Effects of perceived musical rhythm on respiratory pattern

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HAAS, FRANCOIS, SUZAN DISTENFELD, AND KENNETH AXEN. *Effects of perceived musical rhythm on respiratory pattern.* J. Appl. Physiol. 61(3): 1185-1191, 1986.—The effects of rhythmic input on breath period (TT) under constant metabolic drive were assessed in 10 musically trained and 10 untrained subjects. They tapped to a metronome and then to four musical segments, each for 5 min. Ten of these subjects (5 from each group) also listened to the selections without tapping. TT, beat period (TB), and phase coupling (PC) were assessed during the last 20 breaths of each presentation. TT coefficient of variation decreased significantly ($P < 0.001$) in all subjects (base line = 23%; listening = 15%; listening and tapping = 10%). Significant correlation between rhythm and TT, indicating relative entrainment, was found in half of the subjects ($r > 0.45$; $P < 0.01$). Significant integer TT/TB ratio and PC, both indicating tight entrainment between rhythm and breathing, were observed in 12 subjects (though not consistently in each one). These data advance the following hypothesis: musical rhythm can be a zeitgeber (i.e., pacemaker), with its ability to entrain respiration dependent on the strength of its signal relative to spurious signals from the higher neural centers that introduce noise into the central pattern generator. Tapping reinforces the zeitgeber, increasing its signal-to-noise ratio and thereby promoting entrainment.

music; control of breathing; respiratory rhythm; zeitgeber; musical rhythm

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BREATHING SERVES BOTH metabolic and behavioral functions. The considerable body of evidence suggesting that different neural pathways regulate these two systems has been reviewed by Plum (28) and by Mitchell and Berger (25). The metabolic respiratory pathways are located in the reticular formation of the lower pons and medulla. The behavioral respiratory pathways, which are located mainly in the somatomotor and limbic forebrain structures, allow man to adapt to vocalization and complex behavioral acts.

Physical activities requiring repeated rhythmic movement are often accompanied by rhythmic music or chants. That this phenomenon bridges a variety of cultures (e.g., the rowing chants of Amazon river Indians and the cadence call of Western armies) points to this use of rhythm as intrinsically important to the processes underlying integrated motor activity rather than merely being culturally determined. Because chanting consciously coordinates respiratory timing to muscular activity, one wonders if it actually acts to reinforce an underlying unconscious rhythmic relation between these two systems. Although the relationship between respiratory rhythm and muscle rhythm has been the subject of numerous investigations, it remains ambiguous due to equivocal results (1–4, 11, 18–21, 23, 34). The fact that entrainment, the synchronization of breathing pattern to exercise rhythm, has been demonstrated in some studies (1–4, 11, 18, 21, 23, 34) but not in others (19, 20), may be partly due to the difference in methods used to impose exercise rhythm. Some investigators allowed subjects to choose their own exercise frequency (3, 18, 21), whereas others used a metronome or other form of pacing device (1, 2, 19, 20).

Even studies that do show evidence that limb movement can influence respiration, ignore two considerations. Because the metabolic effects on peripheral chemoreceptors are not easily separated from the presumed neural influence of the joint proprioceptors, even passive movements of the limbs are accompanied by hyperventilation (17). Additionally, most investigations presume a mechanism of afferent feedback because the on-and-off points for the respiratory cycles and locomotor events (e.g., footfall) bear a constant temporal relation. It is possible that the relationship is maintained by a common control coupling both the respiratory and locomotor events. Recent studies indicate the presence of both hypothalamic (10) and spinal (32) pattern generators capable of synchronizing respiratory and locomotor activity in the absence of afferent feedback.

Extensive regions of the cerebral cortex influence respiration when stimulated (25, 26). Therefore, as chanting synchronizes breathing and muscular activity, perhaps external rhythmic auditory cues can act as a zeitgeber (i.e., pacemaker) (29) that synchronizes breathing and exercise. The aim of this study is to assess the influences of external rhythm (i.e., a zeitgeber) on respiratory pattern while keeping both metabolic changes and afferent stimuli to a minimum. This was accomplished by using a pure rhythm (i.e., metronome) and embedded rhythm (i.e., musical rhythm) instead of exercise involving gross body movement.

METHODS

Subjects. Twenty volunteers (14 men, 6 women) participated in this investigation. Four of these subjects were very experienced musicians who had received instruction in music theory and regularly played a musical instrument, 6 subjects had had formal musical training but were no longer actively involved with playing an instrument, whereas the remaining 10 subjects had never received any musical training.

Protocols. To minimize the possibility that subjects might try to consciously manipulate their respiratory pattern, they were told that the purpose of the experiment was to see the effects of music on metabolism. Respiratory data were obtained via a calibrated pneumotachograph attached to a face mask. The airflow signal, from the differential pressure gauge connected to the pneumotachograph, was integrated to obtain volume and both were recorded on a polygraph. Although respiratory pattern can be influenced by the presence of a mouth piece (14), any effects were assumed to be constant for the duration of the experiment. In addition, we assessed gross metabolic changes and chemical respiratory drive by measuring heart rate and end-tidal P_{CO_2}, respectively.

After a 15-min familiarization period, subjects listened for 5 min to a metronome set at a rate of 60 beats/min. This tempo approximates the pedaling frequency used in many of the published exercise entrainment studies (2, 11, 18–20). Subjects were instructed to use one finger to tap out the metronome beat on a microphone amplifier, with the amplifier output recorded on the polygraph (Fig. 1). Through the use of the subject's information-processing capacity as a distraction to prevent simultaneous attention to his breathing, this method did not appreciably affect the metabolic component of the respiratory drive.

Subjects were then randomly presented with four musical excerpts and one 5-min. silent period. Lightweight earphones were used. To assure that each subject listened to the selection in comfort, listening volume was determined by the subject and remained constant for the experiment. Ten subjects only listened to each selection during the first presentation. During the second presentation, they were told to tap along with the beat of the music as they perceived it to be. The other 10 subjects were presented each selection only once, during which time they tapped out the rhythm.

Music selections. The four selections, the beginning of the 2nd movement of Beethoven's "7th Symphony," Albinoni's "Adagio," Earl "Fatha" Hines' arrangement of "Boogie Woogie on St. Louis Blues," and Thiago de Mello's "Summer Heat," reflect the need for varying levels of rhythmic complexity and tempi. (Within this context, the specific pieces were strongly determined by the musical bias of the senior author.) The Beethoven selection, for example, is "allegretto" in two-four time, a relatively fast tempo compared with the Albinoni excerpt that is written in three-four time and played at the much slower "adagio" tempo. Table I illustrates the time signatures and tempi of the four pieces and the expected tapping pattern for each.

Data treatment. The last 20 breaths taken from each period were used for analysis. For each breath we determined the breath cycle (T_T), inspiratory duration (T_I), expiratory duration (T_E), tidal volume (V_T), minute ventilation ($\dot{V}_E$), the V_T/T_I ratio, the T_I/T_T ratio, and respiratory frequency (f). T_T (or $T_I + T_E$) is defined as the duration between the onset of two inspirations. The beat period (T_B), defined as the interval between two taps, is shown in Fig. 2.

In accord with the work of Kohl et al. (21), the follow-

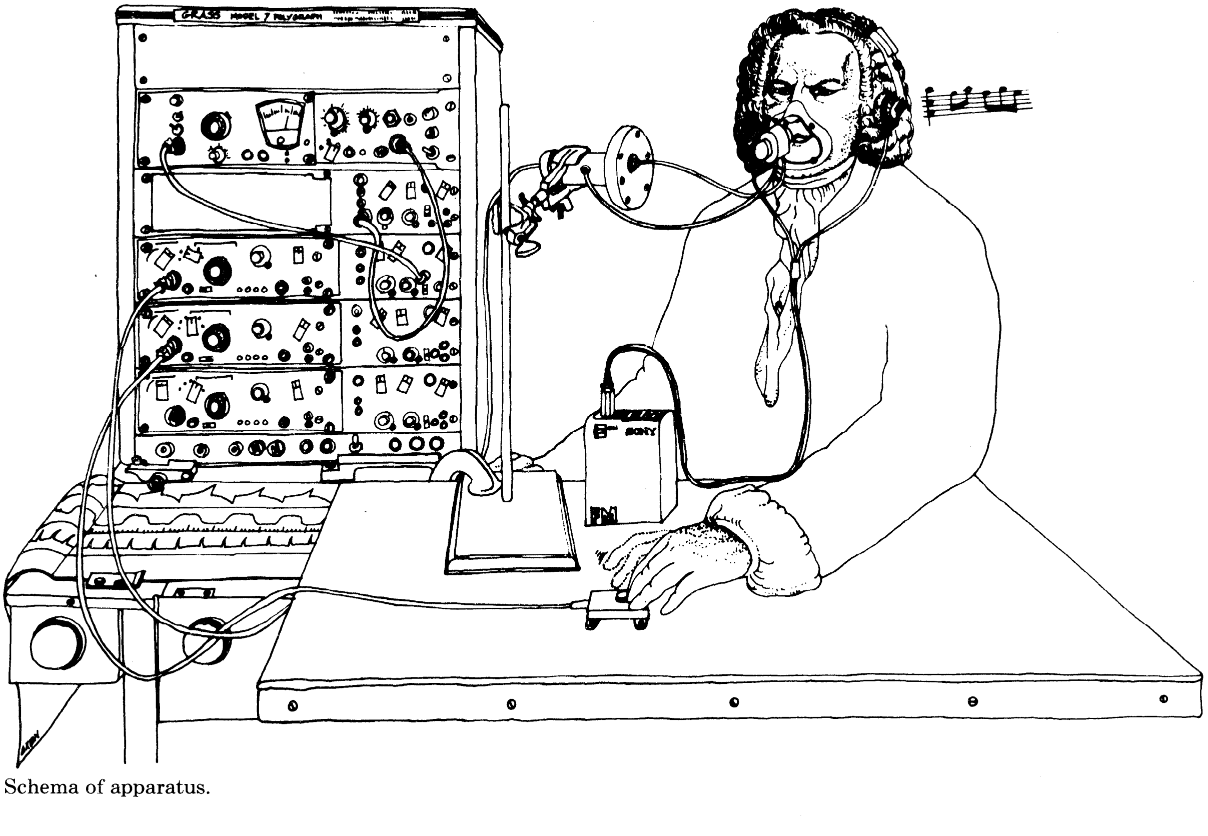

FIG. 1. Schema of apparatus.

TABLE 1. *Selections used in this study arranged according to meter*

Selection	Meter	Tempo
Metronome	1/s	Lento
Beethoven: 7th Symphony, 2nd movement	2/4	Allegretto
Albinoni: Adagio	3/4	Largo
Earl "Fatha" Hines: Boogie Woogie on St. Louis Blues	4/4	Presto
Thiago De Mello: Summer Heat	6/8	Allegretto

Meter is defined as "basic scheme of note values and accents which remains unaltered throughout a composition or a section thereof and which serves as a skeleton for the rhythm. For instance, 3/4 meter means that the basic values are quarter notes and that each third one of these receives a strong accent. This grouping is indicated by barlines which mark off measures. The tempo markings indicate the relative liveliness of the selections (15)." Following Italian terms are standardly used to indicate musical tempo, proceeding from the slowest to the quickest: largo (broad); lento (slow); andante (walking); moderato (moderate); allegretto (quick); presto (fast).

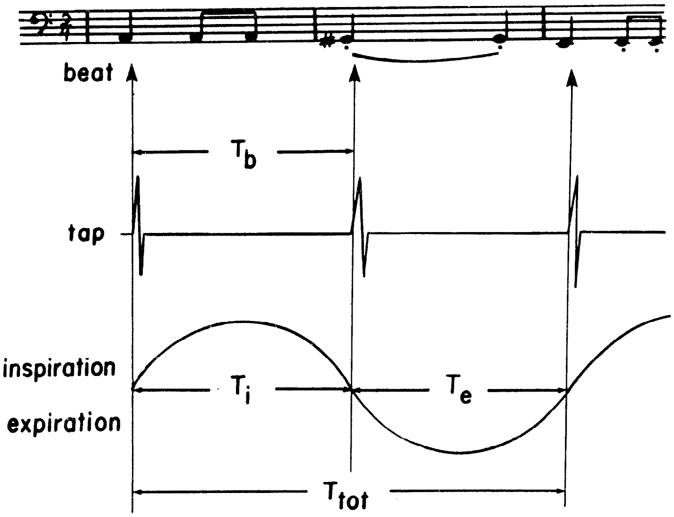

FIG. 2. Determination of integer ratio. Integer ratio is defined as ratio of time of 1 respiratory cycle (Tt) to beat period (Tb) ± 10% = integer. Music illustrated is 1st 3 measures of 2nd movement of Beethoven's 7th Symphony. *Middle tracings* illustrate tapped beats. A beat is defined as the temporal unit of a composition, indicated by (real or imaginary) up-and-down movement of a conductor's hand (15).

ing analysis was used to determine any underlying relationship between beat and breathing pattern. The relationship between the beat frequency and *f* was determined by counting the number of complete beats plus their unfinished decimal parts. Integer ratio (Tt/Tb) indicates that Tt is a multiple of the beat frequency. Deviations from integer ratio were classified into five ± 0.10 deviation ranges (from −0.51 to +0.50). Phase coupling, i.e., inspiration or expiration starting preferentially at a certain point within the measure, was similarly determined (Fig. 3).

Each subject's distribution was subjected to a χ^2 analysis (15). Yates' correction for continuity was used in the χ^2 analysis (15) to correct for the small number of breaths. Integer coupling or phase coupling was accepted as significant at a probability level of $P < 0.01$.

RESULTS

Effect of music on respiratory parameters. Heart rate and end-tidal P_{CO_2} did not change appreciably during the various phases of the experiment.

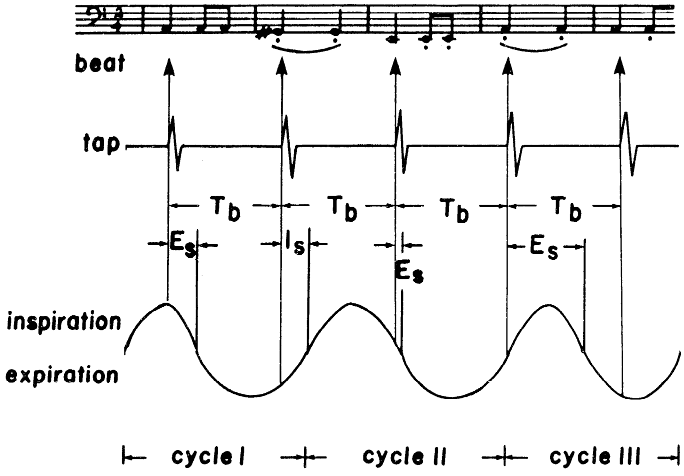

FIG. 3. Determination of phase coupling (tracing as in Fig. 2). Phase coupling is defined as inspiration or expiration starting preferentially at a certain point within the measure. Inspiratory segment (Is)/Beat period (Tb) = inspiratory phase coupling. Expiratory segment (Es)/Tb = expiratory phase coupling.

Despite the relatively small effects of listening to music on the magnitude of respiratory parameters (Table 2), there was a significant increase in *f* (due to decreases in both Ti and Te) with a proportional drop in Vt. This change was observed with all of the musical selections and occurred in most subjects.

In addition, some form of unconsciously occurring coordination between the music and respiratory pattern was found in a majority of the subjects tested. These various forms were: *1*) a significant decrease in the coefficient of variation ($P < 0.001$) for all respiratory parameters during finger tapping. The coefficient of variation (Table 3) during the listening presentation was significantly less than during the silent periods ($P < 0.001$) but significantly greater than with finger tapping (there was no significant difference in the coefficient of variation during tapping between the group presented with the selections once and the group presented them twice); *2*) a small but significant correlation ($P < 0.01$) between music tempo and respiratory rate in 50% of both the trained and untrained subjects (average $r > 0.45$); *3*) integer Tt/Tb ratios in at least two of the five conditions in 30% of the untrained subjects and 40% of the trained subjects; *4*) inspiratory phase coupling in 50% of the untrained subjects and 80% of the trained subjects; *5*) expiratory phase coupling in 40% of both subject groups.

Figure 4 illustrates two examples in two different subjects. The upper tracing, from a musically untrained subject, shows virtually no coordination between breathing and musical rhythm. The lower tracing, from a highly trained musician, demonstrates tight coupling of breathing and musical rhythm. The trained subjects were also more able than the untrained subjects to beat out the musical rhythm accurately (average beat variance 0.09 ± 0.01 and 0.13 ± 0.01, trained and untrained respectively $P < 0.01$). (As a general rule in regard to the types of entrainment we observed, entrainment occurred less often as musical rhythm became more complex.)

TABLE 2. *Effects of music on respiratory parameters for the pooled trained and untrained subjects. Musical selections are arranged by tempo in ascending order*

Selection	T_B, s	T_T, s	T_I, s	T_E, s	V_T, l	$\dot{V}_E$, l/min	V_T/T_I, l/s	T_I/T_T
Silence		3.91±0.21	1.46±0.08	2.45±0.15	0.85±0.04	13.75±0.81	0.58±0.03	0.38±0.01
Albinoni	1.31±0.31	3.00±0.09*	1.18±0.04*	1.80±0.07*	0.75±0.05	15.18±0.91	0.64±0.04	0.40±0.01
Metronome	1.03±0.01	3.10±0.12*	1.20±0.05*	1.90±0.08*	0.73±0.05	13.94±0.95	0.56±0.03	0.39±0.01
Beethoven	1.03±0.08	2.92±0.07*	1.16±0.03*	1.76±0.06*	0.69±0.04	14.26±0.87	0.58±0.04	0.40±0.01
De Mello	1.04±0.06	2.92±0.16*	1.15±0.05*	1.77±0.12*	0.73±0.06	14.96±0.96	0.63±0.03	0.40±0.01
Hines	0.67±0.05	2.70±0.09*	1.08±0.04*	1.62±0.07*	0.70±0.05	15.87±1.16	0.67±0.04	0.40±0.01

Values are means ± SE. T_B, beat period; T_T, breath period; T_I, inspiratory duration; T_E, expiratory duration; V_T, tidal volume; $\dot{V}_E$, min ventilation; V_T/T_I, tidal volume to inspiratory duration ratio (average airflow); T_I/T_T, inspiratory interval to total breath interval (duty cycle). ANOVA indicates significant differences in beat period as follows: Albinoni ($P < 0.001$) < metronome = Beethoven = De Mello ($P < 0.001$) < Hines. See Table 1 for tempos of individual selections. * Significance between silent period and musical selection $P < 0.01$.

TABLE 3. *Breath-to-breath coefficient of variation for respiratory frequency*

Condition	No Tap	Tap
Silence	23.2±2.0%	
Metronome		12.9±2.0%
Albinoni	18.1±3.4%	13.0±2.1%
Beethoven	13.0±1.7%	10.2±1.5%
De Mello	14.6±2.4%	9.8±1.5%
Hines	11.5±1.7%	8.5±1.1%

Values for both no tap and tap data are significantly different from silence data at $P < 0.001$. Values for tap data are significantly different from no tap data at $P < 0.001$.

DISCUSSION

Our data indicate that subjects responded to both the metronome and music in two ways. The first, a general increase in respiratory rate that was independent of the specific stimulus, is consistent with previous work (12) and probably reflects a heightened level of arousal during activity. A similar acceleration of respiratory frequency seen in anticipation of exercise (24), during anger and anxiety (9) and during enhanced attention (12), has been attributed to possible cortical inhibition of the limbic system (27).

The second response, unconscious coordination between stimulus and respiration, appears related to the intrinsic rhythm of the stimulus. Our data indicate that the combination of rhythmic auditory cues and finger tapping is coordinated with respiration in a significant number of subjects. In a similar protocol, Wilke et al. (33) showed entrainment with a combination of finger tapping and visual cues, not with visual cues alone. Although this suggested tapping as the critical determinant of entrainment, it remained unclear whether tapping alone would have been sufficient or whether it simply reinforced the visual stimulus. Our demonstration that, despite rhythmic finger tapping, entrainment occurred less frequently with more complex rhythms points to the auditory stimulus, rather than finger tapping, as the independent variable.

The importance of auditory cues in entrainment of respiration and other motor activity is further supported by the following reported observations. *1*) Bechbache and Duffin (2) and Yonge and Peterson (34) showed significantly more entrainment when a metronome was used to pace exercise. *2*) No entrainment was observed

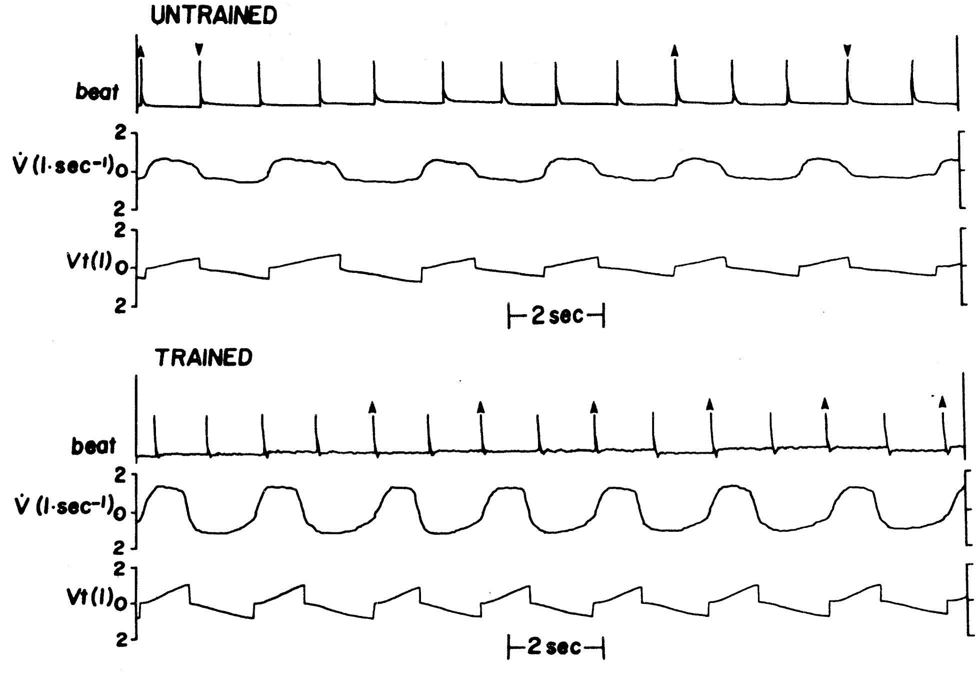

FIG. 4. Redrawn tracing from a typical untrained subject (*top*) and a highly trained subject (*bottom*) during same segment of Albinoni's Adagio. *Upward arrow* indicates inspiration starting on the beat (±10%); *downward arrow* indicates expiration starting on the beat. Taps indicate perceived beat of music. $\dot{V}$, airflow; V_T, tidal volume. Upward deflections are inspiratory airflow and volume. Downward deflections are expiratory airflow and volume.

in the absence of audible pacing (i.e., metronome) (16, 19, 34). *3*) Variation in electromyogram (EMG) activity while performing a repeated motor task decreased significantly when the task was accompanied by an even auditory rhythm, but increased significantly with an uneven rhythmic accompaniment (28).

Respiratory entrainment can be described as the driving of the central respiratory pattern oscillatory system by a second oscillatory system. If the frequencies of the two are similar, coupling will tend to lock them both into the frequency of the driving oscillator. Relative entrainment occurs when the driving oscillator is unable to constrain a precise phase relationship.

The level of entrainment in our study ranged from a small but significant relationship between breathing frequency and musical tempo (relative entrainment) to a tightly coupled coordination (integer ratios in 50% of the breaths) in the most musically trained subject (Fig. 4). The relation between tempo and respiratory frequency agrees with an earlier finding (8) that "in general respiratory rhythm follows that of the music, increasing or diminishing with the latter, without going beyond the limits of extreme variations."

Because of the small number of subjects tested, the effect of musical training on respiratory entrainment did not reach statistical significance and so remains equivocal. Since a greater proportion of trained than untrained subjects evidenced some level of entrainment, and the two subjects with the most musical training showed the greatest entrainment, our data suggests that training reinforces the innate potential for entrainment. This is consistent both with the work of Kohl et al. (21), who found entrainment between respiration and pedalling in 70–100% of the racing cyclist subjects but in only 25–63% of the noncyclists, and with Bramble's (9) observation of almost 100% phase coupling in trained runners.

Theoretical considerations. Theoretically, entrainment can result either from feedback from peripherally located proprioceptors (6) producing a ventilatory stimulus secondary to mechanical excitation during motion (5) or from feedforward during movement through cortical or subcortical "irradiation" to respiratory muscles (7, 10, 22). Irrespective of the exact nature of the entrainment mechanism, the signal-to-noise ratio of the pacemaker signal (i.e., zeitgeber) must be high enough to interact with the central respiratory pattern generator (CPG). This can be achieved either by decreasing the noise into the CPG or by increasing the signal strength.

We envision the CPG as an autonomous oscillator system whose f is primarily determined by metabolic drive. Small variations in f are determined by inherent timing errors of the neural elements making up the oscillator (13) and are relatively small when it is running free. A relatively free-running state is observed in slow-wave sleep (during which breathing is regulated solely by the metabolic respiratory control system) that is characterized by stable respiration (26). Any larger variation in f is assumed to result from the introduction of noise into the CPG.

During undirected arousal of higher centers (i.e., a state in which the individual is not concentrating on a task, such as wakefulness or rapid-eye movement (REM) sleep), not only does respiratory frequency increase due to changed metabolic demands, but inputs from these higher centers introduce noise into the CPG that increases variation in respiratory frequency. Indexes of variability in REM sleep compared with nonREM sleep, for example, increase from between 55–410% (25). As suggested by the reduction of the coefficient of variation (Table 3), directed arousal (i.e., asking the person to perform a task) reduces noise input and the CPG approaches the free-running state. Directing the subject's attention more forcefully, i.e., by tapping, reduces the coefficient of variation even further. We also observed this effect when subjects read poetry or performed arithmetic calculations, indicating that attention, not music, was responsible for the reduced variability (unpublished observation).

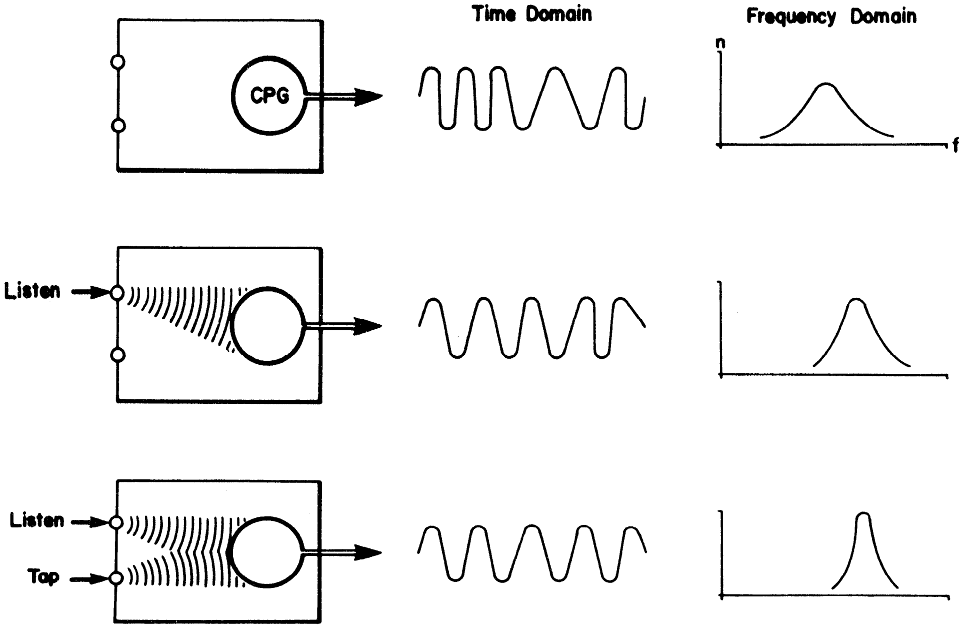

FIG. 5. Model of higher center influence on central respiratory pattern generator (CPG). *Rectangle on left* represents the central nervous system and *circle* the CPG. *Small circles* represent CNS oscillators. *Upper one* is driven by auditory information and lower one by muscular proprioceptor information. *Waves* indicate oscillator outputs. "Time domain" is a schematic representation of airflow tracing obtained during experiment and "frequency domain" is a schematic representation of histogram obtained from air-flow tracing. See text for discussion of model.

Figure 5 illustrates our conceptual model of entrainment. In the upper panel the CPG oscillator system is impinged by noise from the higher centers, resulting in a relatively large variation in *f*. When the CPG is exposed to an external auditory zeitgeber with oscillations from four and eight times the resting breathing frequency, the interaction of the two oscillators results in relative entrainment. The higher frequency of the external oscillator has a magnet effect (30) on the slower oscillator, pulling it to a higher-respiratory frequency (middle panel). When the external oscillator is combined with a second oscillator of the same frequency, the net signal to the CPG increases and entrainment is reinforced (bottom panel).

Any entraining signal is characterized by its periodicity. During running, for example, in which breathing and footfall are tightly coupled (9), each footfall serves as a distinct timing pulse. During bicycling, in contrast, the timing information from one leg is cancelled by timing information from the other leg that is 180° out of phase. It is not surprising, then, that entrainment is unlikely during cycling except with use of a metronome or in trained cyclists. Trained cyclists are specifically taught to maintain a fixed cadence (defined as leg revolutions per minute). To do this, cyclists must be conscious of the proprioceptive information from their legs. We hypothesize that it is this volitional "metronome" to which breathing becomes entrained. This interpretation helps to reconcile the equivocal data published concerning respiratory entrainment to bicycling exercise.

We can also reconcile our findings with those of Wilke et al. (33) who could not demonstrate entrainment with a flashing light alone. The lack of entrainment to the light alone may reflect the subjects' lack of attention, resulting in a signal-to-noise ratio too low to entrain respiration. Tapping may have insured their subjects' attention as well as reinforcing the timing information inherent in the flashing light.

In summary, the data demonstrates that auditory rhythmic cues are a zeitgeber with an ability to entrain respiration. It is dependent on the strength of its signal relative to the spurious signals from other higher neural centers that introduce noise into the CPG that results in large variation in output. Noise into the CPG can be reduced by directed arousal, and the input signal can be reinforced by adding a second signal source, of the same frequency, such as tapping. Tapping reinforces the zeitgeber and increases its signal-to-noise ratio, thereby promoting entrainment.

In conclusion, because both breathing and finger tapping followed the auditory stimulus, these data favor the feedforward hypothesis of entrainment. To the extent, though, that the finger tap closes a feedback loop, feedback can reinforce the entraining signal. Additionally, these observations have direct bearing on two methodological aspects of respiratory timing studies. The first is that entrainment studies involving exercise should carefully consider the possible contributions from auditory cues. The second is that music is often used during respiratory experiments on the assumption that this provides more "natural" breathing. The present data show that this is not the case.

In a speculative bend the question arises as to the importance of such control pathways in normal respiration. Metabolic factors are undoubtedly the dominant control variables driving the CPG and the effects of external cues are probably negligible during normal respiration in healthy subjects. The potential of this latter pathway, however, in driving the respiratory system of individuals with abnormal response to an increase in metabolic drive or in patients with an abnormal CPG has not been adequately evaluated.

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