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PERCEPTION OF LUNG VOLUME IN NORMAL HUMAN SUBJECTS

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PERCEPTION OF LUNG VOLUME IN NORMAL HUMAN SUBJECTS

by

Brenda Lee Plassman

A Dissertation Submitted to the Faculty of the

DEPARTMENT OF PSYCHOLOGY

In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY

In the Graduate College

THE UNIVERSITY OF ARIZONA

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THE UNIVERSITY OF ARIZONA
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As members of the Final Examination Committee, we certify that we have read

the dissertation prepared by Brenda L. Plassman

entitled Perception of Lung Volume in Normal Human Subjects

and recommend that it be accepted as fulfilling the dissertation requirement

for the Degree of Doctor of Philosophy.

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Paul Consroe	5/21/86 Date
James L. Boren	5/21/86 Date
	5/21/86 Date

Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copy of the dissertation to the Graduate College.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

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SIGNED Brenda K. Klassman

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A part of each of you is this work and my future.

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ABSTRACT

Ability to duplicate an inspired volume level was studied in five healthy males using the psychophysical method of reproduction. Three conditions were evaluated in order to investigate the perceptual cues used for obtaining a specific inspired volume. Conditions were designed to progressively remove cues that might affect the subject's ability to duplicate an inspired lung volume. In each, the subject performed a standard inspiration, spanning from end expiratory position to 35% of inspiratory capacity. Conditions were varied as follows: 1) subjects were instructed to perform both the standard and test (reproduction) inspirations at the same flow rate and beginning at the same lung volume, 2) subjects were instructed to make the flow rate of the test inspiration faster or slower from standard inspiration, and 3) subjects were instructed to begin the test inspiration at a different lung volume than the standard inspirations. The group mean error for all conditions combined for the first day on which each condition was performed was 173 ml, compared to a mean error of 133 ml. Reduction in errors for all conditions from the first to the second day of performance indicates a practice effect. There was no significant difference in errors between conditions. These results indicate the final lung volume, which remained constant for all three conditions, is important for accurate duplication of inspired volume. This finding for learned respiratory movements is comparable to that found by other researchers for skilled limb movements.

INTRODUCTION

Skilled respiratory movements appear to require the ability to accurately perceive and control lung volume. Humans exhibit very precise control of lung volume changes in many everyday tasks such as speaking and singing (Wyke, 1974). However, the proprioceptive cues persons use to perform these and less well practiced movements are unclear. The list of possible cues include rate of lung volume change, extent of the volume change, and final lung volume level; any number of afferent mechanisms may provide these cues. The lack of information available on the proprioceptive cues used to make precise changes in lung volume suggested a need for more work in this area.

A similar problem has been addressed regarding the perception and control of limb movements. Several researchers (for reviews see McCloskey, 1978; Russell, 1976) have shown that humans have very accurate kinesthetic abilities for limb position detection. However, the methods used in many of these studies have made it difficult to determine if detection of limb position is based on information about the starting position of the movement, distance of the movement, the act of the movement, or the discrete final position itself. They have also caused confusion in identifying the specific afferent mechanisms underlying position sense, as each of these cues may be subserved by different afferents. Martenuik and Roy (1972) attempted to isolate the information necessary for position sense by varying the distance of the movement. They showed that a given location can be reproduced even when the starting position differs from that of the initial movement and when the course of the movement is varied. This supported the contention that extent of movement is not essential to position sense. Like many of the previous researchers, Martenuik and Roy examined the accuracy of position sense within a few seconds after the movement was stopped, thus confounding the sensory cues associated with the act of movement with those present just at the final position. As McCloskey so aptly stated, "As every position is arrived at through a movement and every movement causes a change in position, it is difficult to devise a test of static position sense in which movement could not be implicated" (p. 806). In a recent study, however, Horch and his colleagues (1975) attempted to have subjects make judgments based solely on static position. The subjects relaxed their muscles and the knee joint was passively displaced 3-4° at a rate of less than 1° per minute, which is below the threshold for movement detection. The subjects reported no perceived movements. Nevertheless, they could detect the altered position and could direct an experimenter moving the other leg to a correct mátching position. In contrast to the work of Martenuik and Roy (1972), this study used a task which was different from most natural movements. Their aim was not only to judge position sense, but also to identify the receptors necessary for position detection. Therefore, there is evidence for the ability to obtain a given limb location regardless of the extent or rate of the movement; although receptors responsible for this are still unclear.

In spite of the large body of information available on limb position sense, few studies have addressed the issue of position sense with regard to skilled respiratory movements, specifically perception of changes in lung volume level. There are many differences between the two systems, making it unwise to directly apply the limb position findings to the respiratory system: 1)humans have less experience making conscious judgments about respiratory positions; 2) there is usually less visual feedback from the respiratory structures than from the limbs; 3) the respiratory system is controlled by two separate motor systems (the medulla and the forebrain); 4) the respiratory system has several functions (metabolic, postural, behavioral) which may affect position sense;

5) visceral, proprioceptive and exteroceptive afferents all probably play a role in controlling learned respiratory movements; and 6) the metabolic constraints (the need to get oxygen) of the respiratory system make it virtually impossible to measure a respiratory static position sense, by eliminating breathing movements.

Previous investigations have examined the ability of humans to discriminate lung volume changes. Some of these have used the psychophysical scaling methods of magnitude estimation and magnitude production (Halttunen, 1974; Bakers & Tenney, 1970; DiMarco, Wolfson, Gottfried, & Altose, 1982); others have also used a variation of the method of reproduction (Wolkove, Altose, Kelsen, Kondapalli, & Cherniack, 1981; Gliner, Folinsbee, & Horvath, 1981; Stubbing, Killian, & Campbell, 1981; Folinsbee, Gliner, & Horvath, 1983) by changing the mechanical conditions from the standard to the test breath. Several studies have demonstrated a sensitive lung volume detection mechanism, regardless of the psychophysical measures used. Bakers and Tenney found that many respiratory sensations fit the Stevens power function (Stevens, 1971). The exponent relating perception of inspired volume to the actual inspired volume during magnitude estimation and production experiments averaged 1.3, indicating a relatively sensitive system. Wolkove, et al. (1981) reported subjects could accurately detect lung volumes within 100 milliliters (ml) regardless of the size of the inspired volume. Gliner et al. (1981) found similar levels of accuracy for low lung volumes, but their data subscribed to Weber's law, in that the degree of error increased at higher lung volumes. The findings of DiMarco, et al. (1982) showed that normal subjects and quadriplegic patients can detect lung volume equally well, suggesting that inputs from the rib cage are not essential for this task.

Folinsbee, Gliner, and Horvath (1982) conducted the only previous study of inspired volume reproduction that has attempted to dissociate cues from extent of movement and final position. They had one condition in which final position and extent of movement cues were confounded and two other conditions in which subjects were forced to rely on either extent of movement or the final volume position. The rate of the movement was not controlled and the final position cue was only tested from one starting position, which happened to be a very low lung volume. Folinsbee et al. found subjects were less accurate in reproducing the final volume position on some of the volume ranges tested. Although values for just-noticeable differences were similar to those found in other studies when all cues were available.

As was the case with early limb position research, most respiratory studies of lung volume perception have confused the information about the movement required to attain a lung volume and information about how the final lung volume level was achieved. In most cases test trials began at resting end expiratory level or the endpoints of the vital capacity (residual volume or total lung capacity) providing a constant extent of movement and starting position cue. Second, the extent of the task training was unclear. This has been shown to be an important variable in psychophysical measurements (Woodworth & Schlosberg, 1954). Finally, in most of the previous studies, drift in the recording systems did not permit accurate measurement of lung volume level or the duration of several consecutive breaths.

Further investigation is needed to determine how accurately humans can duplicate an end tidal volume (end inspiratory lung volume), regardless of the movement by which it was attained. Evaluation of the sensitivity of the respiratory position sense will add to our understanding of the underlying afferent mechanisms for learned control of breathing. The present study examined the ability of humans to reproduce an end tidal volume when information about extent of movement, starting position of the movement and time duration of the movement were removed. The use of a whole body plethysmograph provided a means to measure lung volume consistently over extended periods of time.

METHODS

Subjects

The subjects were five adult males (ages 22-59) with no history of respiratory disease,smoking, or surgery involving any part of the respiratory mechanisms. They were of medium height and weight and could comfortably sit inside the body box. Four of the five subjects had previous training in experimental respiratory maneuvers and one of these participated in the planning of the present study.

Experimental Plan

Subjects were trained to reproduce a standard tidal volume (end expiratory volume to end inspiratory volume) with the use of visual cues. The difference (error) between the standard end tidal volume and the test (reproduction) end tidal volume was measured. The degree of error was obtained for three conditions: 1) when the subject was trained to inspire at the same flow rate for both the standard and test inspirations, 2) when the subject was trained to make the test inspiration flow rate faster or slower than the standard inspiration and 3) when the subject was trained to begin the standard and test inspirations at different lung volumes.

The first condition was designed to allow the subject to use information about the inspiratory time (flow rate), distance of the movement (extent of lung volume change), starting position of the movement, and the final lung volume level. In the second condition reliable cues for the distance of the movement, starting position of the movement, and the final lung volume level were available. Only final lung volume level cues were consistently available in the third condition.

Equipment and Procedures

A volume displacement whole body plethysmograph (body box) (Emerson Resp. Co.) and a Krogh spirometer were used to measure lung volume levels and changes (Mead, 1960). Figure 1 illustrates the experimental set-up. The subject breathed through a mouthpiece in the top of the body box and wore a noseclip to prevent exchange of air through the nasal passage. The air in the box displaced by the subject during inhalation flowed through connective tubing into the Krogh spirometer, providing a direct measure of lung volume change. A potentiometer (Spectrol, 310-9507) attached to the Krogh spirometer provided an electrical output of this change which was recorded on a DC

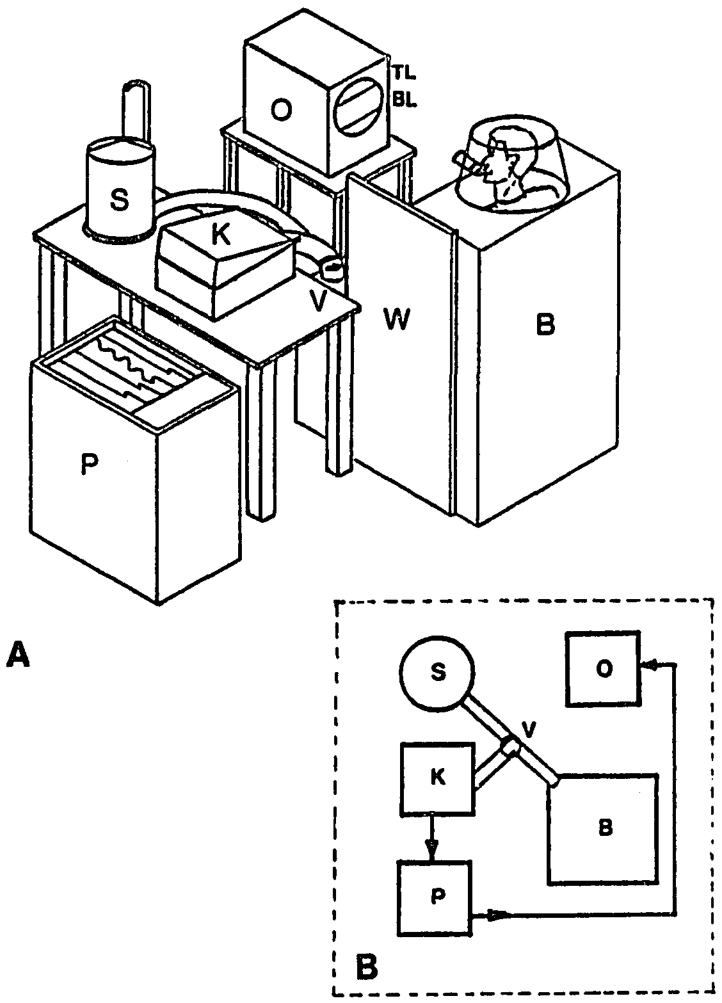

Fig. 1. Arrangement of apparatus. — A. Subject breathed through a mouthpiece while sitting in the closed body box (B). The air displaced by inhalation flowed into the Krogh spirometer (K) through a T-valve (V) and lung volume was recorded on the polygraph (P). Lung volume was also displayed on an oscilloscope (O) within the subject's view. Templates on the oscilloscope face showed how the subject's lung volume compared to the baseline (BL) and target line (TL). A wall (W) prohibited the subject from viewing the rest of the apparatus. A Bell spirometer (S) which could be connected to the Krogh spirometer through the T-valve was used to calibrate the other equipment. B. Schematic of equipment circuit. Abbreviations same as above.

channel of a Grass Instrument polygraph (Model 78B). The polygraph amplifier output was displayed on an oscilloscope (Tektronix, Inc., Type 533) visible to both the experimenter and subject. The Krogh spirometer and polygraph were placed out of the subject's view. A Bell spirometer (Collins, Inc.) was connected to the Krogh spirometer through a T-valve, allowing the Krogh spirometer to be periodically refilled without altering the volume in the body box. The Bell spirometer was also used to calibrate the Krogh spirometer, polygraph and oscilloscope. The body box coolant system was periodically adjusted by the experimenter to maintain a constant temperature inside the box to limit variations in volume due to temperature. The system drift rate was usually between 0-200 ml per minute and often fell within the lower end of that range. A two-way intercom system was used for subject-experimenter communications throughout the sessions.

The instrument settings for the three experimental conditions were as follows. The polygraph paper speed was 3 mm/sec. The amplifier (Grass 7 DAC) frequency limits were DC to 3 Hz (half-amplitude). The amplifier gain was adjusted so that a 1 mm deflection was equal to approximately a 50 ml volume. This permitted accurate error measurements to within 10-15 ml. The oscilloscope gain was set so that there was a deflection of 1 mm/30 ml.

During the Precision Task (see Experimental Protocol), two alterations were made in these settings. The gain on the oscilloscope was increased to 1 mm/10 ml and the half-amplitude high frequency limit on the polygraph amplifier was set a .5 Hz. These adjustments were made to provide the subject with very precise visual feedback on this task without interference from higher frequency fluctuations in lung volume.

Experimental Protocol

During the first of five sessions, the subject signed a consent form and answered a brief questionnaire concerning his general health (Appendix A). The subject was instructed that the purpose of the study was to determine how accurately persons perceive lung volume. He removed his shirt and loosened his pants waistband to prevent cues from restrictive clothing biasing his performance. The subject was then instructed to sit in the body box and breathe spontaneously through the mouthpiece. At the beginning of each session, the subject breathed naturally for 6-12 minutes until the temperature in the box stabilized. During this time, he was allowed to observe his lung volume changes on the oscilloscope in front of him.

The subject was given a self-paced practice session, lasting approximately 20-25 minutes, to familiarize himself with the experimental set-up and procedures. He practiced inspiring to a specific lung volume with visual feedback from the oscilloscope and then attempted to reproduce the tidal volume with progressively less visual feedback. He was instructed to attend to the body sensations present during breathing.

The Precision Task was also performed during the first session. The purpose of this task was to evaluate the performance of the respiratory motor system in obtaining a specific end tidal volume with more sensitive visual feedback. The subject was given continual visual feedback as he inspired to a specific lung volume as indicated by the template on the oscilloscope. Three trials were made at each of two lung volumes, 30% and 60% of inspiratory capacity. It was found that subjects could obtain a given lung volume within ±20 ml at both levels. These findings do not necessarily represent the limits of this motor system, as even more sensitive feedback may improve performance. However, this verified that any error measurements greater than ±20 ml on subsequent tasks were not attributable to limitations of neuromuscular control but rather to perceptual guidance of the movement.

At the end of the first session, the subject's vital capacity (VC) was measured. The greatest volume measured in three attempts was selected as the best estimate of VC. The VC's (in liters) for Subjects 1-5 were 6.05, 6.22, 4.60, 5.05, and 4.42, respectively. All of these were within the normal range for the subjects' height and weight.

The subject was given breathing exercises to practice in order to increase his awareness of respiratory structures and their sensations before coming to the next session. See Appendix B for the breathing exercise instructions given to the subject.

Experimental Tasks

The reproduction method. In the following sessions three conditions were studied using the method of reproduction (also called method of average error). This method was selected because 1) it is economical on subject time (i.e. a measurement is obtained every trial), and 2) the subject controls the stimulus, making it a fairly natural and easy task to learn (Guilford, 1936).

A test trial. The following procedures were the same for all of the conditions. When the subject was ready to begin a trial, he pressed the intercom button and then went to his resting level (end expiratory level). The experimenter adjusted the oscilloscope to the template baseline. Then the subject performed a standard inspiration. For standard inspirations, the subject was instructed to inspire at a relatively slow constant rate (determined by the subject) stopping at the target line displayed on the oscilloscope template. He was instructed to hold that lung volume level for a few seconds with his glottis open, attending to the sensations of the respiratory structures, before passively expiring. Although visual feedback was available for the entire standard inspiration, the subject was encouraged to close his eyes intermittently and attend to respiratory mechanism sensations once he reached the target level. This was done to lessen the subject's dependence on the visual feedback and increase his awareness of respiratory sensations. Following the standard inspiration, the subject closed his eyes and took 2-3 spontaneous breaths. To begin the test inspiration, the subject opened his eyes and brought his lung volume to the baseline (this controlled for any variations in the subject's actual resting level from the standard to test breath). Then he closed his eyes and attempted to reproduce the standard lung volume level. The experimenter covered the oscillscope screen during the test inspiration, preventing the subject from accidently obtaining visual feedback. A trial consisted of a standard inspiration, 2-3 spontaneous breaths, and a test inspiration; and usually lasted from 30-45 sec. The subject took 4-6 spontaneous breaths between each trial. Every 5-8 trials, the subject was given a rest period during which time he breathed off of the mouthpiece and was able to take a drink from a glass of water he had inside the box.

Experimental Conditions. Several practice trials were performed for each condition. During these trials the subject was also given visual feedback on his performance at the end of test inspirations. The three conditions and additional instructions were:

1. Time/Distance/Level (TDL): This condition made available cues for reproducing the end tidal volume from the inspiratory time, distance of the movement (inspiration), starting position of the movement, and final lung volume level. The subject was trained to perform the standard and test inspirations at the same flow rate. The absolute flow rate was not important. Trials were judged to be acceptable if there were not extreme differences between these two inspirations. The inspiratory time cue was only reliable when the standard and test inspiration were performed at the same flow rate. The emphasis is placed on the inspiratory

time rather than the flow rate because in pilot studies subjects reported attending to the timing of the inspiration. However, for ease of understanding later references to the inspiratory time and flow rate cues, their direct relationship should be noted.

2. Distance/Level: This condition made available reliable cues on the distance of the movement, starting position of the movement, and final lung volume level, but no consistent cues on the inspiratory time. The subject was trained to either increase or decrease the flow rate of the test inspiration as compared to the standard inspiration. The exact test inspiration flow rate presented was not important as long as the flow rate of the standard and test inspirations were noticeably different as monitored on the polygraph record.
3. Level: In this condition, only the final lung volume level cue was consistently available to the subject. The standard inspiration was performed as before, but on the test inspiration the subject was trained to begin at the baseline, then inspire or expire until he was instructed to stop. He held that lung volume for 1-2 seconds and then inspired

attempting to reproduce the standard lung volume level. The extent of the first inspiration or expiration was varied by the experimenter within ±50% of the distance between end expiratory level and the standard lung volume level.

For each condition, the standard end tidal volume was 35% of the subject's inspiratory capacity. Depending on the subject's inspiratory capacity this standard level ranged from .93 - 1.3 liters above end expiratory level. Slight variations in the standard level were due to random experimenter error in adjusting the end expiratory level to the baseline and subject error in obtaining the same standard level on repeated trials. However, as measurements were made on within-trial-differences between the standard and test levels, these slight variations did not affect the results. Figure 2 illustrates typical standard and test inspirations for all three conditions. In the Distance/Level and Level Conditions, the instructions on the type of modification (faster or slower, inspire or expire) were given during the spontaneous breaths between the standard and test inspirations. This was done to avoid biasing the subject before the standard inspiration and limit distractions during the test inspiration.

The protocol for the five sessions was as follows:

Session 1: 1) Familiarization with equipment training

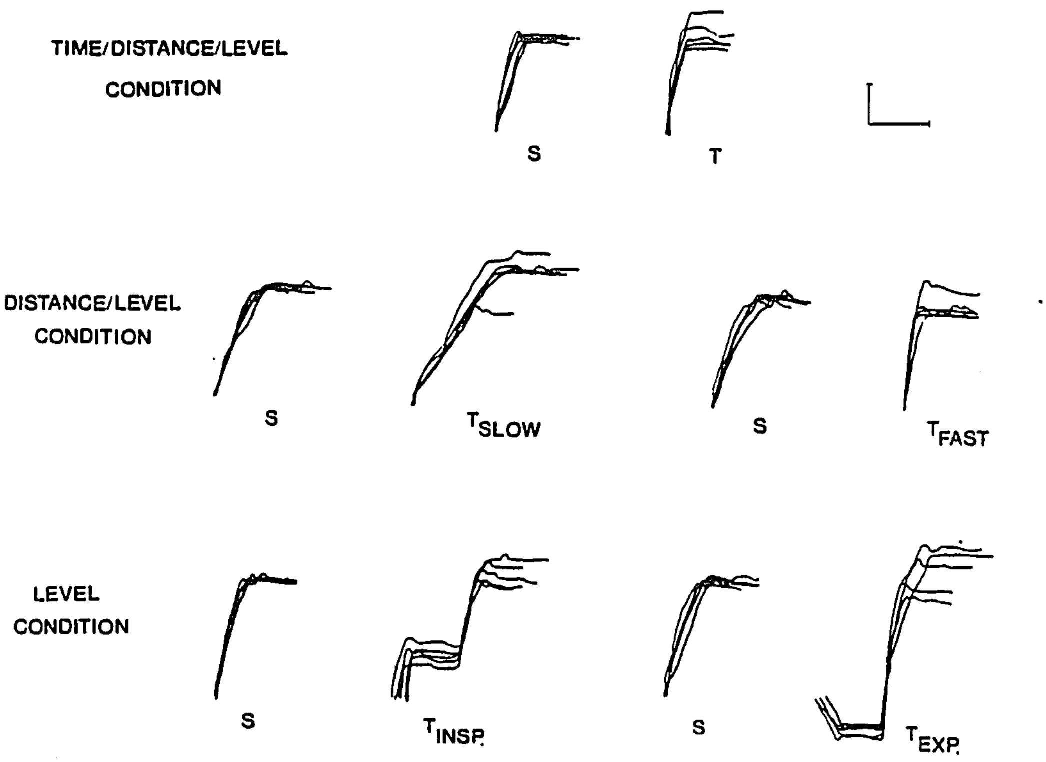

Fig. 2. Representative trials for all conditions for Subject 2. -- Five superimposed trials are shown for each condition. S - standard, T - test. Vertical calibrations equal 500 ml. Horizontal calibrations equal 5 sec. Differences in standard volume level are due to slight variations in experimenter adjustment of end expiratory level to the baseline and subject variations in obtaining standard level.

2) Precision Task

Session 2:
1) Practice trials for TDL Condition
2) 20 TDL Condition trials

Session 3:
1) 2 TDL Condition trials
2) 2 Distance/Level Condition trials - before practice
3) Practice trials for Distance/Level Condition
4) 20 Distance/Level Condition trials

Session 4:
1) 2 TDL Condition trials
2) 2 Level Condition trials - before practice
3) Practice trials for Level Condition
4) 20 Level Condition trials

Session 5:
1) 2 TDL Condition trials
2) Five practice trials for TDL Condition
3) 8 TDL Condition trials
4) Five practice trials for Distance/Level Condition
5) 8 Distance/Level Condition trials

6) Five practice trials for Level Condition
7) 8 Level Condition trials

To simplify later reference to the conditions, the following designations were used. The first time each condition was performed (i.e. Sessions 2-4) is referred to as Day 1 for the condition. Trials in Session 5 are labeled Day 2 for each condition.

At the end of each session, the subject was asked what cues he thought he used to reproduce the tidal volume. The subject was encouraged to be specific, but was given no prompting regarding possible proprioceptive cues.

At the beginning of Sessions 2-5, two TDL Condition trials were performed to re-familiarize the subject with the general procedures. The first two trials of the Distance/Level and Level Conditions were performed without training. This was done in an effort to identify the strategy the subject used to reproduce the standard end tidal volume, by evaluating the direction and extent of the errors on these trials. For example, if the subject was using rate of volume change on the TDL Condition, one would expect his first attempt on the fast trials of the Distance/Level Condition to be higher than the standard end tidal volume. In addition, an indication of the subject's accuracy without prior training or practice was obtained.

During Sessions 2-4, the criterion for the number of practice trials performed was: 1) ten trials or 2) at least two out of three consecutive trials with error measurements below 100 ml (for one subject on the Distance/Level Condition, it was two out of three consecutive trials below 150 ml). Generally, subjects completed 8-10 practice trials for each condition.

The purpose of Session 5 was to evaluate subject performance on the three conditions after previous completion of an equal number of trials in each condition. In an effort to estimate the order effects in Session 5, some subjects performed the conditions in the order given in the protocol and others performed them in the reverse order.

One subject (No. 5) performed Sessions 2-4 in the reverse order, therefore performing the Level Condition first and the TDL Condition third. This change in protocol was done for two reasons. First, this was the subject involved in planning the experiment and his previous knowledge of the conditions may have biased his task strategy. In addition, although pertinent statistical analyses could not be done on the data from one subject, observational information obtained from this subject's results provided insight into condition order effects.

Data Analysis

The error in end tidal volume reproduction was determined by the difference between the standard and test lung volume levels measured from the polygraph record. The measurement was taken from the last stable section of the standard and test inspirations. To prevent undue emphasis on a few extreme observations, any error which was at least 200 ml greater than the next smaller error score during any one session was not used. Under this rule, only two data points were eliminated for the entire experiment. In addition, any trial which was preceded by a high drift rate was excluded. This method was selected over others used to deal with outliers, such as winsorization, because important small data points were not sacrificed. The mean error (average or absolute error) was calculated as the sum of the error scores divided by the number of trials with the sign being disregarded. Standard errors of the means (SEMs) were calculated disregarding the sign of the errors. The constant or algebraic error was determined in a similar manner, except the sign of the error was included. To provide an index of variability and accuracy comparable to other studies, the difference limens or just-noticeable differences (jnd) were calculated as follows: .6745 x SD where SD was the standard deviation of a number of constant error scores for a subject (Woodworth & Schlosberg, 1954).

The jnd describes the amount of change of lung volume needed to perceive a difference.

The Wilcoxon matched-pairs signed-ranks test was conducted in order to evaluate within-subject differences between conditions. Two two-factor repeated measures analyses of variance (Condition by Day) were calculated using means and SEMs for four of the subjects. Post hoc comparisons between specific pairs of means were conducted using the Newman Keuls test. Due to changes in the order of presentation of the conditions for Subject 5, the data for this subject were not included in these analyses. Two single-factor repeated measures analyses of variance were performed using the means and SEM for comparing errors on the faster vs. slower trials in the Distance/Level Condition. The same analyses were done on data from Level Condition comparing the errors on the inspiratory vs. expiratory trials.

RESULTS

Comparison of Accuracy for the Three Conditions

The mean error values for all subjects for Day 1 were as follows: 155 ml for the TDL Condition, 201 ml for the Distance/Level Condition and 162 ml for the Level Condition. The mean error values for Day 2 were 123 ml for the TDL Condition, 159 ml for the Distance/Level Condition and 117 ml for the Level Condition. Individual subject means and SEMs for each of the conditions are given in Tables 1 and 2. A comparison of subject performance (within subject Wilcoxon Matched-Pair Sign-Ranks Test) for the three conditions showed that there were no significant differences between any two conditions for any subject on both Day 1 and Day 2.

The mean errors on Day 2 were significantly smaller than on Day 1 for all conditions combined ($\underline{F}$ (1, 18) = 5.66, $p < .0286$). However, there was no significant reduction in errors from Day 1 to Day 2 for any individual condition (Newman Keuls test). The group means for Subjects 1-4 for both days are shown in Fig. 3 (Subject 5's data were not included in these analyses, as explained in

Table 1. Mean error for all conditions on Day 1.

SUBJECT	CONDITION TIME/DISTANCE/ LEVEL	 DISTANCE/ LEVEL	 LEVEL
1	193 ±29 (38–425)	152 ±33 (0–476)	148 ±28 (0–455)
2	145 ±29 (0–441)	187 ±33 (0–511)	134 ±24 (0–409)
3	139 ±18 (0–318)	291 ±38 (0–655)	183 ±27 (0–350)
4	180 ±28 (0–476)	139 ±40 (0–619)	133 ±22 (13–316)
5	118 ±17 (13–275)	234 ±25 (0–417)	214 ±37 (0–513)
Group Average	155 ±24 (0–476)	201 ±34 (0–655)	162 ±28 (0–513)

All values given in ml. Each subject mean is based on 18–20 trials. Range ( ) and standard error of the mean ± are shown.

Table 2. Mean error for all conditions on Day 2.

SUBJECT	TIME/DISTANCE/ LEVEL	DISTANCE/ LEVEL	LEVEL
	CONDITION		
1	121 ±37 (0–318)	138 ±26 (11–227)	156 ±44 (0–364)
2	108 ±26 (11–261)	134 ±47 (34–443)	134 ±18 (80–227)
3	136 ±23 (35–256)	173 ±41 (0–302)	112 ±24 (0–233)
4	138 ±26 (46–227)	178 ±54 (11–432)	57 ±12 (11–114)
5	113 ±19 (50–200)	172 ±47 (38–413)	126 ±29 (0–250)
Group Average	123 ±26 (0–318)	159 ±43 (0–443)	117 ±25 (0–364)

All values given in ml. Each subject mean is based on 8 trials. Range ( ) and standard error of the mean ± are shown.

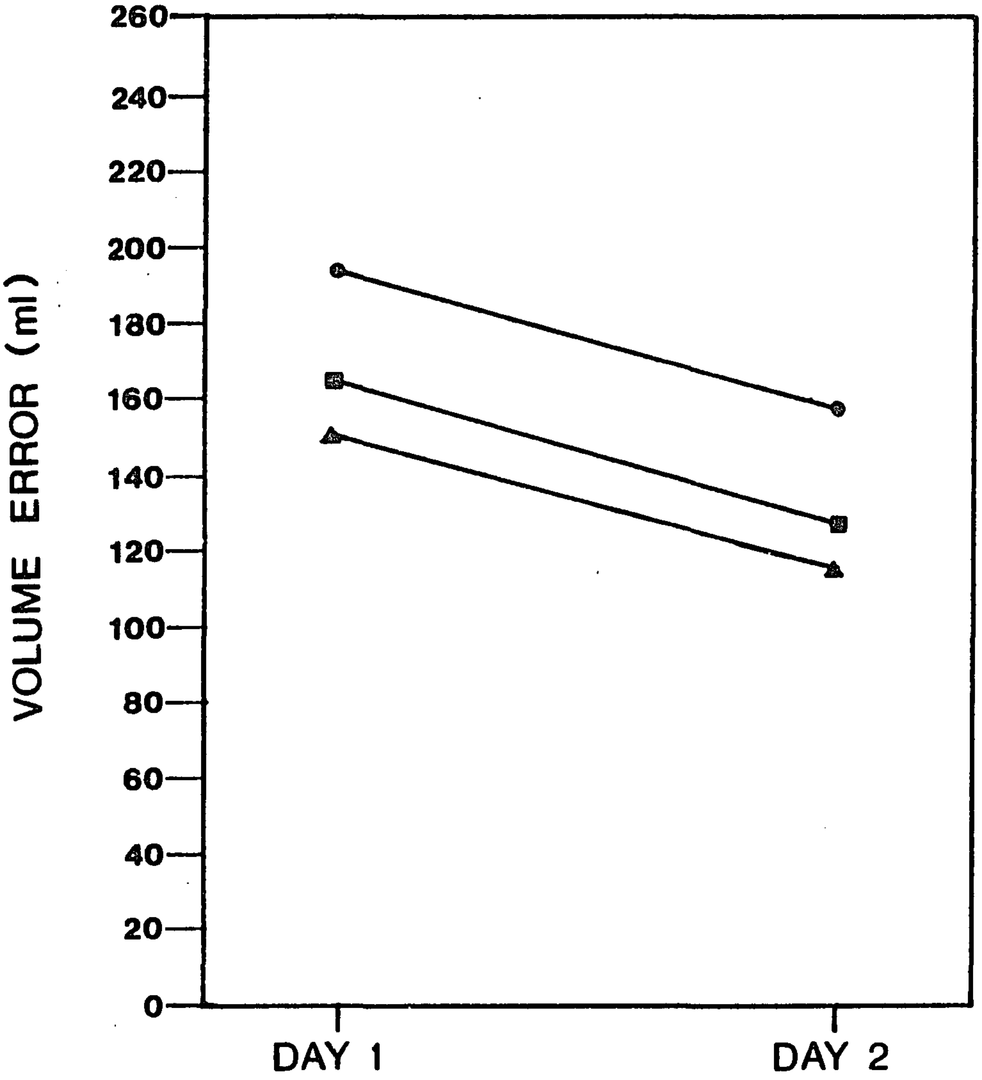

Fig. 3. Comparison of mean errors for all conditions. -- Means are based on data from Subjects 1-4. Time/Distance/Level Condition (■), Distance/Level Condition (●), Level Condition (▲).

previous section). No significant differences in the size of the errors were found between the three conditions. In addition, no interaction was present between the day and condition factors. The SEMs were found to be significantly different for the conditions (*F* (2, 18) = 7.04, $p < .0055$). Post hoc comparisons showed that there were no significant differences between specific pairs of means (Newman Keuls test). The average SEMs for Subjects 1-4 are given in Fig. 4.

The jnds for all subjects and conditions ranged from 23.5 ml to 125.6 ml. Table 3 gives the jnds for each condition, subject, and day.

For all conditions, 100% of the errors were below 655 ml. However, for all subjects 25% of the error values fell below 143 ml and on some trials an error value of 0 ml was reported. Table 4 provides the quartile values for all subjects and conditions combined for Day 1 and Day 2. Figure 5 illustrates a typical distribution of all of the trials for one subject.

Within Condition Comparisons

For the Distance/Level Condition, when subjects were forced to vary the rate of test inspirations, no significant difference was found in mean errors or variability (SEM) for those trials on which the test

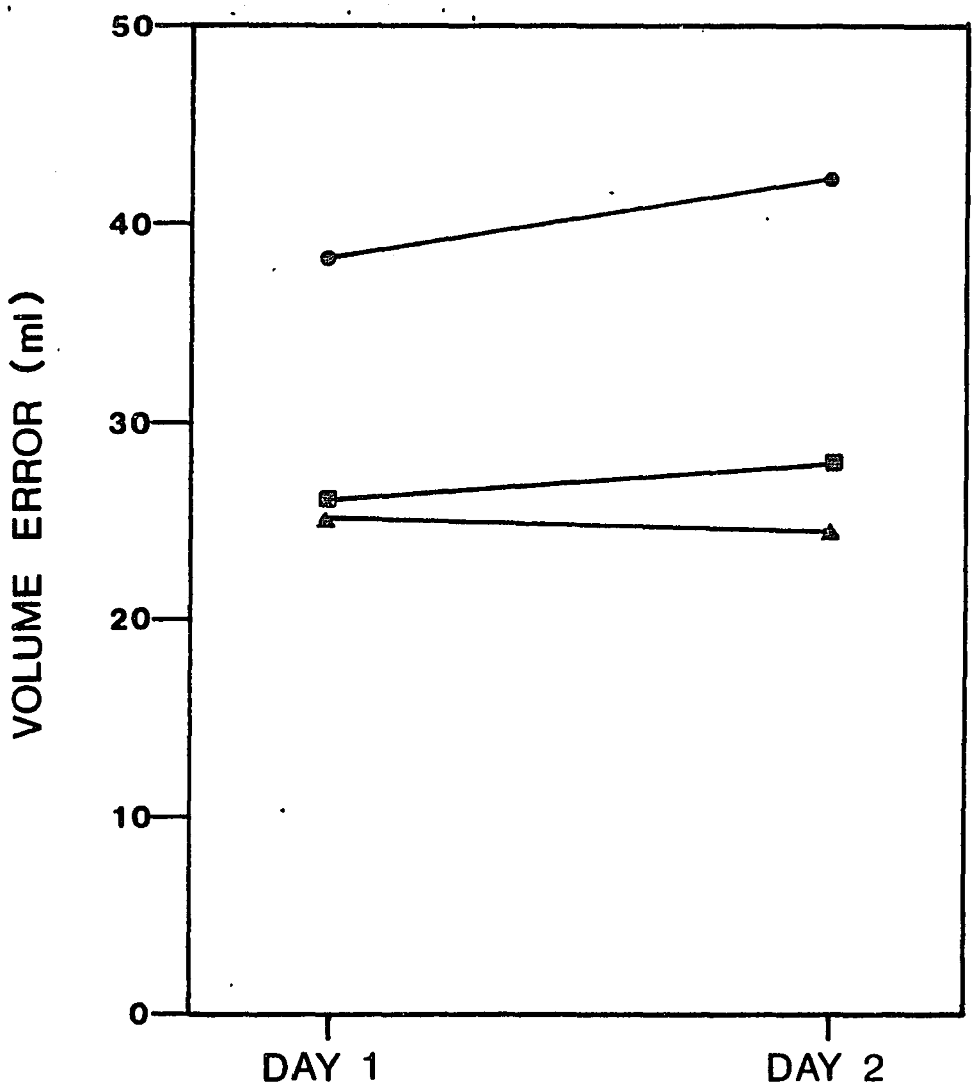

Fig. 4. Comparison of standard errors of the mean for all conditions. -- Value are based on data from Subjects 1-4. Time/Distance/Level Condition (▩), Distance/Level Condition (●), Level Condition (▲).

Table 3. Just-noticeable differences (jnd) and constant errors on Day 1 and Day 2.

	DAY 1		DAY 2	
CONDITION & SUBJECT	JND	CONSTANT ERROR	JND	CONSTANT ERROR
TIME/DISTANCE/ LEVEL				
Subject 1	156	-24	70	121
Subject 2	131	-30	90	28
Subject 3	103	51	57	128
Subject 4	113	-140	96	-77
Subject 5	97	-17	85	-136
Group Average	120	-32	80	13
DISTANCE/LEVEL				
Subject 1	137	-61	151	61
Subject 2	137	121	127	43
Subject 3	168	260	108	138
Subject 4	141	71	106	-175
Subject 5	178	-37	123	-37
Group Average	152	71	123	6
LEVEL				
Subject 1	119	86	139	26
Subject 2	114	52	64	111
Subject 3	126	111	48	112
Subject 4	109	-46	47	0
Subject 5	157	-136	88	-17
Group Average	125	13	77	46

All values given in ml. JND and constant error values for each subject on Day 1 are based on 18-20 trials. Day 2 values are based on 8 trials.

Table 4. Lung volume reproduction errors by quartiles for all subjects.

DAY	CONDITION	25%	50%	75%	100%
DAY 1					
	Time/Distance/ Level	91	191	250	476
	Distance/Level	143	262	429	655
	Level	100	205	359	513
DAY 2					
	Time/Distance/ Level	93	159	193	318
	Distance/Level	80	151	256	443
	Level	91	138	227	364

All values given in ml.

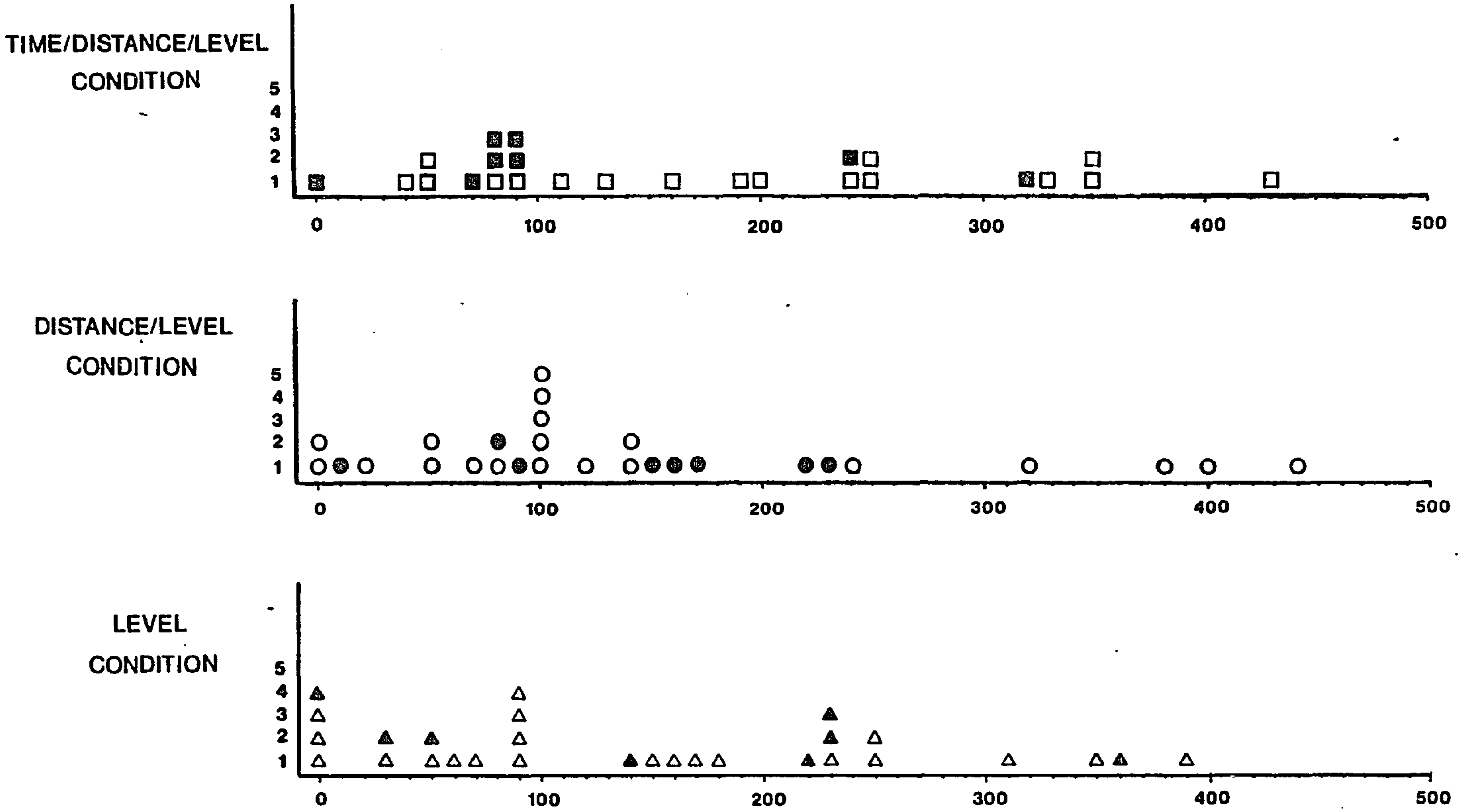

Fig. 5. Distribution of error values for Subject 1. -- Unshaded symbols are errors for Day 1. Shaded symbols are for Day 2 trials. Abscissa represents error value in ml. Ordinate indicates frequency (no. of times a value occurs). Errors are plotted to the nearest 10 ml.

inspiration was fast compared to those in which they were slow. In addition on the Level Condition, when subjects were forced to begin the test inspirations at different levels, there was no significant difference in mean errors or variability (SEM) for those trials on which the initial step of the test inspiration was inspiratory compared to those in which it was expiratory.

There was no consistent pattern of extent or direction of the error on the two trials performed before the practice trials on the Distance/Level and Level Conditions. Thus, performance on these trials did not help identify the cues the subjects were using to reproduce tidal volume.

There was no consistent pattern of either increased or diminished accuracy observed throughout the practice and regular trials within sessions.

Inspiratory Pattern

The flow rate was estimated from the slope of a line of best fit drawn through tracings of five superimposed trials. See Table 5 for the individual subject flow rates for all three conditions. For all subjects on the TDL Condition, the estimated flow rate of the standard inspiration averaged 412 ml/sec and the test inspiratory flow rate averaged 357 ml/sec. On many of the

Table 5. Estimations of flow rate for the three conditions.

	CONDITION							
SUBJECT	TIME/DISTANCE/LEVEL		DISTANCE/LEVEL			LEVEL		
	S	T	S	T_{SLOW}	T_{FAST}	S	T_{INSP}	T_{EXP}
1	359	407	312	141	865	247	224	269
2	585	692	436	264	1462	477	554	895
3	370	210	380	152	693	390	162	349
4	431	231	347	196	597	393	300	342
5	309	245	283	182	698	338	262	246
Group Average	412	357	352	187	863	369	300	420

All flow rates are measured from five superimposed trials as described in the text. All standard (S) flow rates are based on an average of four measurements, as is the test (T) flow rate for the Time/Distance/Level Condition. The test flow rates for the other two conditions are based on the average of two measurements. All values given in ml/sec.

individual trials for a given subject, rates of the standard and test inspiration were similar. Evaluation of several trials on the TDL Condition indicated no evident relationship between the degree of similarity of the flow rates on the standard and test inspirations and the level of accuracy in reproducing the tidal volume.

On the Distance/Level Condition the mean standard inspiratory flow rate was 352 ml/sec. The slow test inspirations averaged 187 ml/sec; while the mean of the fast trials was 863 ml/sec. Only those trials in which the test inspiration was clearly faster or slower than the standard inspiration were included for measurement.

On the Level Condition, the mean flow rate for the standard inspirations was 369 ml/sec. Often the first inspiratory or expiratory step of the test inspiration was slower than the subsequent portion. When the initial step was inspiratory, the rate of the remainder of the inspiration averaged 300 ml/sec. When the initial step was in the expiratory direction, the subsequent part of the inspiration had a mean flow rate of 420 ml/sec.

Often a consistent inspiratory pattern was observed on a subject's standard and test inspiration both within and between trials. Figure 2 illustrates the inspiratory pattern and accuracy variability for one subject on each of the three conditions. Although subjects were allowed on the test inspiration to search for the standard level as long as they deemed necessary, only one subject exhibited searching behavior when performing the task.

Direction of Error

For all conditions, three subjects made more test inspiration responses above the standard lung volume level than below it. For these subjects, the ratio of responses below the standard volume compared to those above the standard were 1 to 3.72, 1 to 1.21, and 1 to 1.44. The other two subjects had comparably more test responses below the standard level than above it. The equivalent ratios for these subjects was 2.08 to 1 and 1.73 to 1.

To provide a comparison with other studies, the constant error is also given in these tables. However, it should be interpreted with caution as it can be strongly influenced by one extreme score.

Subject 5's Results

Subject 5 performed the Day 1 conditions in the reverse order than the others. Because of this difference, his data were not included in the statistical analyses comparing the condition and day effects. As noted in Table 2 on Day 1 this subject performed worse than the others on the Level Condition, but better on the TDL Condition. One explanation would be that there is a general practice effect due to familiarity with any of these tasks. This is substantiated by the fact that on Day 2, Subject 5's mean error values for all conditions were in the mid-range of values for the other subjects.

Subjective Reports

After each session, the subjects were asked what bodily sensations they relied on to reproduce end tidal volume. For the TDL Condition, Subjects 1-4 reported they used the cue of inspiratory time (rate) to perform the task. On all of the conditions, subjects reported attending to "tension or pressure in lungs and chest". One subject said he also relied on abdominal distention. Another subject said he was aware of pressure around the glottis. At least two subjects reported being aware of the pressure of their backs against the body box. However, they did not think they used this cue to reproduce tidal volume.

One subject (Subject 1) reported he did not think he performed very well on the slow trials of the Distance/Level Condition because he could not seem to "pick up any cues". But overall he actually performed better on the slow than on the fast trials. Another subject reported halfway through the Level Condition session, he thought he was doing better on the expiratory trials compared to the inspiratory trials. The data did not correspond with his perception.

Subject 4 reported using a rate or timing cue during the Level Condition. As this was the subject who performed the best on the Level Condition, it was necessary to determine if a consistent flow rate cue was present on this condition. A comparison of the flow rates of the standard and test inspirations were made on several good and poor performance trials. There appeared to be no clear difference in the similarity of the rates on good and poor trials. In addition, the first inspiratory or expiratory step on the test inspiration was usually much slower than the standard inspiration and the rest of the test inspiration, making it doubtful that inspiratory time (or flow rate) was a reliable cue for this subject on the Level Condition.

DISCUSSION

Accuracy of Performance

Errors in end tidal volume reproduction for all subjects and conditions combined averaged 153 ml, but when considering just those trials performed on Day 2, the mean error fell to 133 ml. Subjects performed all three conditions with equivalent levels of accuracy regardless of the difference in available cues from condition to condition. As final lung volume level was the only cue experimentally held constant throughout conditions, the most reasonable explanation for these findings is that final position can be reliably coded to attain a specific lung volume. Support for this conclusion is found in previous breathing movement (Folinsbee et al., 1982) and limb movement (Marteniuk & Roy, 1972; Kelso, Holt, & Flatt, 1980) studies.

Similar levels of respiratory performance have been found in previous studies on tasks comparable to the TDL Condition. Gliner et al. (1981) reported a group average errror of 140 ml with a standard inspiratory lung volume of 25% of inspiratory capacity. The present study, using standard lung volumes of 35% of inspiratory capacity, found comparable error values even on the Distance/Level and Level Conditions when there were no reliable inspiratory time (rate) cues. In addition, according to Gliner's et al. findings, the proportionally larger standard volume level used in the present study should have increased the error. Wolkove and colleagues (1981) reported a group mean error value of 96 ml for a standard lung volume range of 25-50% of inspiratory capacity. One explanation for this smaller error may be that an average of three breaths was used for each trial, thus eliminating extreme scores and preventing a direct comparison from breath to breath.

Comparison of jnd values indicate level of performance in the present study was similar to and sometimes less than that found in other studies. On a task similar to the TDL Condition, Gliner et al. (1981) reported jnds of 110 ml and 135 ml, at 25% and 50% of inspiratory capacity, respectively. These are comparable to the 120 ml and 80 ml (Table 3) reported in the present study for Day 1 and Day 2, respectively, at 35% of inspiratory capacity. Folinsbee et al. (1982) reported jnd values of 142 ml and 162 ml (25% and 50% inspiratory capacity, respectively) on a task similar to the Level Condition. Those were higher than the 125 ml and 77 ml (Day 1 and Day 2, respectively) found in this study. Folinsbee and colleagues reported that in a volume range similar to the present study (25% to

50% of inspiratory capacity), subjects performed more accurately on the task similar to the TDL Condition compared to the final position reproduction task. This finding which is incongruent with the present results may be due to task or training differences in the two studies.

Performance Variability

Level of performance varied from trial to trial with no significant decrease in variability attributable to practice. One indication of this variability (Table 4) was that on Day 2, 25% of all the errors fell below 100 ml, while some errors were over 400 ml. Including the Day 1 trials, the range of errors for individuals often spanned 50-60% of the distance between end expiratory level and the standard level. This variability may be indicative of the subjects' inabilities to consistently attend to a reliable cue.

The Distance/Level Condition was the most variable of the three conditions. In addition, the group means for this condition on both days were slightly higher than the others, although this difference was not significant. Subject reports add little to our understanding of this finding. Two subjects reported this was the most difficult condition; however only the data from one of the subjects corresponded with his perception of the condition.

Factors that Affect Performance

Subjects can locate a position along the inspiratory capacity range of volumes, regardless of the rate of movement or the starting position. Present findings indicate the importance of the final lung volume in performing this task. However, this does not prohibit the use of other cues, such as extent of movement and starting position of the movement, when they are available. It is not clear how subjects use the sensory cues to code the degree of inflation. Possibly through past experiences, subjects develop a personal scale of the range of volumes over the vital capacity, similar to those mentally constructed for limb positions. There might be a central representation of lung volume independent of muscle patterns and the means used to arrive at that location.

The limits of lung volume discrimination were probably not established in the present study nor were all variables influencing performance controlled. Many factors may affect a subject's ability to duplicate a tidal volume. The improved performance on all conditions from Day 1 to Day 2 indicates the positive effect of practice, which may be due to either general familiarity with the experimental setting or experience with the specific tasks. This points out the need to control and report the extent of practice in this type of study; something which is lacking in most of the previous research.

Limb movement studies suggest that increased time and intervening movements between the standard and test movement diminish the level of performance (Poulton, 1977; Keele, 1981). These findings suggest performance might improve if the test inspiration was performed immediately after the standard inspiration without the two spontaneous breaths between them. However, consecutive inspirations that deviate from normal tidal volume may alter the respiratory chemical drive and negatively affect performance. Also the results of studies using consecutive standard and test inspirations (Gliner et al., 1981; Folinsbee et al., 1982) and those separating the standard and test inspirations by 10-15 seconds of spontaneous breathing (Wolkove et al., 1981) were similar. With more extensive practice along with intermittent feedback the performance asymptote for tidal volume reproduction tasks may be reached.

Performance With High Quality Visual Feedback

To the author's knowledge, no other study has tested the ability of the respiratory motor system to obtain a given lung volume using very sensitive visual feedback. The results of the present Precision Task suggest the respiratory motor control system is capable of executing very precise movements and the sensitivity of this system was not a limiting factor in task performance. It is commonly accepted that fine movements can be made, which can be sensed only by visual and not by kinesthetic means (McCloskey, 1978). This corresponds with subject reports on the Precision Task in which subjects often reported that the visual feedback was fluctuating even when they did not perceive a change in lung volume.

Comparison with Limb Movement Studies

The controversy of distance versus location programming of a limb movement has been debated for some time. Congruent with the present findings, the majority of recent evidence suggests the motor system may be optimally organized for achieving final position (comparable to final lung volume level) (for review see Keele, 1981; Russell, 1976). Marteniuk and Roy (1972) found the information on the distance of the movement was not as readily coded and remembered as location information, and starting position cues were not essential for the accurate reproduction of a movement. Kelso and colleagues (1980) showed that subjects more accurately reproduced the end location of a finger movement compared to the distance of the movement. Keele (1981) proposed the opposing-tension theory as an explanation for these results. This theory states each limb location is coded by a specific tension balance between the relevant agonist and antagonist muscles. The application of this theory to the respiratory system is complicated by the fact that many respiratory muscles can perform either agonist or antagonist functions depending upon the condition.

The degree of accuracy of the limb and respiratory motor systems for several variations of the movement reproduction task are similar. As substantiated by this study, the errors often fall in the range of ± 8-12% of the extent of the movement (Kelso, 1980; Zechman & Wiley, 1986; Russell, 1976). Although the many differences between the respiratory and limb systems prohibit a direct comparison, the similarities in these findings suggest the sensory guidance of movement may be comparable for these two systems.

Effect of Change in Chemical Drive

The effect of changing chemical drive on the conscious regulation of tidal volume was not specifically examined in the present study. Increases in tidal volume and short term breath holding probably produced a small change in the chemical drive (hypocapnia or hypercapnia).

The two spontaneous breaths between the standard and test inspiration were used in an attempt to control for chemical drive changes and bring the person back to equilibrium before he performed the test inspiration. Wolkove's et al. (1981) data suggests moderate hypocapnia has no systematic effect on error of volume reproduction. Haltunnen (1974) found that during CO_2 stimulation, a larger volume was inspired for the same subjective magnitude. More research must be done to systematically quantify the effect of changing chemical drive on the accuracy of voluntary respiratory movements.

Subjective Report

Subjective reports provide valuable insight into subjects' perceptions of the cues used to reproduce end tidal volume and the accuracy of performance. However, frequent incongruity between the subjects' perceptions and their actual performance in this and other studies (Banzett, Lansing, & Brown, 1985) supports the need for objective psychophysical testing to evaluate perceptive abilities. The differences in subject report and performance are not that surprising, as well learned patterns of movement are often made without subjective awareness of the many sensory inputs guiding them. In fact subjects are able to discriminate stimuli even when they report not being consciously aware of them. This is the phenomenon of "sub-conscious perception". For example, in "blind-sight" experiments (Perenin, 1979), cortically damaged subjects were unaware of visual stimuli, but when forced to guess they could make crude location, shape and color discriminations. In the present study, subjects were able to reproduce tidal volume fairly accurately even when they reported they could not determine any reliable cues and believed they were guessing.

Afferent Mechanisms

As it took nearly a hundred years to establish that limb muscle receptors give rise to kinesthetic sensations (Matthews, 1977), it is not surprising that the afferent mechanisms underlying the sensation of lung volume change remain unclear (for reviews see Lansing & Banzett, 1986; Zechman & Wiley, 1986). DiMarco et al. (1982) found no difference in the errors of quadriplegics and normal subjects in reproducing tidal volumes. In quadriplegics the lack of feedback from muscle spindles in the intercostal muscles, from joint receptors at costochondral and costovertebral junctions, and from skin tactile and pressure receptors on the chest wall, suggests that input from these afferents are not essential for the perception of lung volume changes. In addition, it is generally believed that joint receptors fire predominantly at the extremes of joint movement (McCloskey, 1978), making it unlikely that they provide information over the whole range of movement or during a mid-range movement as performed in the present study. Studies using upper airway anesthesia and varying the flow rate from standard to test inspiration indicate that upper airway receptors are not essential to mediate the sensation of inspired volume (DiMarco et al., 1982, Wolkove et al., 1981). It should be noted that none of the subjects in the present study mentioned attending to upper airway cues; however, one did mention pressure around the glottis. Wolkove and colleagues found an error difference when the respiratory mechanical load changed from standard to test inspiration suggesting that pulmonary stretch receptors are not the sole source of information for lung volume perception. In another study (Banzett et al., 1985), tracheostomized, high-level quadriplegics could detect tidal volume changes indicating pulmonary afferents are important for perception under some conditions. Possibly intramuscular afferents in the diaphragm or respiratory accessory muscles play a role in lung volume perception. The information gained in the present study does not establish whether phasic or static receptors are contributing to lung volume discrimination (Matthews, 1981). Differences in the pattern of chest wall movements in the quadriplegics and normals with no coincident difference in errors in volume reproduction, indicate a specific pattern of movement is not esential to the perception of lung volume change (DiMarco et al., 1982).

The findings from these previous studies indicate multiple afferents from different sources may be available for the sensation and perception of lung volume change. If several alternate or parallel inputs to the brain exist, disruption of one may have little effect on the sensation detected. It also seems likely that the relevant sensory mechanisms may vary between persons and conditions.

Conclusion

Subjects are able to reproduce an end tidal volume with equivalent levels of accuracy regardless of variations in the rate and starting position of the movement. This finding indicates the importance of the final level cue in attaining a given lung volume. In the control of skilled respiratory movements, the degree of muscle activation requires elastic recoil forces that are peculiar to specific lung volume levels. These forces may provide reliable information about level which is not dependent on the rate and extent of the movement.

This study was not able to evaluate the relative contribution to lung volume detection of various sensory sources (i.e. rib cage joints, respiratory muscles, upper and lower airway afferents, pulmonary afferents, and skin). However, these findings may in the future assist in identifying the afferent mechanisms. For example, these data on normal subjects can be compared with those found when disease or special manipulations have selectively altered these afferent inputs. In addition, how well people discriminate degrees of respiratory inflation and deflation is important for understanding and treating a variety of physiological conditions, such as asthma and quadriplegia, which alter respiratory sensation and perception.

APPENDIX A

SUBJECT INFORMATION FORM

SUBJECT INFORMATION FORM

1) Name ____

2) Sex: M ______ F______

3) Age: _______

4) Do you have a neurological or muscular disorder?
_________ If YES, briefly explain:

5) Have you had surgery on any part of the speech or respiratory mechanisms (i.e., abdomen, chest, throat, etc.)? ________ If YES, briefly explain:

6) Are you having difficulty breathing now? ____________

7) Do you smoke? ________

8) Do you have any chronic respiratory problems? ________

9) What experience or training have you had in breathing exercises?

10) Are you currently taking any medication? _____________
If so, what is it? ___________________________________

APPENDIX B

INSTRUCTIONS FOR BREATHING EXERCISES

INSTRUCTIONS FOR BREATHING EXERCISES

The purpose of this study is to see how well people can detect their lung volume level. We would like you to practice attending to the sensations (feelings) in your chest, abdomen, throat and mouth during breathing. We think that doing the following breathing exercises will help you focus on breathing sensations.

Please practice the following steps several times before coming to the next session.

1. Take a long slow deep inspiration. Hold that position with your glottis open and close your eyes, attending to the sensations in your chest, abdomen , throat, and mouth. What sensations do you feel in the muscles? Slowly expire.
2. Repeat the above steps varying the depths of your inspiration. Can you tell the difference between deep and shallow breaths (high and low lung volumes)?
3. Now repeat the above steps taking fast and slow inspirations.

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