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Effects of voluntary changes in breathing frequency on respiratory comfort

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Abstract

Previous experiments on voluntary breathing have suggested that spontaneous breathing is partly determined by the minimization of respiratory sensations. However, during instructed breathing, respiratory sensations may be confounded with difficulty in achieving the prescribed pattern. In the present experiment, we tested the hypothesis that the subjective assessment of respiratory comfort and the difficulty in following breathing instructions are closely related. A total of 15 subjects adjusted breathing frequency to prescribed values ranging from 40 to 250% of individual spontaneous levels. Then, they scored the difficulty of this task and the discomfort associated with the target frequency. Difficulty scores sharply increased above 100% (spontaneous level) and discomfort scores displayed a similar shape. A significant positive correlation between discomfort and difficulty was found, thus suggesting a possible influence of the difficulty to follow ventilatory instructions on respiratory sensation scores. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

It has been suggested that the control of breathing in awake subjects is in part determined by the minimization of respiratory sensations (Chonan et al., 1990; Kikuchi et al., 1991). This assumption was based on several experiments in which the subjects voluntarily modified their breathing pattern while P_{CO_2} was artificially maintained at a constant level. For example, the subjects were asked to maintain target ventilation levels ranging from 22 to 108 l/min while the end-tidal P_{CO_2} was maintained at a constant level of 50 Torr by adding CO_2 to the inspired gas. For each level of ventilation, the subjects rated the sensation of respiratory discomfort using the Borg scale. The plot of these scores against the levels of ventilation displayed a V-shape, with the lowest score corresponding to the spontaneous level of ventilation. In another experiment, the subjects were asked to maintain target breathing frequencies ranging from 40 to 250% of spontaneous values. Again, the plot of dyspnea scores versus frequency displayed a V-shape reaching its minimum at spontaneous frequency. The authors inferred from these observations that the minimization of respiratory sensations may be one of the optimization principles which govern the adjustment of breathing pattern in normal conditions.

The present study addresses the possible influence of the difficulty of the ventilatory task on the scores of respiratory discomfort. The voluntary control of breathing in accordance with given instructions (adjusting frequency, tidal volume or ventilation to target values, tracking a preregistered signal etc.) shares certain characteristics with most sensori-motor tasks (Gallego et al., 1986, 1991; Gallego and Perruchet, 1991; Blanc-Gras et al., 1994). In particular, the attention load and the mismatch between the target and the actual pattern generate a subjective feeling of difficulty. This raises the problem of the possible influence of these feeling of difficulty on discomfort scores. According to Chonan et al. (1990) and Oku et al. (1996), voluntary control of breathing may act as a distractor of respiratory sensations. Under this hypothesis, one may logically anticipate that the more difficult the ventilatory task, the more distracting this task, and the more distracting the task is, the lower the discomfort scores. Therefore, discomfort and difficulty would be expected to be negatively correlated.

However, an alternative hypothesis is that during voluntary breathing, the feeling of task difficulty aggravates respiratory discomfort. If so, discomfort and difficulty would be expected to be positively correlated. This possible influence of task difficulty on respiratory discomfort scores is crucial to the interpretation of respiratory sensation scores during instructed breathing. Contrary to Chonan et al.'s (Chonan et al., 1990) contention that the V-shaped pattern of respiratory sensations reflects a general principle of optimization, it may be simply posited that this result was due to the influence of task difficulty; the larger the deviation from spontaneous pattern, the more difficult the control; and the more difficult the control, the higher the estimation of respiratory discomfort.

Because the sensation of difficulty is inherent to the artificial laboratory conditions, the pattern of changes in respiratory sensations should not be extended to natural situations in which breathing is automatically driven. Consequently, the posited role of respiratory sensations in ventilatory control during spontaneous breathing would be strongly questioned.

In view of this, we carried out an experiment in which the subjects adjusted breathing frequency (f) to prescribed values above and below their individual spontaneous resting value. This experiment was not a replication of the previous studies by Chonan et al. (1990). We did not use the same descriptors for respiratory sensation, the subjects of the present study received no CO_2 stimulus and their breathing pattern was voluntarily changed around the spontaneous resting level. We focused on f because it is the easiest breathing variable to voluntarily control, to measure with non-invasive devices, and also because the control of breathing frequency is omnipresent in rehabilitation contexts or sports practice. We asked the subjects to independently score the subjective difficulty of adjusting breathing frequency to the prescribed value and the respiratory discomfort associated with this new pattern. Under the hypothesis that respiratory discomfort is influenced by the difficulty of achieving this control, a significant correlation should be expected between the two scores.

2. Methods

2.1. Subjects

A total of 15 athletes (mean ± S.D. age: 22 ± 2 years) volunteered for one session. All gave informed consent for this experiment. All were unaware of the purpose of the experiment, and none had previous exposure to ventilatory tasks.

2.2. Apparatus

A respiratory inductive plethysmograph (Respitrace Plus, Non-Invasive-Monitoring-Systems Miami Beach, FL) was used for ventilatory measurements. The coils of the Respitrace were placed on the chest above the nipple line and on the abdomen at umbilical level. Because we were interested in ventilatory changes from baseline, we used the Qualitative Diagnostic Calibration method (Sackner et al., 1989; Sartène et al., 1993) without quantitative calibration. The signals from the Respitrace were processed by a computer (Software Respi-Events, NIMS) to produce breathing frequency (f), and tidal volume (V_T). This software allowed the on-line display of f (in breath/min) and V_T on a breath-by-breath basis. V_T and mean ventilation (calculated as the $f \times V_T$ product) were expressed as percentages of baseline levels. A breath was identified if V_T was larger than 25% of baseline V_T. This threshold corresponded to the standard approximation of anatomic deadspace. No other criteria were used.

2.3. Procedure

The subjects were seated facing the computer screen displaying the respiratory signals, with arms resting on their thighs, their legs relaxed, and their feet on the floor. The subjects remained seated throughout the session and the calibration of the inductive plethysmograph was performed in this position. The subjects were asked to refrain from moving throughout the session. After the 5 min period of calibration, spontaneous breathing was recorded again for 5 min to determine the baseline level off. Then, the individual values of the seven targets for f were determined. These targets corresponded to 40, 60, 80, 100, 150, 200 and 250%, respectively of individual spontaneous f-values at rest. Then, the subjects were trained to adjust their f-values to these targets by using visual feedback on this variable. This preliminary training lasted 10 min. The two scores were explained to the subjects. Respiratory discomfort was defined as the feeling of well-being corresponding to each new pattern. The difficulty scores concerned the task of adjusting breathing frequency to the target value displayed on the computer screen. Then, each target was verbally announced by the experimenter in a randomized order, and the subjects were asked to adjust their f-value to these target values for 2 min by using visual feedback. After completing each trial, the subjects estimated the respiratory discomfort on a six-point scale, ranging from ‘very comfortable’, score 1, to ‘very uncomfortable’, score 6. Then, they estimated the difficulty of the adjustment on another six-point scale ranging from ‘very easy’, score 1, to ‘very difficult’, score 6. The order of the two scorings was the same for each target in order to avoid any confusion between them. No comment was given during or after each trial, and in particular, no cue was given on how the values of the targets compared with the spontaneous level. Each trial was followed by a rest period of 90 s.

2.4. Data analysis

The accuracy of the adjustment off to prescribed values was assessed by two performance indices: the percentage deviation from the target calculated as: $100 \times (\text{actual}\, f - \text{target}\, f)/\text{target}\, f$, (referred to as relative error) and by the absolute value of this index (referred to as absolute error). Difficulty scores, discomfort scores, and breathing variables were analyzed separately using analyses of variance (Superanova Software, Abacus Concepts, Berkeley, CA) with f (seven levels) as a repeated measures factor. To take account of the heterogeneous correlations among the repeated measurements with more than two degrees of freedom, we adjusted the degrees of freedom using the Huynh–Feldt epsilon factor. Within-subject main effects and interactions are presented along with p-values based on these adjusted degrees of freedom (Crowder and Hand, 1991). In addition, we performed correlation analyses between subjective scores (Statwiew 4.01 software, Abacus Concepts, Berkeley, CA). We used Fisher’s r to z transformations to determine whether the individual correlations between the variables under study were significant. All the tests on correlation coefficients were done using this transformation.

3. Results

3.1. Performance in the ventilatory task

Spontaneous levels of *f* ranged from eight to twenty breaths/min (mean ± S.D. = 14.13 ± 2.8 breaths/min). The target-*f* were calculated as 40, 60, 80, 100, 150, 200 and 250% of these individual spontaneous *f*-levels. The mean target-*f* ranged linearly from 5.6 ± 1.2 breaths/min (40% baseline) to 35.4 ± 7.0 breaths/min (250% baseline). The plots of actual versus target *f*-values revealed a high level of accuracy in the ventilatory tasks (Fig. 1). This accuracy was confirmed by the analysis of performance indices (Fig. 2). The largest percentage error was obtained for the smaller *f*-target. However, absolute percentage error remained below 15% on average for the whole group (Fig. 2).

3.2. Estimated task difficulty

The score of subjective difficulty varied as a function of the target-*f* ($F_{6,84} = 12.95$, $p < 0.001$, Fig. 3). Above the spontaneous level (100, 150, 200, 250%), the difficulty scores displayed a significant increasing trend ($F_{3,42} = 20.01$, $p < 0.0001$). On the other hand, below the spontaneous level (40, 60, 80 and 100%), the estimated difficulty scores were not significantly different ($F < 1$).

Individual analyses showed that relative error and absolute error poorly correlated with the subjective difficulty scores. In fact, the correlation between estimated difficulty and relative error was significant in one subject only. Correlation between estimated difficulty and absolute error was also significant in one subject (different from the previous one). Mean correlation between error scores and estimated difficulty for the whole group were not significantly different from zero. In contrast, the subjective difficulty score seemed to correlate with the variability off, indexed by

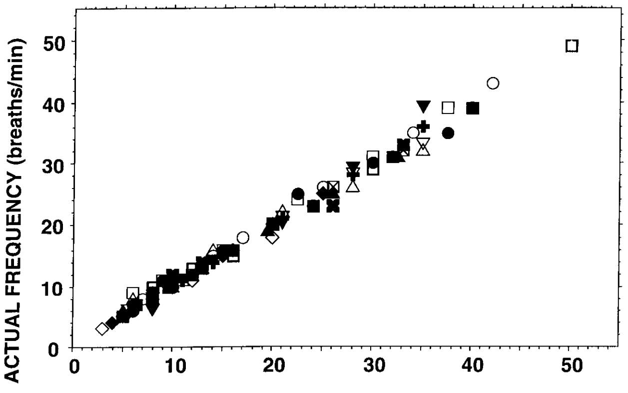

Fig. 1. Relationship between target and actual breathing frequency. Each subject ($n = 16$) is represented by a symbol.

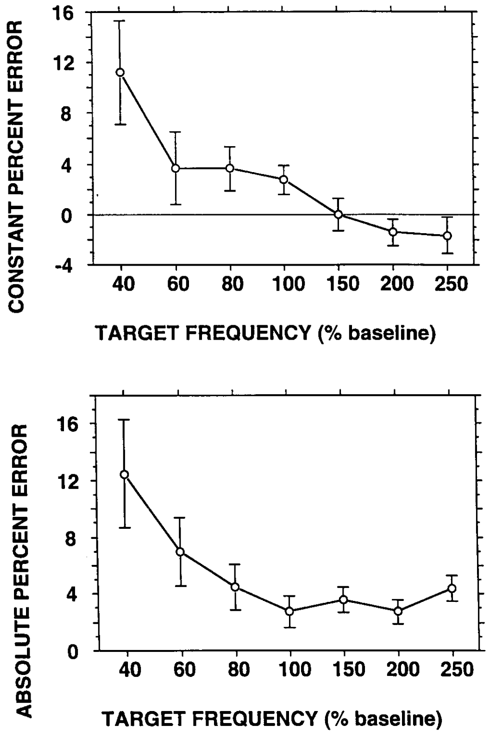

Fig. 2. Performance scores for each target-*f*. Constant percentage error is the mean percentage deviation from the target over each test. Absolute percentage error is the absolute value of the percentage deviation from the target. Values are mean ± S.E.M. ($n = 16$).

its variation coefficient. A significant correlation ($p < 0.05$) between the estimated difficulty and the coefficient of variation off was found in six subjects ($p < 0.10$ in four more subjects). A one sample *t*-test on the whole sample of subjects rejected the hypothesis that the mean correlation was zero ($t_{14} = 4.75$, $p < 0.0003$).

3.3. Respiratory discomfort

The plot of respiratory discomfort scores displayed a convex shape, with a minimum reached for the spontaneous level (Fig. 3). This pattern was similar to the one observed for estimated difficulty. The main effect for target-*f* was highly significant ($F_{6,84} = 13.68$, $p < 0.0001$). This was mainly due to the increase in difficulty scores for *f*-targets above 100%. A partial ANOVA on the 4 target levels ranging from 100 to 250% yielded a significant main effect for target ($F_{3,42} = 48.81$, $p < 0.0001$). In contrast, a partial ANOVA on the levels 40 to 100% revealed a non significant main effect for target ($p = 0.11$). Partial comparisons revealed that scores corresponding to 100% spontaneous level were not significantly different from scores for 80 and 60%, and only marginally lower than scores for 40% ($F_{1,14} = 3.89$, $p < 0.687$).

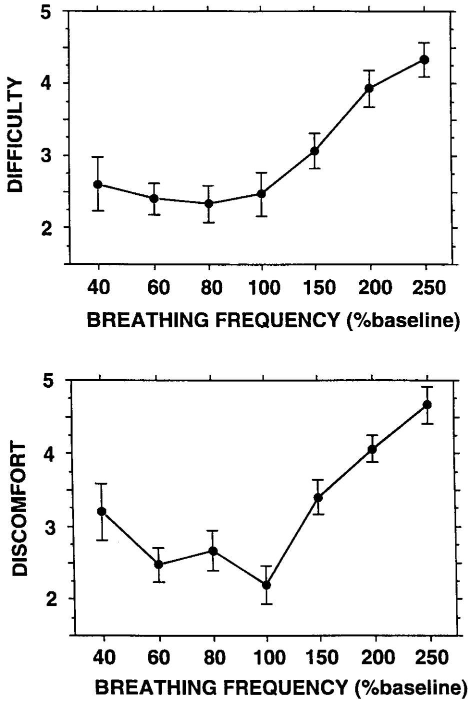

Fig. 3. Effects of voluntary changes in breathing frequency on difficulty and discomfort scores. Values are mean ± S.E.M. ($n = 16$). The spontaneous value of breathing frequency corresponded to 100% baseline.

The individual regression plots between difficulty and discomfort are shown in Fig. 4. We observed a significant correlation in seven subjects out of the sample of 15. The correlation coefficients failed to reach significance ($p < 0.10$) in two more subjects. A one-sample t-test on the whole sample of subjects rejected the hypothe-

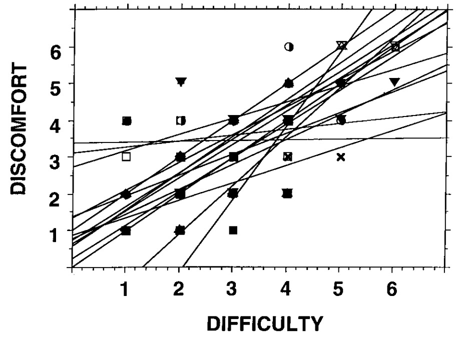

Fig. 4. Individual regression lines between difficulty and discomfort scores. Each subject is represented by a symbol. (See text for the statistical analyses).

sis that the mean correlation was zero ($t_{14} = 7.80$, $p < 0.0001$). Then, the entire sample of subjects was split into those who displayed a significant correlation between discomfort and difficulty and those who did not. We did not observe any significant difference in any of the above dependent variables. This suggested that the lack of correlation in those subjects was a consequence of the greater variability in intra-individual data, rather than a discriminative characteristic. Taken together, these data suggested a strong correlation between difficulty and discomfort scores.

The comparison between discomfort and difficulty scores was further examined by studying the difference between them: (difficulty score-discomfort score). A one-way ANOVA showed that the difference was not significantly influenced by the target-f. A paired t-test on the scores of difficulty and discomfort averaged over the seven targets failed to show any significant difference ($t_{14} = 1.43$, $p < 0.17$, N.S.).

3.4. Breathing variables

Finally, we investigated the possible relationships between the subjective scores (discomfort and difficulty) and breathing variables (other than frequency). Voluntary adjustment off-values to target-f caused spontaneous changes in V_T. Ventilation increased from $87 \pm 37\%$ (for the lowest f-value) to $187 \pm 42\%$ (for the highest f-value). Alveolar ventilation was roughly estimated using the conventional approximation of dead volume as 25% of resting V_T. Using this approximation, alveolar ventilation ranged from 75 ± 35 to $125 \pm 41\%$ of baseline, i.e. $\pm 25\%$ around baseline. Ventilation and the estimated alveolar ventilation were not significantly correlated with respiratory discomfort or difficulty.

4. Discussion

The aim of this study was to examine to what extent respiratory sensations during instructed breathing may be influenced by the difficulty of adjusting breathing pattern to the prescribed values. We observed that discomfort and difficulty scores were positively correlated and displayed similar patterns of variations as a function of the target-frequency. This result does not support the hypothesis that the psychomotor task of controlling breathing pattern acts as a distractor of respiratory sensations: if so, then the more difficult the task, the more distracting the ventilatory task would be, and the lower respiratory discomfort would be. This would lead to a negative correlation, contrary to the present results. Our contention that the distractor effect is not determinant is in line with previous observations that increasing the attentional load by asking the subjects to perform manual copying of ventilatory tracings did not significantly affect breathlessness scores (Adams et al., 1985).

For both variables, the target-frequency corresponding to the spontaneous level corresponded to the minimal discomfort scores. This confirms Chonan et al.'s data (Chonan et al., 1990), despite important procedural differences between the two studies. However, the similarity between difficulty and discomfort scores suggested that the subjective experience of difficulty in controlling breathing may strongly have influenced discomfort scores. Arguably, the more familiar frequency—i.e. the spontaneous value—corresponded to the easiest frequency, and by consequence, to the lowest discomfort. This contrasts with Chonan et al's interpretation that the requirement to breathe in prescribed patterns did not appreciably affect respiratory sensations, and that the V-shaped pattern of respiratory sensations reflected a general optimization principle in the control of breathing.

However, the results reported by Chonan et al. (1990) are in clear contrast with those reported by Adams et al. (1985). These latter authors asked the subjects to voluntarily copy their breathing pattern previously recorded during an oscillatory hypercapnic stimulation. Dyspnea scores did not display any change during these voluntary changes in breathing pattern. An important difference between Adams et al. (1985) and Chonan et al. (1990) studies was the descriptors used to assess respiratory sensations. Adams et al. (1985) asked the subjects to 'quantify their sensation of breathlessness by relating to their common experience of that feeling of an uncomfortable need to breathe'. These authors found that the voluntary changes in minute ventilation were not associated with changes in breathlessness scores. Chonan et al. (1990) asked the subjects to rate 'the sensation of difficulty in breathing' without giving them further clarification, and without asking them to distinguish between the different dimensions of the respiratory sensation. These authors observed significant changes in these scores. In a subsequent discussion of conflicting data from analogous experiments, Altose et al., (1988) noted that these two different descriptors may lead to opposite results. Recently, Jones and Wilson (1996) argued that the term 'need' used by Adams et al. (1985) implies a necessity or compulsion to change breathing. This action is, at least to some extent, independent to the subject's will whereas, 'difficulty' implies the subject's effort. This would establish a clear difference between these two subjective experiences, in keeping with the general view that different terms may tap different components of respiratory sensations (Simon et al., 1990; Elliott et al., 1991). In addition, the influence of the terminology used (difficulty vs. breathlessness) may have been further aggravated by the fact that the tasks designed by Adams et al. (1985) and by Chonan et al. (1990) may have yielded different levels of effort. In Chonan et al.'s study (1990), the task of breathing at the frequency set by a metronome while maintaining a constant volume and a constant end expiratory volume was certainly demanding. In contrast, Adams et al. (1985) used a simple tracking task consisting of copying a ventilatory tracing by using visual feedback. All the subjects were able to perform this task without difficulty. It may be that discomfort scores were not influenced by task difficulty, and indeed these scores did not vary during voluntary changes in ventilation.

One possible limitation of the present data is that the pattern of variation of subjective scores reflected the specific conditions in which the subjects controlled breathing. In particular, it is likely that the sensitivity of the visual feedback influenced the feeling of difficulty of the task. Furthermore, the fact that the subjects achieved voluntary breathing by using visual feedback prompted them to perform short-term corrections of breathing pattern. This has certainly increased the variability of breathing pattern, and possibly influenced the feeling of discomfort, as suggested by the positive correlation between the difficulty scores and the variability of breathing frequency. Arguably, different experimental conditions would have led to qualitatively different results. In a earlier experiment on voluntary control of breath patterns (Blanc-Gras et al., 1994), the subjects displayed better performance for the large breaths (large amplitude and duration) than for the small breaths (small amplitude and duration). These previous observations contradict the present one that performance was better for high frequencies than low frequencies. This difference may be explained by a procedural difference between the two studies. In Blanc-Gras et al.'s experiment (1994) the subjects adjusted the entire breath shape to a target shape. This was basically a tracking task, in which long and large breaths were easier to track than rapid and short breaths. In contrast, in the present study, the control of breathing frequency was fundamentally a time production task, and it is known that small durations are easier to produce than long durations (Schmidt, 1988). This suggests that performance and difficulty data may be highly dependent on the specific nature of the ventilatory task and should not be generalized to all situations of voluntary control of breathing. However, this limitation does not detract from the general outcome of the experiment: whatever the nature of voluntary control, different patterns may yield different feelings of difficulty, which in turn differently influence respiratory sensations.

Performance indices poorly correlated with subjective difficulty scores. This was probably due to the general fact that actual performance does not necessarily reflect the mental effort required to complete the task correctly. In the present task, the subjects achieved high levels of accuracy, especially above the spontaneous level. Performance was nearly constant above spontaneous-*f*, but this performance was possibly not achieved with the same feeling of difficulty. In contrast, the subjective scores of difficulty were positively correlated with the variability of breathing frequency. Variability reflected the number and magnitude of self-corrections to adjust actual frequency to target-frequency, and it was therefore a good indication of the mental effort required by the task.

Respiratory scores are the end-point of numerous sensory and cognitive processes, especially at the final stage which consists of assessing the respiratory sensation with respect to memorized reference levels. The feeling of difficulty may be one of the cognitive processes which shapes respiratory sensations. Although they are a priori distinct, it is difficult to decide whether discomfort and difficulty are dissociable subjective experiences during instructed breathing, despite the fact that the pre-test verbal instructions clearly distinguished between the two notions. We may speculate that difficulty was interpreted in terms of the ability to achieve an accurate adjustment to the prescribed frequency, which may be assimilated to a sensori-motor skill. The subjects of the present experiment were all undergraduate students in sports education, and therefore highly familiarized with this notion. How respiratory discomfort was construed is less clear. It was possibly interpreted in terms of the amount of respiratory muscle activity and the different relaxed psychological states which are thought to be associated with low breathing frequency. Whether discomfort is a component of respiratory sensation during instructed breathing or an independent factor is unclear. However, this difficulty does not detract from our contention that respiratory discomfort during instructed breathing reflects the task difficulty, and therefore cannot be directly extended to spontaneous control of breathing.

The positive correlation between discomfort and difficulty is in line with the hypothesis that during instructed breathing, respiratory sensations are influenced by task difficulty, thus providing an inaccurate image of what actually occurs during spontaneous breathing. However, it may be objected that the correlation between difficulty and discomfort scores does not necessarily reflect a causal relationship. Both scores may have exhibited a similar pattern of variation for independent reasons. Specifically, the V-shaped pattern of difficulty may be caused by the increasing difficulty of adjusting breathing pattern as the target departs from the spontaneous pattern, while the V-shaped pattern of respiratory discomfort may reflect the optimal control of breathing suggested by Chonan et al. (1990). This cannot be totally discarded on the basis of the present data. However, our interpretation that discomfort was influenced by task difficulty has endowed certain advantages. Firstly, it is more parsimonious than inferring the existence of a general optimization principle. Secondly, as noted above, the different levels of difficulty of the ventilatory tasks designed by previous authors may explain their conflicting results. One possible way to clarify this issue and to control for the possible confounding influence of difficulty may be to provide sufficient training in the ventilatory task. However, it has been shown that the attentional load created by a simple control of inspiratory duration remains high even after extended training (Gallego and Perruchet, 1991). Another possibility would be to clearly specify the exact dimension of respiratory sensations which the subjects are asked to score by providing appropriate instructions. The clear determination of what the subjects actually score is an absolute prerequisite for the inference of general laws on respiratory sensations on the basis of data obtained from voluntary breathing.

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