SDT ANALYSIS OF EXPERIMENTAL THERMAL PAIN, WITH "SIGNAL" AND "NO-SIGNAL" BEING DETERMINED PSYCHOPHYSICALLY[1,2]

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Summary.—In a signal-detection experiment, the effects of repeated pain stimulation and the induction of fear on pain thresholds and SDT parameters were studied. "Signal" and "no-signal" were not defined physically, but by means of an independent criterion as the primary sensations "pain" and "no-pain." First, the relationship between sensation levels for "phasic" (short stimulus, used in the SDT procedure) and "tonic" (longer stimulus, used in the criterion measurement) heat stimuli was determined in 14 subjects. It was quadratic (polynomial regression) and sufficient to define the distinction between "signal/pain" and "no-signal/no-pain." In the signal-detection experiment, a significant upward trend (adaptation) in threshold parameters, but no systematic change in the SDT parameters (discrimination ability and response bias) was found. Manipulation of anxiety by instructions caused unsystematic changes in discrimination ability. The procedure employed determines both the absolute strength of pain sensation and the ability to discriminate pain from no pain. These variables proved to be independent.

The signal detection theory (SDT) was adopted in pain research with great hopes at first, since it seemed to permit separating the sensory and cognitive-motivational components of pain. However, numerous subsequent experiments have shown that the relationships between these pain components and SDT parameters are not simple (8, 9). Rollman (14) provided another objection to SDT, saying that the SDT parameters do not enable one to measure either the absolute or the relative strength of pain directly but only represent the quality of perception in general, and so are not a substitute for traditional psychophysics. The need for lengthy series of stimuli, which limits its clinical usability, was a further reason why SDT methods have lost importance in pain research.

The present study attempts to show ways of moderating or refuting the objections cited, so that the undisputed advantages of SDT methodology (2) can still be used for pain research. "Signal/pain" and "no-signal/no-pain" are defined psyochophysically as the stimuli which elicit pain and no pain according to an independent criterion. This takes account of the fact that pain is a psychological quality, which cannot be defined physically. For this, we need an independent pain criterion, which can provide the distinction

[1]This study was supported by Grant Str 273/1-1,1-2 from Deutsche Forschungsgemeinschaft.
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stated. In such an SDT experiment, the ability to discriminate between "pain" and "no-pain" can be studied, thereby meeting Rollman's objection. Definition of "signal/no-signal" along psychological dimensions is known from work in social and mnemonic psychology (3, 10, 19), but has not been used in pain research. A psychophysical definition also offers the advantage of reducing the number of stimuli needed, by appropriate selection of intensity range.

The independent pain criterion must divide the physical stimulus continuum into two intensity classes, which are sensorily suitable for eliciting pain or no pain. This is the only practical way to pose a psychophysical signal-detection task meant to refer to the primary sensations. Therefore, it is necessary to find a method of pain measurement which is insensitive to response bias, so that it is suitable for an independent pain criterion. This is true of a modification of the sensitization method described by Severin, *et al.* (16). In an adjustment procedure, the pain threshold for thermal stimuli is determined. The experimental subjects are stimulated over a period of 30 seconds at the temperatures thus determined. Stimuli of this intensity and duration usually result in a weakening of the sensation (adaptation) in the nonpainful range, and a strengthening of the sensation (sensitization) in the painful range. The compensation of these changes in sensation demanded subsequently indicates any initial bias towards overestimating or underestimating the threshold temperature. Furthermore, the procedure can be carried out quickly, enabling one to correct the psychophysical "signal/no-signal" determination at short intervals.

Therefore, the main objective of this study was to try out a two-stage procedure, with the sensitization method being used to determine the psychophysically defined variables "signal/pain" and "no-signal/no-pain" in Stage 1, and the stimulus classes thus obtained being employed in a signal-detection procedure in Stage 2. The following hypotheses are assumed:

(a) *Variations in the absolute magnitude of pain perception* (such as long-term adaptation to repeated pain stimuli) cause variations in the independent pain criterion but do not affect the SDT parameters for discrimination ability and response bias, since variations of the absolute magnitude can be taken into account in determining "signal" and "no-signal."

(b) *Psychological manipulations* ("anxiety induction" in this study) that cause quantitative and qualitative variations in perception in the pain threshold region are reflected by the SDT parameters thus obtained.

In Exp. 1, the quantitative relationship between the sensation levels upon "tonic" (longer stimulus) and "phasic" (shorter stimulus) heat stimuli must be determined first—since tonic stimuli are used to derive the independent criterion by the sensitization method, and phasic stimuli in the SDT experiment itself. This estimate of the relationship is needed in the

SDT experiment for determining individually the "signal" and "no-signal" classes. Then, in Exp. 2, the hypotheses stated above are to be tested.

Exp. 1: Heat Pain Perception During Phasic and Tonic Thermal Stimuli

Method

Subjects.—Healthy subjects participated (7 women, 7 men, of mean age 26.9 yr., standard deviation ± 3.4). They were informed of the course of the experiment and the question being studied. It was also pointed out that they might stop participating at any time. They were paid for participating.

Apparatus (identical for Exps. 1 and 2).—Cutaneous heat stimuli were applied by means of a stimulator developed in the Department of Neurology of the Max Planck Institute for Psychiatry. The device controls a Marstock thermode (for technical details, see [7]), which functions on the Peltier principle and can be either heated or cooled. The temperature obtained at the interface between the thermode and the skin was recorded continuously on a pen recorder (Phillips PM8252). This served to check the major stimulus parameters (amplitude, shape of leading edge, duration). The site of the stimulation and measurement was the thenar of the right hand, which was lying on a hemisphere made of hard PVC. The thermode was installed in this hemisphere and was pressed against the skin with a constant pressure by a spring. In the procedures requiring adjustments to be performed, the subjects regulated the temperature by means of a knurled wheel located in the hemisphere, within reach of the index finger. All other stimulus indications were given as spoken ratings.

Procedure.—At the start of the session, the subjects determined their pain thresholds by stimulus adjustment five times. Fifty phasic stimuli were then applied in random sequence, starting from a base temperature of 38° Celsius, with three fixed temperatures of 40°C, 42°C, and 44°C, as well as with temperatures varying about the mean of the threshold values determined initially (mean − 1.5°C, − 0.5°C, + 0°C, + 0.5°C, + 1.5°C). The phasic stimuli had a triangular wave form, with leading edge gradients from 3°C to 6°C per second, depending on the magnitude of the stimulus. After each phasic stimulus the subject had to adjust a tonic stimulus to elicit the same intensity of sensation as that produced by the phasic stimulus. This led to a subjective equivalence of sensations produced by the two stimuli. The highest temperature set during this adjustment of the stimulus (mean duration of stimulus adjustment 23.8 sec.) was recorded as the measurand (tonic temperature).

Results

To describe the relationship between the given phasic and the adjusted tonic stimuli, a polynomial regression function was calculated, for each subject separately, and for the pooled data of the whole group. There was a pronounced linear component (significant for all subjects, $p \leq 5\%$), and for nine persons, there was also a significant quadratic term ($p \leq 5\%$). The polynomial fitted to the pooled data for the whole group contains both significant linear and quadratic components ($p \leq 0.1\%$ in both cases) and a cubic one ($p \leq 5\%$). However, the latter is of no practical relevance for the goodness of the estimate and is disregarded in the following. The quadratic term for the individual subjects and the pooled data of the whole group arose from overestimation of the preset phasic stimuli at low stimulus temperatures. Thus the tonic stimulus temperatures were greater than the phasic ones in theses cases. Fig. 1 shows raw data with the fitted polynomials.

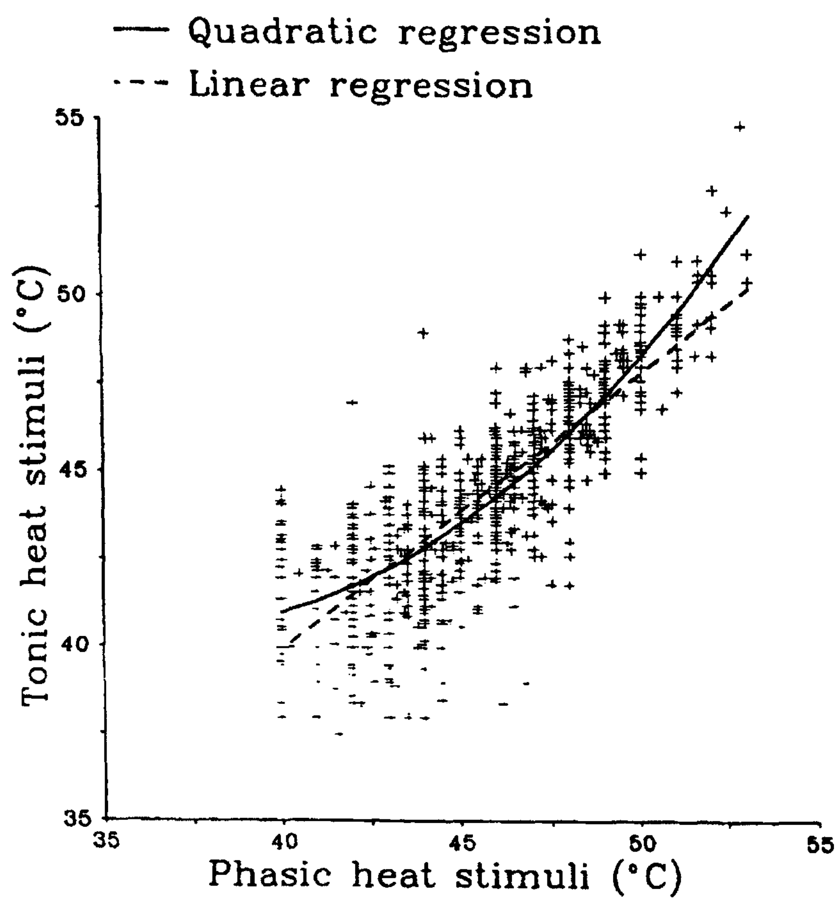

FIG. 1. Relationship between sensation levels for phasic and tonic heat stimuli; raw data ($n = 700$) with linear and quadratic regression, "tonic" onto "phasic"

Despite the significant differences between the individual regression equations ($p \leq 0.1\%$), the differences near the threshold values are so small that the regression function computed from the pooled data for the whole group could be used for Exp. 2 (number of stimulus pairs used in the regression: $n = 700$):

$$t = b_2(p - 40)^2 + b_1(p - 40) + b_0 + 40$$

where p is the temperature of the phasic stimulus, t that of the corresponding tonic stimulus, and b_i the constants of the regression equation: $b_2 = 0.045$, $b_1 = 0.281$, and $b_0 = 0.981$. For the equation presented, the standard error of estimation is 1.553. This ensures that it is good enough to estimate the phasic stimuli for the "signal/pain" and "no-signal/no-pain" classes from the independent pain criterion by tonic stimulation (sensitization procedure) in Exp. 2. For this, the above equation must be solved for p, in order to obtain the desired direction of prediction (20):

$$p = \frac{-b_1 + \sqrt{b_1^2 - 4b_2b_0 + 4b_2(t-40)}}{2b_2} + 40$$

This equation was used in Exp. 2 to make a distinction between "signal/pain" and "no-signal/no-pain": t was taken as the temperature value of the threshold for tonic heat pain produced by the sensitization method and the resulting p then gave the temperature value which separated the two signal classes.

Exp. 2: SDT Analysis of Experimental Heat Pain

Method

Subjects.—Healthy subjects took part in the study (7 men and 7 women, mean age 29.6 yr., standard deviation ± 4.2). The conditions under which they participated were the same as those for Exp. 1. One subject did not complete the study so his data were not included in analyses.

Apparatus.—The same material arrangements were used as those for Exp. 1.

Procedure.—In Exp. 2 a two-stage procedure was used. The strength of the stimulus which separates the painful from the nonpainful range was determined by an adjustment procedure with tonic thermal stimulation (sensitization procedure) in Stage 1. Then the subjective equivalent for phasic stimulation (called the "cut-off point") was calculated by means of the correction formula derived in Exp. 1. Next in Stage 2, phasic stimuli above and below the cut-off point were applied to be discriminated as "signal/pain" and "no-signal/no-pain" in an SDT procedure.

In Stage 1, the sensitization procedure was followed. For the reasoning behind the procedure, see the Introduction. The pain threshold for thermal stimuli was determined by stimulus adjustment, and then the hand was stimulated for another 30 sec. at the adjusted temperature. Depending on the strength of the stimulus, a subjective strengthening of the sensation (sensitization, in the painful range), weakening of the sensation (adaptation, in the nonpainful range), or no change in the sensation (in the threshold region) occurs during this interval. These changes in sensation reflect variations in the primary processing of the stimulus and are therefore hardly subject to response bias (16). After the constant stimulation, the subjects were to readjust the stimulus to achieve the same sensation as in the first adjustment. The second stimulus adjustment usually tends to compensate for the changes in sensation that have occurred, correcting errors in the first adjustment. So the second temperature setting was used as the measure of the pain threshold for tonic stimuli. Next, the phasic temperature corresponding to the tonic stimulus was determined, according to the correction formula derived in Exp. 1. This provided the independent pain criterion required (see Introduction), in the form of a cut-off point for the "painful" and "nonpainful" ranges, for the SDT experiment.

In Stage 2, the SDT procedure involved 20 phasic stimuli of differing levels which stimuli were applied in a randomized order. The temperatures 40°C, 42°C, and 44°C were each applied twice, to enable the strength of the sensation for physically equal temperatures to be determined. The remaining 14 stimuli had levels distributed symmetrically around the cut-off point (analogous to Exp. 1: cut-off point −1.5°C, −0.5°C, +0°C, +0.5°C, +1.5°C). The stimulus form was the same as that in Exp. 1. Each stimulus was announced by a signal tone, at an interval ranging from two to five seconds before the stimulus. After the stimulus, the period for evaluation was indicated visually. The subjects were to rank the stimuli on a nine-place scale, ranging from "very painful" (1) to "imperceptible" (9). The distinction between not painful and painful lay between Ratings 4 and 5.

The two-stage procedure, in the form described, was carried out three times (three experimental blocks, consisting of Stages 1 and 2). Thus there were 60 stimuli available for the SDT evaluation, with the cut-off point being redetermined before each block, that is, "signal/pain" and "no-signal/no-pain" being defined afresh. The influence of psychological manipulations on the SDT parameters was checked by announcing stronger stimuli ($n = 7$) or weaker ones ($n = 6$) through instructions before the third block. The effect of such induction of anxiety is known from other SDT experiments (5, 11, 15). We wished to compare it with the effect for a psychophysical definition of "signal/no-signal."

Data analysis.—Only the psychophysical measures are presented here. Details of the statistical analysis are provided in the respective sections of the presentation of the results.

The parameter of the pain threshold for tonic thermal stimulation was provided by the sensitization procedure. To obtain a pain-threshold parameter for the phasic thermal stimuli applied during the SDT procedure, the "isotonic" (monotonic) regression of stimulus strength on sensation rating was calculated for each experiment block. With this nonparametric method (1), the perception-probability curve can be determined even for incomplete and short series of stimuli—such as in this experiment. From these curves, the 50% point according to Stevens (17) was calculated as the threshold value.

Since the distribution assumptions of the parametric SDT model could hardly be fulfilled with the small number of stimuli and the novel psychophysical "signal" and "no-signal" definitions, only nonparametric SDT measures were used. The parameters were always calculated for a block, that is, for 20 stimuli. The plane P(A) under the ROC ("receiver-operator characteristic") curve was used as the parameter of the discrimination ability. The measure B proposed by McNicol (12) was used for the response bias. The "signal" and "no-signal" classes were determined in two different ways, and evaluated separately:

Open class: signal = all stimuli above the cut-off point, no-signal = all stimuli below the cut-off point.

Bounded class: signal = all stimuli up to 3°C above the cut-off point, no-signal = all stimuli down to 3°C below the cut-off point.

The use of bounded classes provides more homogeneous classes but limits the number of stimuli included. If the "signal" or the "no-signal" class contained less than three stimuli, no SDT parameters were calculated for this block.

Results

Variations of threshold and SDT parameters over time.—The threshold and SDT parameters, which had been calculated separately for the three blocks (see Data analysis), were subjected to an L-test for monotonically increasing or decreasing trends according to Page (13). Such trends are to be expected, in the form of adaptation or sensitization, during repeated pain stimulation over a longer period (6). Both for the sensitization threshold for tonic thermal stimulation, and for the 50% threshold for phasic thermal stimuli, a significant increase of the threshold over the blocks was found ($p \leq 5\%$ in each case). Both group trends are illustrated in Fig. 2.

Neither of the two SDT parameters [discrimination ability: *P(A)*, response bias: B], showed a significant trend, for either of the two ways of forming the "signal" and "no-signal" classes (see Data analysis). Therefore only the results for the bounded classes are shown in Fig. 3.

The location of the bias values about 4.5 in the three blocks shows that the subjects used a neutral criterion on average, i.e., were not biased towards reporting pain or no pain (zero bias at 4.5, <4.5 = bias towards reporting pain, >4.5 = bias towards reporting no pain). No proof of trends due to the instructions that heightened or reduced anxiety was found on comparing the two instruction groups, for there were no significant differences in trends for the threshold or SDT parameters (Mann-Whitney *U* test,

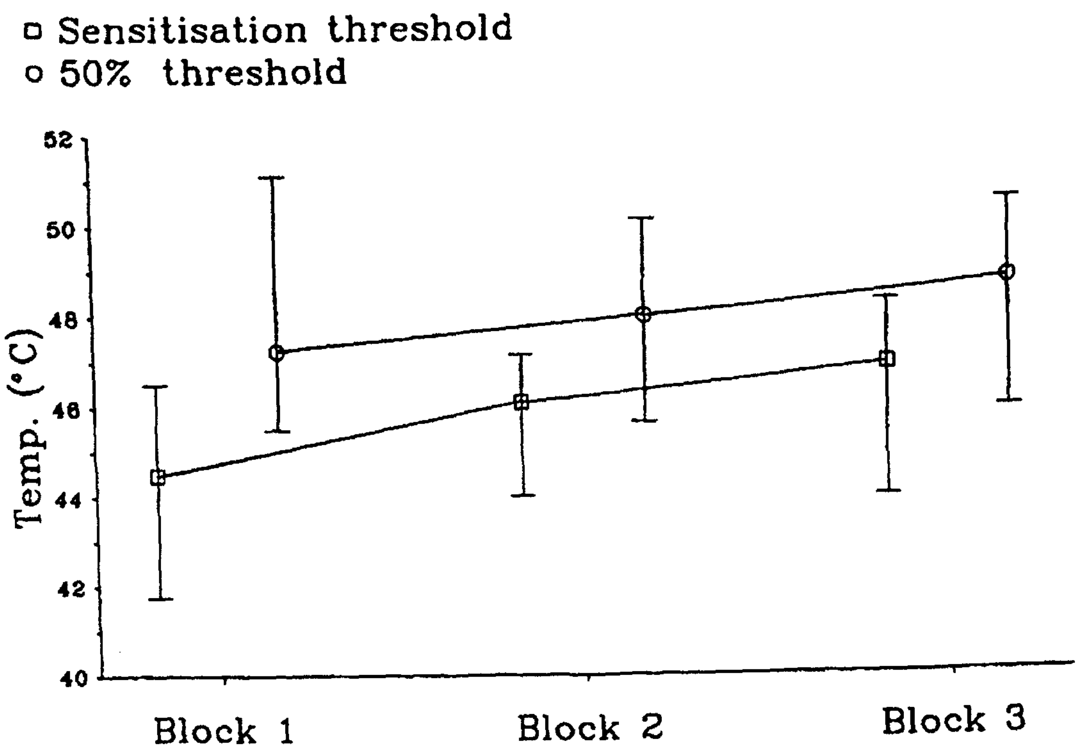

FIG. 2. Median with interquartile range of the sensitization and 50%-point thresholds in the three experimental blocks (20 stimuli per block); $n = 13$ each block

$p > 5\%$). The evaluation up to here only covers the mean variations in the group. To test for intraindividual variations, reliability was determined by means of Spearman rank correlations, calculated between the values of the

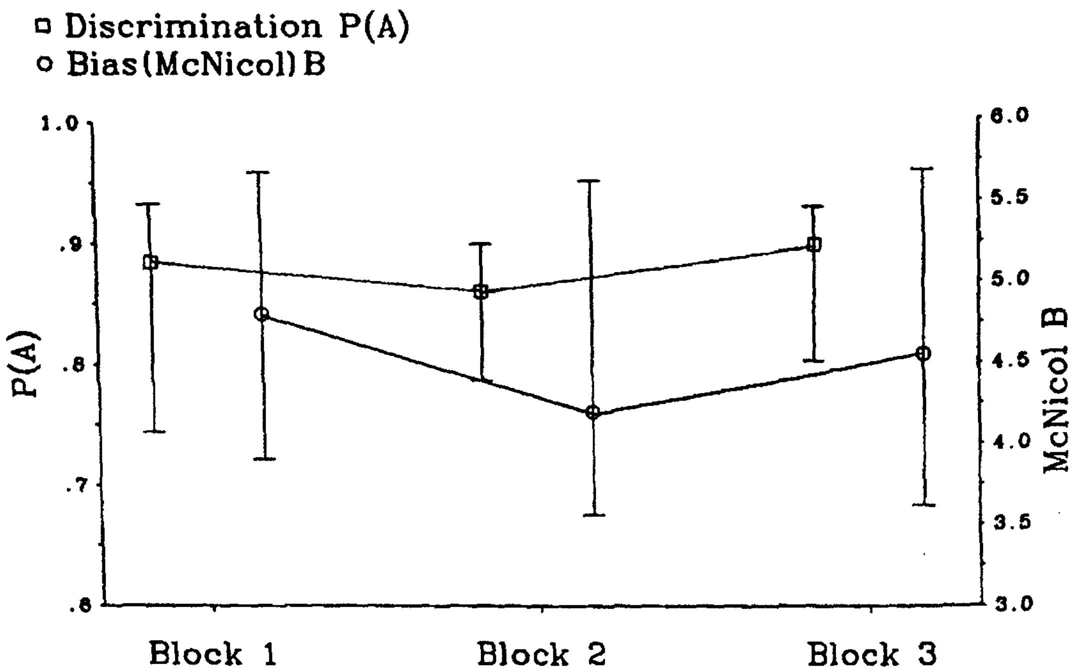

FIG. 3. Median with interquartile range of the discrimination ability P(A) (scale on left abscissa) and McNicol's B bias measure (scale on right abscissa) in the three experimental blocks (20 stimuli per block); evaluation for bounded "signal/no-signal" classes (see Data analysis of Exp. 2); $n = 10$ in Block 1 and $n = 12$ in Blocks 2 and 3 each

individual blocks. This checks whether the rank order of the individual parameters, which is not affected by common trends over the session, is maintained at different times. The results are shown in Table 1.

TABLE 1
CORRELATIONS BETWEEN EXPERIMENTAL BLOCKS FOR THRESHOLD AND SDT PARAMETERS

Parameters	Between Blocks 1 and 2		Between Blocks 2 and 3	
	r	*n*	*r*	*n*
Threshold				
Sensitization Threshold	.71*	13	.87*	13
50%-point Threshold	.85*	13	.80*	13
SDT				
Discrimination P(A)	.88*	10	-.34	11
Bias McNicol's B	.49	10	.36	11

Note.—20 stimuli per block, evaluation for bounded "signal/no-signal" classes (see Data analysis of Exp. 2).
*Spearman's rank correlation, $p \leq 1\%$.

The sensitization and 50% thresholds showed fairly strong correlations between the blocks, that is, considerable stability. For the bias parameter B, the correlations between Blocks 1 and 2, and 2 and 3, are also similar, but much weaker and not significant. Only for the discrimination ability parameter P(A) do the correlations between the blocks vary during the session. While Blocks 1 and 2 correlate strongly, the relationship between Blocks 2 and 3 is only weak. For the results on P(A) and B the manner in which the classes are formed for "signal" and "no-signal" is immaterial (see Data analysis).

The trend and correlation analyses together show a common trend to higher values for the threshold measures, which does not affect the ranking among individuals. The SDT parameters show no common trend over the session. The response bias remains relatively stable intraindividually, too. After an initial high intraindividual stability, discrimination ability shows individually differing variations when the instruction for expectation is introduced; these do not display a common trend.

Specific instruction effects on threshold and SDT parameters.—The disappearance of the high, significant correlation between Blocks 1 and 2, after the introduction of the instructions between Blocks 2 and 3 (see above and Table 1), may be considered an unspecific instruction effect on the measure of discrimination ability P(A). This applies to both kinds of instruction taken together. Specific instruction effects could not be evaluated, since the treatment groups already differed significantly in the threshold parameters before the instructions ($n = 7$, instruction increasing anxiety, $n = 6$, instruction reducing anxiety; for difference of both sensitization and 50%

thresholds in Block 2, $p \leq 5\%$, Mann-Whitney *U* test). Since the SDT parameters depend on the threshold parameters, because the "signal" and "no-signal" classes were defined psychophysically, these variables cannot be evaluated for specific instruction effects, either.

Discussion

The main purpose of the present study was to define "signal" and "no-signal" psychophysically instead of physically, in contrast to previous SDT approaches in pain research. A two-stage procedure was tried, with painful and nonpainful stimulus levels being determined first (Stage 1), and these classes of stimulus then being used in the SDT experiment (Stage 2).

Since a procedure with tonic thermal stimulation was needed in Stage 1, but phasic thermal stimuli in the SDT experiment (Stage 2), the relationship between the strength of the sensations of phasic and tonic thermal pain stimuli had to be determined in a preliminary experiment (Exp. 1). A quadratic relationship, strong enough to permit prediction of the phasic stimulus temperatures for the "signal" and "no-signal" classes in Exp. 2 from the tonic pain threshold measurement, was found.

For Exp. 2, two hypotheses were formulated (see Introduction): (a) Adjusting the boundary (cut-off point) between "signal/pain" and "no-signal/no-pain" to the current pain threshold should keep the SDT parameters stable when the absolute strength of pain perception varies. Variations of the sensation level were demonstrated, as was to be expected for repeated pain stimulation over a longer period (6). They appeared as a monotonic trend to higher pain threshold values over the session, representing a long-term adaptation. The group averages for the SDT parameters (discrimination ability and response bias) remained stable with this procedure—as Hypothesis 1 required. Different variations were found in some individual cases—especially for discrimination ability.

(b) The SDT parameters obtained under this procedure should reflect psychological treatments—in this case, induction of anxiety by instruction. A general effect of the instruction on discrimination ability for the anxiety increasing and decreasing instructions was demonstrated. However, the discrimination ability varied independently of the kind of instruction. Nor was the direction of change uniform, but differed from case to case. Specific effects of the two instructions could not be demonstrated; this is due also to the preexisting differences between the instruction groups. The results of this study of the effects of anxiety increasing and decreasing manipulation on SDT parameters agree with the mixed results of previous research, which did not demonstrate unambiguous effects of anxiety manipulations on discrimination ability and response bias, either (5, 11, 15, 18).

The results of this attempt to define "signal/pain" and "no-signal/no-pain" psychophysically, and subject them to an SDT analysis, counter some arguments against SDT methods in pain research (14). This applies in particular to Rollman's objection that SDT procedures are not able to deal with some relevant aspects of pain experience. The two-stage procedure tried out here provided both measures for the strength of the pain experienced (classical threshold concept) and indicators of the discrimination between pain and no pain. This therefore makes it possible to study absolute and relative characteristics of the pain experience together. However, the SDT parameters must be interpreted differently with this approach. The discrimination ability indicates not only how sharply physical variables—in this case temperatures—are differentiated sensorily, but also how well psychological states—in this case "pain" and "no pain"—can be distinguished. Thus the detection task also refers to the primary sensations. And so the response bias not only indicates from what temperature on pain is reported but also to what extent the reflection of the states "pain" and "no pain" in the ratings is distorted. It was demonstrated that most of the subjects showed little or no response bias in their ratings. This study also showed that the SDT parameters are independent of the absolute strength of pain perception. This permits variables that influence the absolute and/or relative perception strength to be identified. That there is a need for this is shown by the large number of studies proving complex effects of psychological, physical, and biochemical treatments on pain perception (4). An anxiety induction was shown to have an isolated effect on discrimination ability when evaluated in this respect. But initial differences between the instruction groups prevented a clear-cut interpretation. Since differing effects on the strength of absolute and relative pain perception are to be expected in this case, as well (15), further experiments using the method presented are justified.

The procedure demonstrated also shortens the long series of stimuli otherwise required in SDT procedures, by selection of the critical stimulus values, thus increasing their usefulness. Further improvements are desirable, especially in determining the "signal/pain" and "no-signal/no-pain" classes.

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Accepted April 20, 1989.