulus strength, so that a constant increment in stimulus amplitude produces a constant level of discriminability. Under these conditions, a reduction in neural activity would leave d′ between adjacent signals unaffected.

In the multiplicative relationship, the variance of the normal distributions will be proportional to their means, and a logarithmic transformation of the

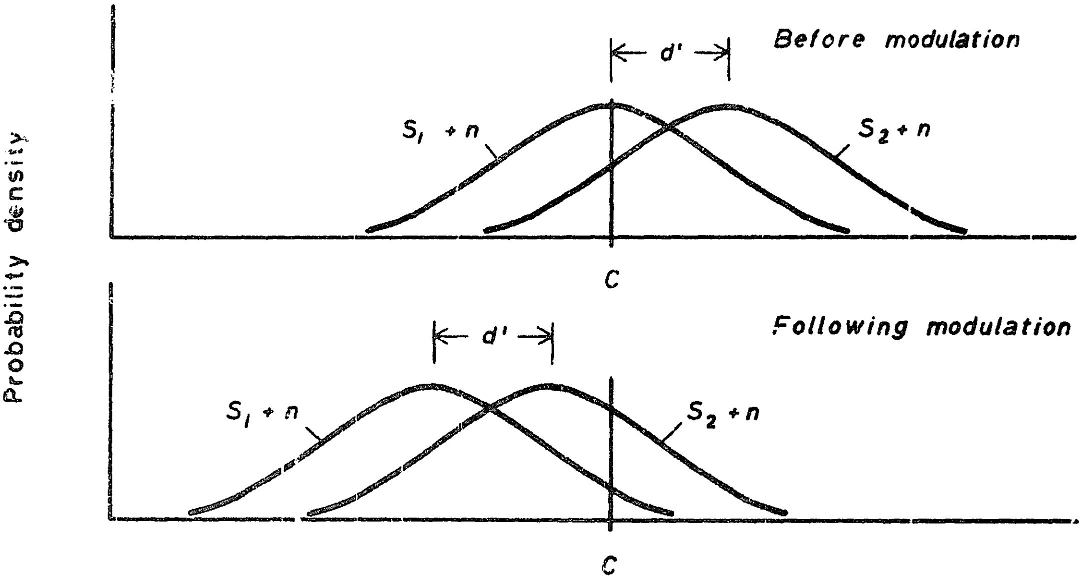

Fig. 2. Representation of a possible change produced by an analgesic modulation procedure. The sensory effects of noise plus both the weaker (S_1) and stronger (S_2) stimuli are reduced, but d′ remains constant.

abscissas in Fig. 2 will allow that figure to describe the effects of a neural modulation. In the range where Weber's law applies, d′ should remain constant, despite decreasing activity, since the two distributions are shifted proportionately. If the neural effects are in the range where Weber's law does not hold, then d′ might be reduced.

Therefore, a reduction in neural activity could cause d′ to increase, to remain constant, or to decrease, depending upon both the nature of the inhibition process and the amount of neural activity, relative to internal noise, produced by the stimuli which are presented. The point to note is that under a variety of assumptions, a potent analgesic could reduce the sensory pain components of two stimuli, yet d′ would not change.

Pain would be altered; discrimination would not. Because the distributions shift with respect to a level of activity required to produce a pain report (Clark and Goodman's [17] "sensory magnitude criterion"), one would mistakenly conclude that the criterion had been raised. Acupuncture or transcutaneous stimulation might act as powerful analgesics; signal detection analysis would wrongly suggest that only the subject's predilection for reporting pain had been affected. The basis for this problem is simple: in the usual detection or discrimination experiment, manipulation of one stimulus leaves the distribution for the other one unaffected. In pain modulation, both distributions are free to vary.

Thus, the findings of Clark and Yang [21] and of Bloedel et al. [4,5] need not indicate that acupuncture and transcutaneous stimulation affect only response bias. Rather, they may indicate quite the opposite. Likewise, it is possible that strong suggestion (as well as hypnosis) could affect a central biasing mechanism which inhibits the lower response to noxious stimuli, without any observed change in d′ resulting. TSD cannot distinguish between drastically different effects.

Perhaps one would agree that the discriminability of adjacent pairs of signals need not change when a neural modulation takes place, but suggest that this effect should be reflected in the reduction of d′ between strong stimuli and a blank. There are two factors mitigating against this. First, d′ can only be calculated when there is some overlap in the responses given to the two stimuli. But subjects will rarely give the necessary "false alarms" to a blank: indicating that it is painful. In the experiment by Chapman et al. [12], for instance, observers gave essentially no reports of "moderate" or "strong" pain on blank trials. "Faint pain" was reported for less than 1% of the blanks, "hot" for about 4%, "warm" for about 16%, and "nothing" for nearly 80%. Since subjects probably never indicate "nothing" when the intense stimulus is given, calculating d′ between such a signal and a blank requires one to ignore at least 80% of the data collected on the blank trials. When only 50 noise trials are presented to a subject, this is an ill-afforded luxury. Their calculations and plots are based on 10 blank trials per subject, from which they determine 3 distinct criteria along the ROC curve.

The second difficulty with computing d′ for a signal compared to noise, before and after attempted pain modulation, is that it requires the assumption that the noise distribution is fixed. It does not, however, seem implausible that electrical stimulation or a drug could block or reduce the spontaneous activity level in peripheral and/or central loci, shifting the noise distribution lower. If so, the signal plus noise distribution would shift as well, as in Fig. 2, and once again one would have a situation where marked neural attenuation does not produce a d′ change.

A similar paradox occurs in odor adaptation. There are considerable data to indicate that the subjective intensity of a weak odor is reduced after prolonged exposure to a strong adapting odorant. Berglund et al. [3] failed to find a corresponding reduction in d′, suggesting that the distribution of the internal noise had itself been attenuated by the adaptation process.

How does one deal with those instances where d′ does change? First, one has to ensure that the proper TSD conventions were applied, since, under certain conditions mentioned below, a criterion shift might be mistakenly taken as a change in d′. Second, one must question why a reduction in the discrimination of adjacent stimuli provides any information about their painfulness. A decreased d′ only indicates greater confusion between signals. Third, one could grant that a reduction in d′ coupled with other evidence of pain relief might indicate that the modulation has a sensory effect. Carbocaine reduces pain. It also reduces discrimination ability [22]. Neither is an unexpected effect of peripheral nerve block. In the case of tooth pulp stimulation, some treatment which attenuates the neural response to noxious levels of stimulation more than that to less intense pulses could reduce, as well, the d′ for discriminating between them. But a d′ reduction itself indicates neither analgesia induction nor the nature of the discriminability loss, since interference with a central decision process could reduce d′ without a concomitant change in sensory pain.

Researchers who determine d′ during pain modulation study discrimination between different stimulus intensities, not pain. When discrimination ability remains, even though subjects indicate the stimulus is no longer distressing, they conclude that only a motivational or emotional shift has occurred. Thus Chapman [7] claims that when one has delivered a "noxious stimulus to the human skin and the subject is able to process the presence of that tissue-damaging stimulus and yet verbally deny that he has felt any pain, [there] is a change in response bias". Clark and Yang [21], who found that acupuncture decreased both the proportion of arm withdrawals and the reports of pain to intense radiant heat without decreasing the discriminability of adjacent signal levels, concluded that the subjects experienced unchanged levels of pain, but "were less likely to admit that a given sensory experience was painful".

However, analgesia is not anesthesia. Pain could be attenuated while discriminatory ability remains (contrary to assumption 4). Alternatively, discriminatory ability could be diminished while pain remains (contrary to assumption 3). The TSD proponents mistakenly link pain and discrimination. When Melzack and Casey [41] label one component of the pain response as the "sensory-discriminative dimension", the two terms are not synonymous. A change in d′ is neither a necessary nor sufficient indication that a treatment has any analgesic properties. The fact that no satisfactory alternative is available to measure sensory and emotional components of the complex pain response fails to compensate for the shortcomings of the signal detection approach. Nor is it relevant to argue that since some recognized anesthetics and analgesics decrease d′, any procedure which fails to reduce discrimination ability is *ipso facto* not an effective analgesic [22]. It is an error in logic to utilize TSD parameters to reach definitive conclusions about mechanisms altered during pain modulation.

METHODOLOGICAL REQUIREMENTS

Problems of experimental methods

The critique presented above was based on theoretical and logical grounds. Even if the TSD model were unambiguous about d′ and criterion changes, it is vital to recognize numerous procedural difficulties which must be considered when interpreting the results now available. The signal detection approach to the study of sensitivity and discrimination involves assumptions about sensory and decision processes which have been overlooked. It also requires exacting data collection procedures. A number of these will be examined below. Table II summarizes the salient methodological characteristics of each of the studies reviewed earlier.

For example, psychophysicists generally present large numbers of signal and noise trials. Green and Swets [30] have suggested that about 250 trials of each are appropriate. In a discrimination experiment, then, such large numbers of trials should be presented for each of the stimuli to be discriminated. Yet to each subject, Craig presented 10 or 12 trials per intensity, Clark used 12—25, and Chapman presented 50—100. Each session may have been lengthy, because 4—10 intensities were used. It would have been preferable to limit these and increase the number of trials per stimulus.

Second, psychophysicists use carefully trained subjects. Green and Swets [30] present data indicating that performance may take many sessions before it stabilizes; certainly it can vary considerably within the first session of several hundred trials. Yet in some pain studies, practice is limited to a few sample trials. The main body of data is collected precisely during the period when subject performance fluctuates maximally. Clark and Yang [21], for example, note that both d′ and criterion showed increases during a testing session. The changes were non-significant, but the number of trials was limited. Lloyd and Wagner [35] found that two of their 3 response bias measures changed between baseline and acupuncture periods for 7 out of 8 subjects. Green and Swets [30] note that such asymmetrical decision criteria in forced tasks arise rarely and are usually eliminated after practice.

Third, there is some question concerning the optimum number of categories in a rating scale. McNicol [38] enumerates the problems associated with a large number of categories — the difficulty observers have in using them consistently, the chance that some categories will not be used, and the

TABLE II

METHODOLOGICAL DETAILS

Investigator	Extensive TSD training for Ss	Ss per group	No. of rating categories	No. of sessions per condition	No. of intensities in a session	No. of trials per intensity	Blank stimuli presented?	d′ between all signals and noise or adjacent signals
Bloedel								
Bloedel et al. [14]	No	407	6	2	3	24	No	Adj.
Chapman								
Chapman and Feather [9]	No	12	5	3	5	50	Yes	Adj.
Chapman et al. [10]	100 trials	14	7	2	4	75	Yes	Adj.
Chapman et al. [12]	No	14	6	1	4	50	Yes	Both
Chapman et al. [13]	100 trials	15	7	2	4	75	Yes	Adj.
Feather et al. [29]	No	9	4	1	2	50	No	Adj.
Harkins and Chapman [31]	100 trials	10	6	1	2	100	No	Adj.
Clark								
Clark [14]	No	22	13	1	5	25	Yes	Adj.
Clark and Goodman [17]	No	10	11	1	6	12	Yes	Adj.
Clark et al. [18]	No	6–12	12	1	6	12	Yes	Adj.
Clark and Mehl [19]	No	32	11	1	6	16	Yes	Adj.
Clark and Yang [21]	No	12	12	1	6 *	24	Yes, but not reported	Adj.
Craig								
Craig and Coren [24]	No	25	10	1	5	12	No	Adj.
Craig and Ward [25]	No	10	100 **	2	10	10	No	Adj.
Lloyd								
Lloyd and Wagner [35]	No	8	Forced-choice	1	4	50	Yes	Adj.

* In their report, Clark and Yang presented only the data for two intensities.

** Analyzed by decades.

inability to accurately estimate successive hit and false alarm rates based on small numbers of trials. He concludes, "probably 10 categories can be used by an observer after a reasonable amount of practice". However, subjects in the pain experiments frequently used 7—12 categories, often with negligible practice.

Fourth, sensory TSD studies generally present only one pair of stimuli per session, either a signal and a blank or a pair of signals. Pain studies have generally presented many values. Green and Swets [30] summarize a series of psychoacoustic experiments demonstrating a decrement in performance as more frequencies are added to the set of possible stimuli. Another study [49] has suggested that the variance of the signal plus noise distribution increases when the observer detects two different light flashes. Since criterion variance may increase as well with the introduction of added stimulus intensities, precise estimates of either the sensitivity or bias parameter cannot be obtained.

Finally, all but one study of modulation have relied upon subjective ratings of perceived magnitude. These ratings are used in a manner very different from sensory studies, although that in itself is an acceptable deviation. Consider an experiment to discriminate two levels of radiant heat. The psychophysicist would present a large number of trials at two stimulus levels and the observer would issue ratings ranging from, "I feel fairly certain that you presented the weaker signal", to "I feel fairly certain that you presented the stronger one". The subject is thus trying to discriminate between two values of heat. The uncertainty on each trial is reflected in the ratings he produces, and there are, in fact, some right and wrong answers. However, when two levels of radiant heat (or any other noxious stimuli) were applied in pain studies, the experimenter required reports of subjective reactions, the uncertainty was ignored or abolished, and there was no relationship between stimulus and response which could be specified as right or wrong. The subject makes no error when he says that a moderate stimulus, at that moment, feels painful. The procedures used are a legitimate extension of the TSD model. The experimenters have properly assumed that the data could be treated in a manner equivalent to that used if the subjects had focused their attention on the discrimination judgment. Furthermore, Clark and Mehl [20] found no differences in d′ obtained from ratings of observer confidence or subjective magnitude. However, the criterion seems to be influenced by the definition of the observer's task. Clark and Mehl [20] showed differences in d′ for binary decisions and ratings which indicated a considerable variance in criterion when judging thermal stimuli, particularly when a large number of criteria were to be maintained simultaneously.

Problems of result consistency

Since the statistical analyses performed in the pain studies were based upon the d′ and criterion values obtained from each of a number of subjects, accuracy in the determination of those parameters is crucial, particularly when important conclusions are drawn from a failure to reject the null hypothesis. It is evident that sizeable variations have existed within a laboratory. In one example provided by Clark and Goodman [17], the mean d′ prior to verbal suggestion ranged, across groups of 10 individuals, from 1.33 to 1.94. For one pair of intensities, Chapman et al. [10] found a baseline range, across groups of 14, that was 1.30—1.97. The shifts in d′ between baseline and test sessions for their control groups were frequently considerable. To lend some perspective to the range of 0.67 for baseline d′ across groups, it should be noted that acupuncture changed the discrimination index for the three pairs examined by 0.63, 0.54, and 0.69. Nitrous oxide decreased d′ by 0.02, 0.10, and 1.12. In other experiments, as well, effects were found for some pairs of intensities but not others. In the Chapman et al. [10] study, all the d′ shifts were in the predicted direction and an analysis of variance indicated clearly significant effects. The point of these selected examples is not to repeat the observation that human behavior is variable, but to caution the reader that mary of the published studies present complex interactions requiring careful interpretation.

More troublesome are the inconsistent findings across laboratories in the effects of procedures such as acupuncture, placebos, and transcutaneous stimulation. It is not a question of a moderate d′ shift in one study and a sizeable one in another. Rather inconsistencies yield strikingly different interpretations of the physiological processes involved in pain modulation and the clinical utility of analgesic techniques. Is sensitivity or response bias changed by acupuncture and transcutaneous stimulation? No unequivocal statement is possible.

Clark and Chapman disagree about the effects of acupuncture. Clark [14] used radiant heat; Chapman et al. [10,13] stimulated the incisors. However, the two laboratories agree [13,18] that transcutaneous stimulation decreased d′ for their form of pain production. Yet, Bloedel et al. [4,5], while favoring a sensory interpretation, found that transcutaneous stimulation raised only the criterion parameter for radiant heat.

Problems of data analaysis

A TSD experiment requires attention to certain details when the critical parameters are determined. Unfortunately, d′ and C do not emerge as obviously from a collection of data as do measures such as percent correct or threshold intensity. Complex computational and graphical procedures are necessary to reduce the information obtained from a 12-point rating scale to a single estimate of sensitivity [27]. Other considerations are necessary when combining data across subjects and conditions.

For instance, an individual's data could be cumulated according to certain rules and plotted in the form of the receiver operating characteristic (ROC) [27,30], which presents false alarm rate on the abscissa and hit rate on the ordinate. On a normal-deviate transformation of the axes, the simple TSD model predicts a straight line with unitary slope. In such an instance, d′ can be calculated from the graph directly, it can be computed with the aid of a table showing the area under a normal distribution, or its value can be obtained from published tables providing d′ for various combinations of hits and false alarms [28]. The latter two techniques are legitimate only if the ROC function has a slope of one, indicating equal variances for the two overlapping distributions. Yet many determinations of d′ in the pain studies came from data not subject to this important test. In one condition with thermal stimuli, Clark [14] found a slope of about 1, but Feather et al. [29], in another experiment, found slopes of 0.7—0.8. Nor is the assumption valid for electrical or mechanical stimulation of the skin [46,47]. Failure to follow special conventions required to extract the sensitivity parameter in such instances can cause an experimenter to report a d′ shift when actually a criterion change occurred, or vice versa. As Theodor [55] has shown, "d′ is independent of response bias only when (the ratio of the variances of the distributions) has been taken into account; ...it is necessary to know (the ratio) in order to properly calculate d′." Thus, basic assumptions of the TSD model can be violated when one simply determines d′ from pairs of hit and false alarm rates.

Even after one ascertains whether the ROC function on a double-probability graph has unitary slope, further conventions should be considered. Chapman et al. [10,13] utilized a technique presented by Richards and Thornton [45] which calculates a least-squares fit to the straight line equation of a transformed ROC. Since least-squares procedures require, inappropriately, that the false alarm rate is not free to vary, some psychophysicists have developed maximum likelihood estimation techniques for specifying the parameters of the ROC function, while others fit a line by visual inspection. In the case of unequal variances of signal plus noise, the Richards and Thornton method estimates d′ at the point where the line intersects the ordinate of the ROC rather than following the general practice of noting where it intersects the negative diagonal. Neither matter is likely to have greatly affected Chapman et al.'s determinations of discriminability and response bias, but the example illustrates the need for future pain researchers to familiarize themselves with the many ways available for estimating signal detection indices and the mathematical assumptions underlying them.

Difficulties can also be introduced by the procedure used to combine data. d′ should be determined for each subject and then averaged across them. Examples, such as those presented by Clark [14,15], might lead an experimenter to pool the proportion of responses in each category across subjects before determining a single d′. McNicol [38] has demonstrated that sizeable errors can be introduced by the latter procedure when the data from observers differing considerably in sensitivity are combined.

Problems of d′ interpretation

When stimuli range from zero to some potentially painful level, there are two ways to determine d′ for each signal. The first of these, the sensitivity measure (sensitivity in detecting the stimulus, not in registering it as painful), is obtained by computing d′ between each level and the internal noise. The second, the discrimination measure, is obtained by computing d′ between adjacent stimulus pairs. As discussed earlier, the dearth of pain responses to blank presentations has caused almost all pain researchers to determine discrimination ability, not sensitivity.

A few studies have, in fact, obtained d′ between a weak stimulus and a blank. For more intense signals, however, they have turned to the discrimination index. Only one study, that of Chapman et al. [12], measured d′ at all intensity levels against the responses to noise. They reported that 33% nitrous oxide reduced d′ for 3 values of radiant heat when compared to blanks. The gas did *not*, however, "change sensitivity to the differences between adjacent non-zero stimulus pairs". Thus, the sensitivity measure was reduced, but the discrimination measure was not. This crucial point has been repeatedly overlooked in later papers which claim that a known anesthetic will reduce d′. The Chapman et al. [12] results are cited in support of the discrimination measure as an index of pain, when, in fact, the discrimination d′ was unaffected by nitrous oxide, even though the pain responses decreased.

EPILOGUE AND SUMMARY

This paper has been critical of the TSD approach without offering an alternative solution to the vexing problems of pain measurement. There are no entirely satisfactory answers now available. Pain is not a unidimensional sensation; experimental pain forces "the researcher to work with a conceptual oversimplification of the human pain experience, and to deal with laboratory tasks that bear little resemblance to pain states occurring naturally [8]". Nonetheless, experimental studies of pain modulation must continue in the laboratory, precisely because the conditions there permit the assessment of physiological effects under conditions unhampered by the high levels of anxiety which accompany persistent, unbearable, uncontrollable clinical pains [40].

Signal detection theory has emphasized that even simple psychophysical judgments are composed of both sensory and decisional components. It has helped pain researchers to realize that pain measurement which relies upon thresholds is inadequate and misleading, for pain report and pain sensation are not equivalent. A treatment that raises threshold for pain may fail to influence the observer's true sensitivity or felt pain. It would be an advance of the first order it we could distinguish unequivocably between alterations in response which arise from sensory attenuation and those which are due to changes in anxiety, attitude, emotion, motivation, and reactivity. All of these latter terms have been subsumed by the TSD researchers under the general heading of response bias or subjective criterion.

The theory does not provide us with this desired advance. The methodological inadequacies of some TSD experiments can be overcome, but the ambiguities which exist are not attributable simply to deficiencies in experimental design or the selection of modulation parameters. Difficulty arises because the TSD studies do not determine a true estimate of the painfulness of a stimulus or allow an unbiased assessment of whether such painfulness has been reduced. At best, they ask whether one stimulus changes in discriminability from another one. Must a powerful analgesic necessarily reduce the ability to discriminate between adjacent pulse levels? Alternatively, must a treatment which makes it more likely that two signals are confused necessarily effect the severe pain such signals engender? If not, the premise on which these studies rest is untenable. The conclusions of some individual studies may be correct, but they are not inevitably so. There is no certain way of knowing whether the experienced pain, in any given experiment, has been modified or not.

Signal detection theory remains a powerful tool for studying other forms of sensory detection and discrimination. It requires careful training of observers, long periods of data collection for each individual, a strong appreciation of the theoretical assumptions underlying the treatment of results, and elaborate computational procedures for extracting the parameters of interest. But is does not measure pain; it measures discrimination. An analgesic need not be anesthetic; pain and discrimination cannot be equated. Those who have applied TSD to the study of pain have examined discrimination in an attempt to independently measure pain sensitivity and response willingness. Unfortunately, such a distinction does not yet seem attainable.

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