Biological Psychology 33 (1992) 133–156

Muscle tension patterns during auditory attention

Barry H. Cohen

New York University, New York, NY 10003, USA

Richard J. Davidson, Joseph A. Senulis, and Clifford D. Saron

University of Wisconsin-Madison, Madison, WI 53706, USA

Douglas R. Weisman

State University of New York at Purchase, Purchase, NY 10577, USA

Although there is much evidence demonstrating muscle tension changes during mental work, there are few data concerning muscle tension patterns during effortful attention to simple sensory stimuli. In the present study, sensory attention was evoked by a pitch discrimination task at three levels of difficulty, with a digit retention task administered for comparison. Twenty-four females each performed both tasks at all levels of difficulty, while the EKG, and the *corrugator supercilii*, *frontalis*, lip, jaw, chin, and forearm area EMG were recorded. As expected, heart rate decreased significantly with increasing difficulty of the pitch task. A pattern of facial EMG responses accompanied the pitch task, which included significant increases in *corrugator* and *frontalis*, and decreases in the jaw as a function of difficulty, and time within trials. The tension pattern observed during sensory intake is discussed in terms of its relation to emotional expressions and motor theories of attention.

Keywords: Muscle tension patterns, electromyographic specificity, heart rate, auditory attention, sensory intake, motor theory of attention

Introduction

There is a wealth of evidence that mental effort is accompanied by increases in skeletal muscle tension in various bodily areas. For example, several studies have shown that when subjects solved numerical problems mentally, the tension increased in their forearms (e.g., Clites, 1936; Davis, 1939; Hadley, 1941), and foreheads (e.g., MacNeilage, 1966; Schnore, 1959). Moreover, when subjects read under distraction, or memorized lists of words, the tension was found to increase in the muscles associated with producing speech (e.g., Locke and Fehr, 1970; McGuigan and Rodier, 1968). In fact, the locations of these muscle tension changes have sometimes been found to be related to the specifics of the task. For example, McGuigan and Winstead

Correspondence to: Barry H. Cohen, Department of Psychology, New York University, 6 Washington Place, New York, NY 10003, USA.

(1974) found greater lip than tongue tension when subjects mentally rehearsed words containing bilabial phonemes, and the reverse pattern when subjects rehearsed words containing lingual-alveolar phonemes.

Various motor theories of attention (see Cohen, 1986 for a review) predict that muscle tension should also increase during effortful attention to external stimuli in a pattern of bodily locations that depends on the nature and modality of the stimulus. Surprisingly few studies, however, have recorded muscle tension patterns during this type of mental effort. In most of the early muscle tension studies in which subjects attended to external stimuli, considerable high-level cognitive processing was also required. For instance, in Wallerstein's (1954) study of attentive listening, and in Bartoshuk's (1956) replication, the stimuli were complex stories or essays. In the study by Vaughn and McDaniel (1969), the learning of complex visual discriminations was required. These studies found rising gradients in facial muscle tension over time. Unfortunately, these types of studies cannot discern whether the muscle tension changes observed were the result of higher-level processing or attention to external stimuli per se. A series of studies by Travis and Kennedy (e.g., Travis and Kennedy, 1949) demonstrated that reaction times to simple stimuli were lengthened when forehead tension spontaneously dropped (suggesting a reduction in alertness), but those studies were not designed to determine whether increased tension accompanied increased efforts at external attention.

More recently, there have been several studies in which muscle tension changes have been monitored while subjects attended to, or waited for very simple stimuli. Unfortunately for our purposes, most of these studies recorded muscle tension from only one location; their focus was not on muscle tension patterns but rather on overall bodily activation (or conversely, somatic inhibition), in order to observe cardiac-somatic coupling (e.g., Obrist, Webb, and Sutterer, 1969). In one such study, Coles (1974) used chin EMG as a measure of general somatic activity, and also recorded the EKG, while subjects made visual discriminations at three levels of difficulty. Heart rate fell to lower levels as the difficulty of the discrimination increased. Although the chin EMG levels were fairly highly correlated with heart rate over time (albeit at a lag of 1 s) within each trial, the chin EMG did not vary significantly with difficulty level, prompting Coles to conclude that the cardiac and somatic systems "...are clearly not 'coupled' in respect of their response to the requirements of the task" (p. 122).

In one recent study in which several muscles were monitored during the fixed foreperiod of a reaction-time study, Haagh and Brunia (1984) found a reduction of chin EMG (more specifically EMG from *m. mylohyoideus* – a muscle in the base of the mouth) concurrent with increased tension in task-relevant muscles, but with no change in tension in other task-irrelevant muscles. Such results led Brunia (1984) to speculate that somatic inhibition may be specific to the muscles of the face, because "by reducing noise, selective quieting in this communication system could contribute to better perception and therefore better preparation for a response" (p.215). Consistent with Brunia's hypothesis is the finding by Salomon and Starr (1963) [confirmed in a larger sample by Djupesland (1965)] that the contraction of a muscle in the middle ear, tensor tympani, was associated with strong voluntary closure of the eyes and even "facial movements such as grimacing and smiling" (p. 164). Contraction of most nonfacial muscles studied did not produce auricular activity. Because the contraction of middle ear muscles attenuates auditory sensitivity, it could be reasoned that the relaxation of all facial muscles, including *corrugator supercilii* and *frontalis*, would be advantageous during auditory attention, as such relaxation would reduce the extraneous coactivation of auricular muscles.

Nonetheless, based on the few relevant EMG studies thus far we may expect muscle tension to exhibit positive gradients in the brow or forehead region of the face (Bartoshuk, 1956; Wallerstein, 1954), and negative gradients in the chin area (e.g., Haagh and Brunia, 1984), while subjects actively attend to external stimuli. It could also be predicted that these gradients would be steeper, and thus reach more extreme levels as more effort is exerted to maintain attention.

Predictions with respect to the pattern of facial muscle tension changes during sensory attention could also be made based on the literature concerning the facial expressions that accompany the various emotions. The emotion that is relevant to attention to external stimuli is that which Tomkins (1962) and Izard (1977) call "interest." According to Tomkins (1962), the principal muscle movement accompanying "interest" is a lowering of the eyebrows along with tracking, looking, and listening. Izard (1977) concedes that "the facial patterns in interest are not as distinct as they are in many of the other emotions" (p. 215), and suggests that the interest expression "probably involves a slight raising (or lowering) of the eyebrows... as though to increase the field of vision (or sharpen the focus of the eyes)" (p. 215).

Darwin (1872) suggested that the contraction of the brows, originally associated with difficult visual discriminations, later became associated with any difficult discrimination, noting that: "the eyebrows ... are acted on under certain circumstances in a useless manner, from having been similarly used, under analogous circumstances, for a serviceable purpose" (p. 226). Recently, Smith (1989) found brow tension to be specifically responsive to the anticipation of effort.

Darwin (1872) also noted that: "when we wish to listen intently to any sound, we either stop breathing, or breathe as quietly as possible, by opening our mouths, at the same time keeping our bodies motionless" (p.283). Hass (1970), in addition to mentioning a "widening of the eyes", observes that: "a further sign of interest, as Darwin (1872) himself noted, is the opening of the mouth" (p. 113). Hass then stated that "it is still debatable whether this stems from the relaxing of the jaw muscles – in consequence of heightened attention – or whether it is an aid to keener hearing" (p. 114). There is some evidence to suggest that jaw tension reduction is associated with improved auditory attention. In an auditory reaction-time study by Holloway and Parsons (1972), those normal subjects who were faster exhibited significantly greater heart rate deceleration immediately before the stimulus, and fewer jaw EMG responses. This pattern also held true for the trials involving faster responses within each subject.

Finally, Salzen (1981) based on his own review of the literature, associated the following muscle actions with the emotion of interest: "focal attention with stare, frown, and spreading reaction of tense mouth" (p. 155). Notably, the facial expression accompanying interest is not described precisely by the above-cited authors, and it is unclear whether to expect a "tense mouth" simultaneously with a relaxed jaw, or in which instances the brows will be raised and in which lowered. The actual expression occurring during a particular situation may depend on the object of interest, whether it is: visual or auditory; near or far; clear or vague; potentially threatening or apparently harmless; external or only imagined.

In the present study we chose auditory stimuli partly to see if jaw relaxation would occur, as might be predicted by Darwin, and partly to discern changes in brow tension unconfounded by the squinting that might accompany the discrimination of a visual stimulus. [Cacioppo, Petty, and Morris (1985) observed of the *corrugator supercilii* region that: "EMG activity increased markedly whenever a visual stimulus was presented", p.378.] An auditory discrimination task was employed, analogous to the visual task used by Coles (1974), so that difficulty level, and hence attentional effort demands, could be controlled systematically. To minimize demands on higher-level processing, we chose a very simple discrimination task based on changes in the pitch of a pure tone. For comparison, a task expected to involve environmental rejection, the short-term retention of a string of digits, was also employed.

The two tasks were carefully designed to use the same sensory stimuli during the recording of physiological responses, so that only the attentional demands (intake vs. rejection) could account for physiological differences. In order that response preparation would also not differ between the tasks, the responses to both tasks were identical – the pressing of one of two buttons – and no motor responses were required during the recording of the physiological measures. To facilitate further comparison, each task was presented at three levels of difficulty, determined comparable across tasks (in terms of percentage of correct judgments) based on pilot experimentation.

Six muscle locations were selected for EMG recording: *corrugator supercilii* (lowers brow) and *frontalis* (raises brow) because of their prominent role in the facial expression associated with environmental interest (Izard, 1977), as well as their general association with mental effort and alertness (e.g., Bartoshuk, 1956; Travis and Kennedy, 1949); the chin and jaw areas, because both have been measured in previous studies of somatic inhibition (Coles, 1974; and Holloway and Parsons, 1972, respectively); the perioral or lip area because it may be especially sensitive to subvocalization (Cacioppo and Petty, 1981; Cohen, 1983); and the left forearm extensors (extend the fingers) in order to provide a non-facial area, uninvolved with response execution. [1]

In order to identify bursts of EMG activity coincident with overt movements, such as yawning or swallowing, we chose to videotape unobtrusively the subject's face, so that during analysis trials associated with movements could be eliminated. The electrocardiogram (EKG) was recorded in order to assess the expected cardiac deceleration during environmental intake. In contrast, cardiac acceleration was expected to vary with the difficulty of the digits task, as found for the digit transformation task employed by Kahneman, Tursky, Shapiro, and Crider (1969).

The experiment was designed principally to test the following hypotheses:

1. The pitch task will meet the heart rate requirements for an environmental intake task: (a) heart rate will decrease as difficulty increases (Coles, 1974); (b) heart rate will decrease within trials, and (c) begin to rise back towards its initial level after the subject detects the pitch change.
2. The digits task will meet the heart rate requirements for an environmental rejection task: (a) heart rate will increase as difficulty increases; and (b) heart rate will increase within trials (Kahneman et al., 1969).
3. Muscle tension will change from baseline for each task, but in a pattern that differs between the two tasks.
4. Muscle tension will vary as a function of difficulty for each task, but in a different pattern (i.e., there will be a task by difficulty level interaction). Specifically, jaw tension will decrease for increasing difficulty of the pitch task, while tension in the upper face (i.e., *corrugator* or *frontalis*) will increase. Tension in the lip, chin, and possibly the jaw area should increase with difficulty of the digits task due to subvocalization.
5. Both positive and negative tension gradients will appear within trials of both tasks, but the pattern of gradients will differ between the two tasks.
6. Tension gradients will reverse during trials of the pitch task during which the pitch changes and the subject detects it.

---

[1] We followed the older guidelines for placement of chin, jaw, and forearm electrodes (J.F. Davis, 1959) in order to facilitate comparisons with previous studies, and because newer guidelines (Fridlund and Cacioppo, 1986) were not available when our study was conducted. We believe that the separation of the electrodes under the old guidelines is too large to specify the location by a specific muscle. On the other hand, for *corrugator supercilii* and *frontalis*, we used our own specific placements (described in Method), which are similar to those in the new guidelines.

Method

Subjects

The subjects were 24 female undergraduates (mean age = 21.0; range = 18 to 31). All subjects were right-handed (as assessed by questionnaire), and none had any gross physical or neurological impairments. The subjects were paid at the rate of four dollars per hour for a single session which lasted between three and a half and four hours.

Apparatus

The subject sat erect in a padded armchair in a small (2.0 m × 2.5 m) room facing a blank translucent screen. All recording equipment was housed in an adjacent room. Stimuli were administered through a pair of lightweight Sennheiser headphones. A response box with a keypad was mounted on a wooden board and placed across the arms of the chair so that the subject could press either one of two "active" keys to signal her response. Instructions were given via a speaker placed to the right and slightly behind the subject. The subject could be heard through a microphone placed to the right and slightly in front of the subject.

The EMG was recorded from five facial locations (*frontalis*, *corrugator supercilii*, lip, chin, and jaw; for exact placements, see section below), using pairs of Beckman miniature silver/silver chloride electrodes (diameter = 11 mm). The EMG was also recorded from the forearm extensors of the left arm using a pair of Beckman standard silver/silver chloride electrodes (diameter = 16 mm), placed according to the guidelines of J.F. Davis (1959). Slight skin abrasion with Omni-Prep (Weaver Co., Denver) was used to ensure that the inter-electrode impedance was below 10 kilohms for each pair. A Beckman standard electrode attached to the middle of the forehead served as a ground. The EMG signal for each of the six locations was amplified by a separate Grass Instruments A.C. preamplifier (Model 7P5), with the high-pass set to 10 Hz (−3 db), and the low-pass set to 500 Hz (−3 db). The EMG was then high-pass filtered above 30 Hz (and 20db amplified) by cascading two Rockland (Model 432) filters to attain a 48db/octave roll-off.

The output of each filter was sent to a Coulbourn Contour-Following Integrator (Model S76-01), with the time constant set to its minimum value (20 ms). The integrated output was then sent to the analog-to-digital converter (Model AD11-K) of a PDP-11/34A mini-computer (Digital Equipment Corporation) for on-line digitization at the rate of 125 samples/s. The output of each of the integrators was also displayed on a Grass Model 7 polygraph with the paper speed set to 15 mm/s to monitor for gross artifact. A calibration signal allowed the output of the A/D converter to be transformed to microvolts. The calibrated EMG was averaged over each one-second epoch of the 10 s physiological recording period of each trial.

The EKG was recorded from two Beckman standard electrodes, one attached to the lateral surface of each arm, and amplified by a Grass EKG preamplifier (Model 7P6B). An electronic circuit produced a 100 ms pulse corresponding to each R spike. The digitized pulse was submitted to a software routine which used the inter-beat intervals to calculate an average heart rate for each one-second epoch of the 10 s physiological recording period. However, it was not possible in this way to determine the average heart rate for the first one-second epoch following tone onset, thus the heart rate data began with the second one-second epoch.

To facilitate artifact rejection, the subject's face and neck were visually monitored by a SONY (Model AVC-3260) video camera placed 1 m directly in front of the subject and hidden by a screen. The output of the camera was recorded by a Magnavox 4-head VHS recorder (Model VR8425SL01) for subsequent artifact detection. Prior to the experiment, none of the subjects was told of the presence of the video camera, but each subject was informed about being videotaped during the debriefing after the experiment.

Facial electrode placements

The chin EMG electrodes were placed at the midline, according to the guidelines of J.F. Davis (1959; 3/4 in. above and 3/4 in. below the point of the chin). However, the four other facial EMG locations were arranged in one of two configurations: right *frontalis*, right *corrugator*, left jaw, left side of the mouth; left *frontalis*, left *corrugator*, right jaw, right side of the mouth. Subjects were randomly assigned to one of the two configurations with the restriction that half of the subjects be assigned to each configuration. The *frontalis* electrodes were placed following the recommendations of Davis, Brickett, Stern, and Kimball (1978): one electrode was placed 2.5 cm above the brow in line with the pupil, and the second was placed on the same vertical line 2.5 cm above the first. For *corrugator supercilii*, both electrodes were placed just above the brow; the more medial of the pair was placed directly above the internal canthus, and the more lateral electrode was placed so as to yield a center-to-center separation of 19 mm. The perioral electrodes were placed as follows: one electrode was placed just lateral to the corner of the mouth and the second was placed immediately below the lower lip so as to yield a center-to-center separation of 19 mm. The jaw electrodes were placed according to the guidelines of J.F. Davis (1959; the first electrode was 3/4 inches anterior to and 1/2 inches above the angle of the jaw; the second was 2 inches directly above the first).

Stimuli

The 10 s tone was generated by an IBM PC, bandpass filtered by Rockland Model 852 filters, and recorded on audio tape using a Technics

Model 1506 tape recorder. The filtering was necessary because the IBM PC produces a squarewave, and a relatively pure tone was desired. The tone was produced by the "sound" command in Microsoft Basic at a frequency of 350 Hz. The digits were spoken by a male at the rate of 1.5 digits per second, and recorded on the same tape recorder. All of the stimuli were presented binaurally; the position of the headphones was reversed after each block of 24 trials (with respect to which earpad was placed on each ear). The decibel level of the 10 s tone was set to be 65 db (SPL) measured at each earpad by a Simpson (Model 886) sound pressure meter. All of the stimuli were recorded on one channel of the stereo tape recorder; 20 Hz signals were recorded on the second channel, and were detected by Coulbourn logic modules during runtime to control the timing of the digitization software on the PDP-11 mini-computer.

Tasks

The auditory discrimination task consisted of the presentation of a 0.5 s warning beep, followed after one second of silence by a 10 s tone. On half the trials the pitch of the tone changed at one point. Hence, we refer to this task as the "pitch" task. In all trials, the tone began at 350 Hz. During trials within which the tone changed, the change occurred either 3, 4, 5, 6, or 7 s after onset; the time of change was varied quasi-randomly. The difficulty level of each trial was determined by the amount of pitch change as follows: 4 Hz = easy; 2 Hz = moderate; 1 Hz = hard [2]. Half of the pitch changes were to higher frequencies and half were lower (determined quasi-randomly). The warning beeps signalled the difficulty level as follows: 100 Hz = easy; 400 Hz = moderate; 800 Hz = hard. Of course, on half of the trials ("catch" trials) the warning beep provided false information, as the tone did not change at all.

After the offset of each tone the subject was required to press one of two buttons with her right hand: "0" for no change, or "1" for change. One second after her response the subject heard two short high beeps if her response was correct, or two short low beeps if her response was incorrect. Either response by the subject began a timer which triggered the presentation of the next trial 5 s after the response to the previous trial. The subject received a block of 24 trials in which, randomly mixed, were eight trials with each warning beep half of which involved a pitch change of the warned amount, and half of which were actually "catch" trials. After a three minute rest period, the subject received a second similarly-designed block of 24

---

[2] The frequency changes in our filtered 350 Hz square wave tone were more noticeable than would be corresponding changes in a pure 350 Hz sine wave. Our levels of difficulty were determined by pilot experimentation with the same filtered tone used in the present study.

trials. Of the total (across both blocks) of eight trials at a particular difficulty level in which the tone changed, two trials each changed at 4, 5, or 6 s after tone onset, and one each at 3, or 7 s.

The task involving digit retention, which we will refer to as the "digits" task, consisted of the following sequence: a series of randomly-selected digits, one second of silence, a 10 s tone, one second of silence, a second series of digits. On half the trials the second series of digits was identical to the first; on the other half the second series was the same except for the reversal of two adjacent digits (but not involving digits near the end or the beginning of the string). The subject's task was to judge whether the second series was the same (press "0"), or different (press "1"). The subject received immediate feedback in the manner described for the pitch task. The level of difficulty of each trial, as determined by pilot experimentation, corresponded to the following numbers of digits in the series: 6 digits = easy; 7 digits = moderate; 8 digits = hard. Similarly to the pitch task, two blocks of 24 trials were formed by randomly mixing 8 trials of each difficulty level. The 10 s tones in the middle of each digits trial were the same tones, in the *same sequence*, as were used in the pitch task. However, for the digits trials, subjects were instructed that any changes in the tones were irrelevant.

Counterbalancing

In addition to the digits task, a second environmental rejection task [3] was included, so that a total of three tasks were given to each subject. All six orders possible with the three tasks were assigned. All subjects received the same blocks of trials, but for half of the subjects the order of the two blocks was reversed in each task. By crossing the two block order conditions with the six task orders, twelve combinations were formed. Finally, these twelve task conditions were crossed with the two facial electrode configurations to form 24 unique combinations. One subject was randomly assigned to each of the 24 conditions.

Procedure

After being provided with a false rationale concerning the electrodes (i.e., that the electrodes measured patterns of blood flow to the brain), the subject signed a consent form and the electrodes were attached. Resting baseline periods were recorded, the first with the eyes open and the second with the

---

[3] The second environmental rejection task involved the retention of short strings of musical notes. However, the physiological results as a function of difficulty level were neither monotonic nor consistent, and there was considerable variability within subjects; hence the data for this task are not reported.

eyes closed. Then, the subject was instructed to perform her first task and was given practice trials. Task instructions were followed by directives to refrain from unnecessary movements (even coughing, swallowing, etc., if possible) during the 10 s tone (the period during which physiological responses were being recorded), to keep her eyes open at all times (unless instructed otherwise), and to exert as much effort as possible without being overly concerned with performance.

The two blocks of the first task were presented with a brief rest break between the blocks, and then two more baseline periods were recorded as at the beginning. Next, the subject was instructed in her second task, presented with two blocks of that task, and one more set of baseline periods. Finally, the subject was instructed in the third task, and given two blocks of that task, after which the electrodes were removed. Each block of trials took between 8 and 14 min depending on the type of task. From the first baseline until the last experimental trial, the elapsed time varied between 90 and 120 min.

After electrode removal, the subject completed a questionnaire concerning the use of particular mental strategies during each task, as well as a medical history questionnaire. The mental strategies questionnaire consisted of nine potential strategies to each of which the subject responded on a 10-point scale. The subject was then debriefed, including an explanation of the true function of all of the facial electrodes, a request to use the videotape for research purposes, and payment for participation.

Artifact rejection

The videotapes of each subject were inspected for visible facial, jaw, and neck movement, such as yawning, swallowing, and nail-biting. Time periods containing unusually high activity on the polygraph record were examined especially closely. Trials, or half-trials, were eliminated from analysis if they were coincident with noticeable head, hand, or facial movement. In addition, trials or half-trials in which the forearm EMG reached the maximum value of the A/D converters were also eliminated even if the hand or arm activity could not be seen.

Statistical analysis

All of the repeated measures ANOVAs were performed by the ANOVA procedure of the SAS statistical package (SAS Institute, 1982). For all of the ANOVAs involving more than two repeated measures, significance levels were based upon the adjustment suggested by Huynh and Feldt (1976) as provided by the ANOVA procedure of SAS (however, the original rather than the adjusted degrees of freedom are shown).

Results

Performance

It was important to confirm that the difficulty manipulations produced the expected range of performance levels for each task. For the pitch task, the percentage of correct judgments (hit rate and false alarm rate percentages, respectively, are presented in parentheses) was 95% (97.7%, 7.4%) for the easy trials, 86% (94.0%, 21.0%) for the moderate trials, and 65% (57.3%, 27.0%) for the hard trials. For the digits task, the corresponding percentages were 88% (86.6%, 10.9%), 80% (78.3%, 19.2%), and 68% (74.6%, 38.3%).

To test the statistical significance of these differences in performance, the traditional signal detection measures, d′ and β (Snodgrass and Corwin, 1988), were calculated for each subject at each difficulty level for each task. d′ is based on the difference of z scores representing hit and false alarm percentages and as such indicates how discriminable catch trials are from trials with a change. On the other hand, β reflects the subject's relative bias toward indicating the detection of a change rather than a catch trial, and thus represents the subject's criterion. Paired *t*-tests were performed on these measures for adjacent difficulty levels. For the pitch task, the mean d′s and βs were: 2.71, 0.87 (easy); 2.12, 0.83 (moderate); and 0.78, 1.23 (hard). The easy and moderate levels differed significantly in d′, $t(23) = 3.51$, $p < 0.005$, as did the moderate and hard levels, $t(23) = 6.77$, $p < 0.005$. Whereas the difference in βs was quite small and insignificant between the easy and moderate levels, the difference between the moderate and hard levels did attain significance, $t(23) = 3.63$, $p < 0.005$. For the digits task, the mean d′s and βs were: 2.14, 1.05 (easy); 1.67, 1.35 (moderate); and 0.96, 0.95 (hard). Again, the easy and moderate levels differed significantly in d′, $t(23) = 2.92$, $p < 0.01$, as did the moderate and hard levels, $t(23) = 4.70$, $p < 0.005$. None of the βs differed significantly from each other.

Artifact rejection

Each of the 24 subjects was presented a total of 48 pitch and 48 digits trials. Out of the total of 2304 trials, there were 93 trials that were completely eliminated: 30 from the pitch trials, and 63 from the digits trials. In addition, there were 120 trials in which only half the trial had to be rejected: 46 from the pitch trials and 74 from the digits trials. For each subject the total number of pitch trials eliminated (two half trials were counted as one full trial) was subtracted from the total number of digits trials eliminated. These differences were then subjected to a Wilcoxon signed-rank test for matched samples (Howell, 1987). As expected, more digits than pitch trials were eliminated (due to facial and bodily movements), Wilcoxon $T(19) = 24.5$, $p < 0.01$ (two-tailed).

Mental strategies

An analysis of the mental strategies questionnaire found that three of the strategies discriminated the two tasks. Two of these, "created visual images" and "imagined my own voice", were used more often for the digits task [$t(23) = 2.49$, $p < 0.05$, and $t(23) = 2.21$, $p < 0.05$, respectively]. "Just listened to the tone" (the tone which changed in pitch, and in the digits trials, separated the two strings of digits) was rated much more highly for the pitch than the digits task, $t(23) = 7.58$, $p < 0.001$.

Effects of difficulty level

Heart rate

Due to a technical error during recording, the EKG for 9 subjects could not be accurately analyzed for heart rate. Therefore, heart rate results are based on the remaining 15 subjects. A single value for each 10 s task trial and for each 30 s eyes-open baseline period was computed by averaging all of the one-second values for that time period except for epochs eliminated due to artifact (for one subject the entire baseline preceding the digits task had to be eliminated). Next, all trials with the same difficulty level were averaged for each task. A 2 (pitch vs. digits task) $\times 4$ (three difficulty levels plus the eyes-open baseline preceding each task) repeated measures ANOVA was conducted on the averaged heart rates. Only the main effect for difficulty was significant, $F(1, 13) = 10.3$, $p < 0.005$, due to generally higher heart rates during the tasks than the resting baselines (see figure 1).

Three planned contrasts were then performed among the difficulty levels of each task separately. First the baseline period was compared to the average of the three difficulty levels for the pitch task. This comparison was significant: $F(1, 14) = 5.42$, $p < 0.05$. Then the easy and moderate difficulty levels were compared, demonstrating a significant decrease at the moderate level, $F(1, 14) = 7.28$, $p < 0.02$. The decrease between the moderate and hard levels did not approach significance.

The same three comparisons were conducted for the digits task, yielding significance only for the comparison of the baseline with the average of the three difficulty levels, $F(1, 13) = 8.99$, $p < 0.05$. This effect was due to heart rates which were higher than baseline at all difficulty levels.

Muscle tension

After averaging the one-second EMG values in the manner described for heart rate, a 2 (pitch vs. digits task) by 4 (three difficulty levels plus baseline) ANOVA was performed for each of the six muscle locations. To control the experiment-wise alpha, a procedure based on Bonferroni's inequality was used (Howell, 1987), reducing alpha to 0.0083 for the testing of each muscle

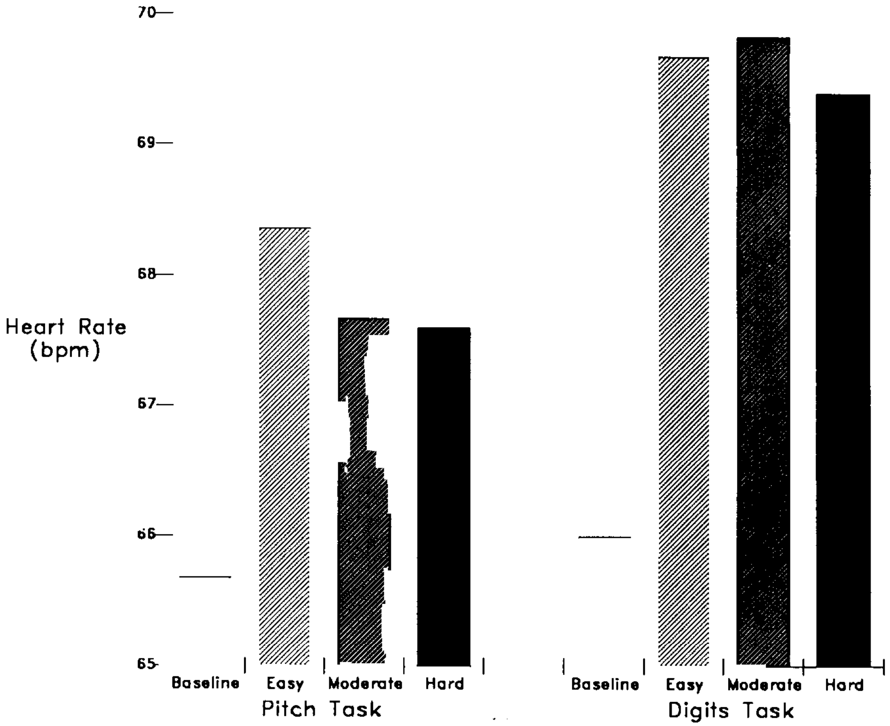

Fig. 1. Mean heart rate (in beats per minute) as a function of difficulty level (including baseline) for both tasks.

location. The main effect of difficulty was significant for two of the muscle areas: lip, $F(3, 66) = 16.0$, $p < 0.0005$; and chin, $F(3, 66) = 12.1$, $p < 0.005$, and approached significance for *corrugator*, $F(3, 66) = 5.57$, $p < 0.05$. In addition, for the chin, the main effect of task, $F(1, 22) = 14.3$, $p < 0.005$, and the task × difficulty interaction, $F(3, 66) = 12.0$, $p < 0.005$ were also significant. The latter effect is due to the sharp rise from baseline to the digits task compared to the slight decrease from baseline for the pitch task (see figure 2).

The same three planned contrasts described for heart rate were also performed for each muscle area for each task. For the pitch task, none of the muscle areas were significantly tenser than baseline, but the increases for *corrugator*, $F(1, 22) = 5.68$, $p < 0.05$, and lip, $F(1, 22) = 6.87$, $p < 0.05$ approached significance. Comparing the easy and moderate levels of difficulty, *frontalis* rose significantly, $F(1, 23) = 9.08$, $p < 0.008$, while the decrease in jaw tension approached significance, $F(1, 23) = 6.56$, $p < 0.05$. Comparing the moderate and hard levels of difficulty, only *corrugator* tension changed, evincing a sizeable increase in tension, $F(1, 23) = 22.2$, $p < 0.0001$.

For the digits task, the tension in two muscle areas rose significantly above baseline: lip, $F(1, 23) = 18.4$, $p < 0.0005$; and chin, $F(1, 23) = 32.8$, $p < 0.0005$. The rise in *corrugator* tension approached significance, $F(1, 23) = 5.01$, $p < 0.05$. None of the muscle tension changes among the three task difficulty levels approached significance.

Changes over time

Heart rate

It was expected that the heart rate decline within a trial would reverse after the subject heard the tone change in pitch, but that the decline would continue during the catch trials. Because the tone changed pitch at different points within different trials (from 3 to 7 seconds after tone onset), temporal effects were explored by averaging all of the one-second heart rate values (across the trials of each task/difficulty combination) that shared the same relative position with respect to pitch change. For example, all one-second values (for a particular task and difficulty level) that were 4 seconds before the pitch change were given the relative time value of -4 and averaged (the one-second period immediately preceding the pitch change was coded as "0"). Note, however, that a trial in which the tone changed 3 seconds after onset could not contribute any time periods labeled -4, because in that case the tone and hence the physiological recording had not yet begun. To facilitate comparison of the pitch-change trials with the catch trials, pitch-change times were quasi-randomly assigned to the latter, which were then averaged according to time relative to the assigned pitch change point. A 2 (pitch change trial vs. no pitch change) by 3 (difficulty levels) by 9 (relative time periods) ANOVA was then conducted. The interaction of pitch change and time was significant, $F(8, 112) = 3.89$, $p < 0.01$, as was the three-way interaction of pitch change, difficulty, and time, $F(16, 224) = 3.10$, $p < 0.05$. The source of the three-way interaction can be seen in figure 3. There is a clear reversal in the heart rate decline for trials in which the pitch changes, and the degree of the heart rate recovery depended upon difficulty level. The decline of heart rate during trials for which the pitch does not change is nearly monotonic. This analysis was repeated using only trials for which each subject responded correctly. There was a reduction in degrees of freedom due to missing values and a consequent reduction in significance level, but the resulting pattern of effects was nearly identical.

It is reasonable to compare pitch trials with no pitch change to digits trials. (Although all digits trials contained tones during the 10 s physiological recording period, and half those tones changed in pitch, analyses demonstrated that pitch change had no effect on digits trials. Therefore, we believed it justified to combine digits trials regardless of pitch change.) For this analysis, it was appropriate to use real time; that is, time measured from

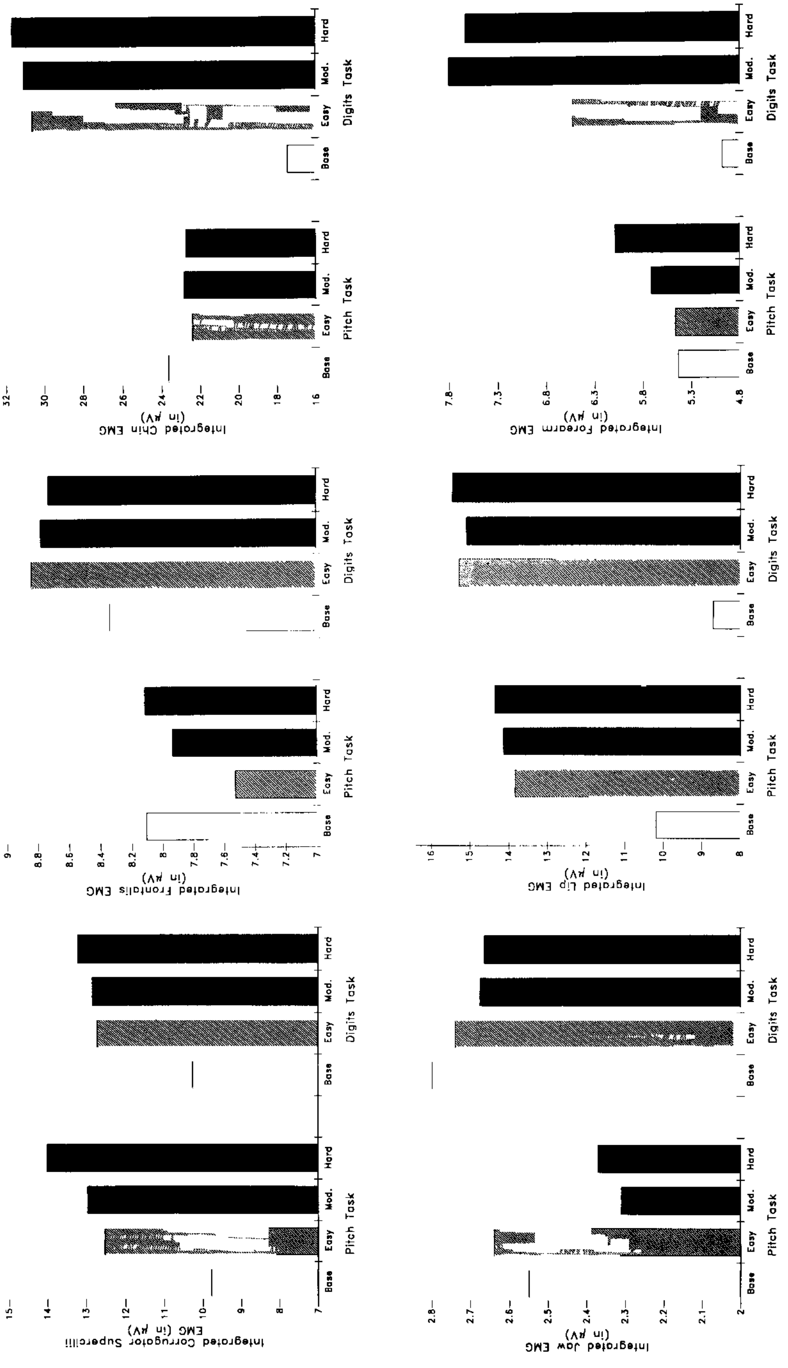

Fig. 2. Mean integrated EMG (in average μV) as a function of difficulty level (including baseline) for both tasks at each muscle location.

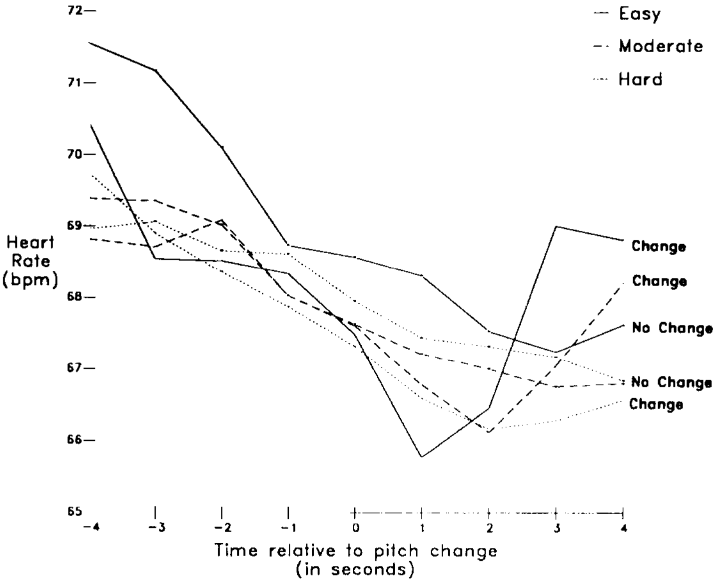

Fig. 3. Mean heart rate (in beats per minute) as a function of pitch task difficulty level and time relative to the pitch change, comparing trials during which the pitch changed to "catch" trials (pitch-change times assigned quasi-randomly to the catch trials).

tone onset. However, software limitations rendered both the first and last seconds unanalyzable for heart rate, and thus the following analysis is based on the middle 8 one-second periods. A 2 (pitch vs. digits) ×3 (difficulty levels) ×8 (time periods) ANOVA was performed. Both the effect of time, $F(7, 98) = 17.5$, $p < 0.0005$, and the interaction of time with task, $F(7, 98) = 9.19$, $p < 0.0005$, were significant. As depicted in figure 4, these effects are due to the general decline of heart rate over time for both tasks, and the steeper decline for the pitch task.

Muscle tension

Temporal effects for muscle tension were analyzed by first averaging the one-second values of each muscle location, according to their position relative to the pitch change, as was done for heart rate. The 2 (pitch change vs. no pitch change) by 3 (difficulty levels) by 9 (relative time periods) ANOVA was performed for each muscle location with the alpha adjusted appropriately for each comparison. The three-way interaction was significant for *corrugator*, $F(16, 368) = 3.33$, $p < 0.005$, but did not approach significance for any other muscle areas. The nature of the interaction for *corrugator* is easily seen in Fig. 5(a). For trials with a pitch change there was a large gradient reversal for the easy trials only, whereas tension continued to rise

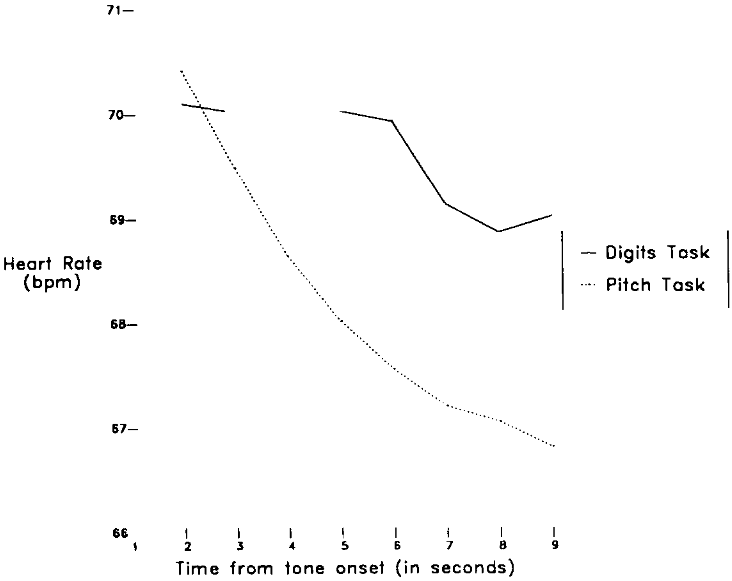

Fig. 4. Mean heart rate (in beats per minute) as a function of time relative to tone onset for both tasks (collapsing over difficulty levels).

steadily for trials during which the pitch did not change. When the difficulty level by time interaction was analyzed separately for trials that changed and trials that did not, the interaction was highly significant for trials that changed, $F(16, 368) = 4.38$, $p < 0.001$, but non-significant for trials that did not, $F = 1.1$.

Although the three-way interaction described above was not significant for *frontalis*, there was a significant pitch change by time interaction for this muscle area, $F(8, 184) = 4.48$, $p < 0.005$. This interaction arises because *frontalis* tension (collapsing over difficulty levels) increased and then declined for trials with a pitch change, but continued to rise for trials in which pitch did not change (see figure 5b).

Pitch trials with no pitch change were then compared with digits trials as a function of time from tone onset, as was done for heart rate. In this case the first second of each trial was analyzable but the last second was not, thus the following analyses were based on 9 one-second periods. A 2 (pitch vs. digits) ×3 (difficulty levels) ×9 (time periods) ANOVA was conducted for each muscle location, adjusting alpha accordingly. Whereas the three-way interaction did not approach significance for any muscle location, the task by time interaction was significant for arm, $F(8, 184) = 4.24$, $p < 0.008$, and approached significance for lip, $F(8, 184) = 5.61$, $p < 0.01$. For both of these muscles, the interaction involved a general decline in tension over time for

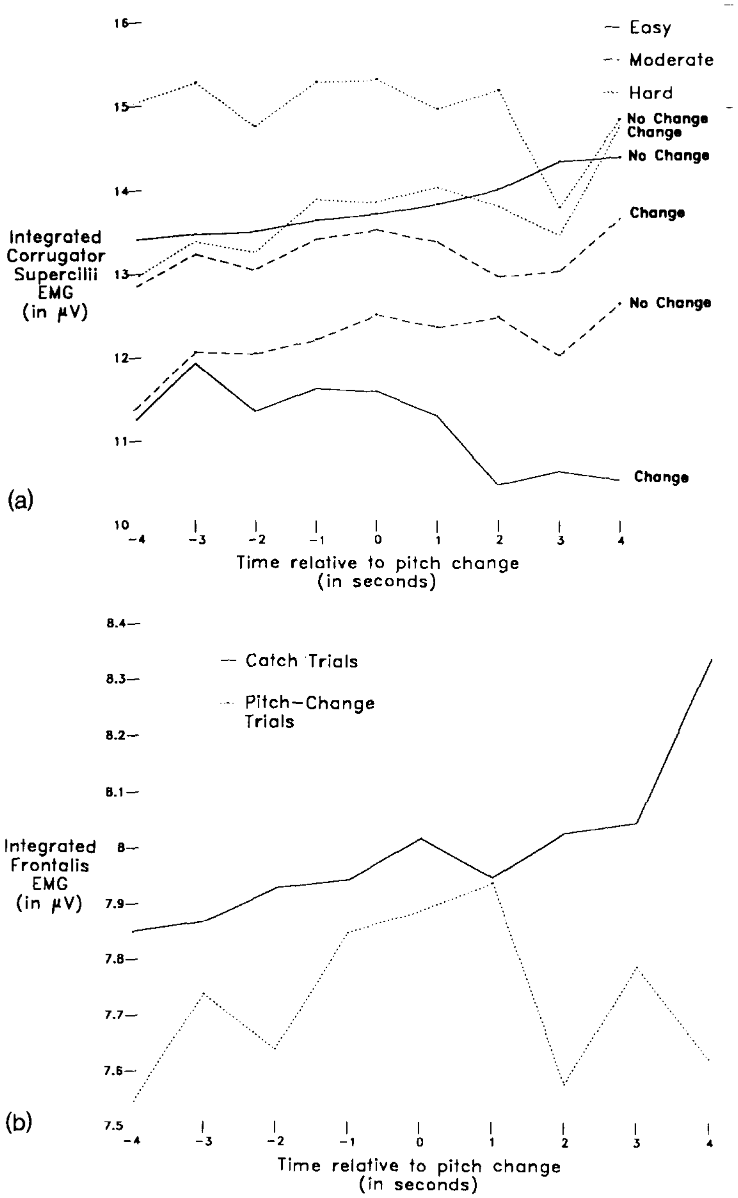

Fig. 5. (a) Mean *corrugator supercilii* EMG (in average μV) as a function of pitch task difficulty level and time relative to the pitch change, comparing pitch-change trials to "catch" trials (pitch-change times assigned quasi-randomly to the catch trials). (b) Mean *frontalis* EMG (in average μV) as a function of time relative to the pitch change (collapsing over difficulty levels), comparing pitch-change trials to "catch" trials (pitch-change times assigned quasi-randomly to the catch trials).

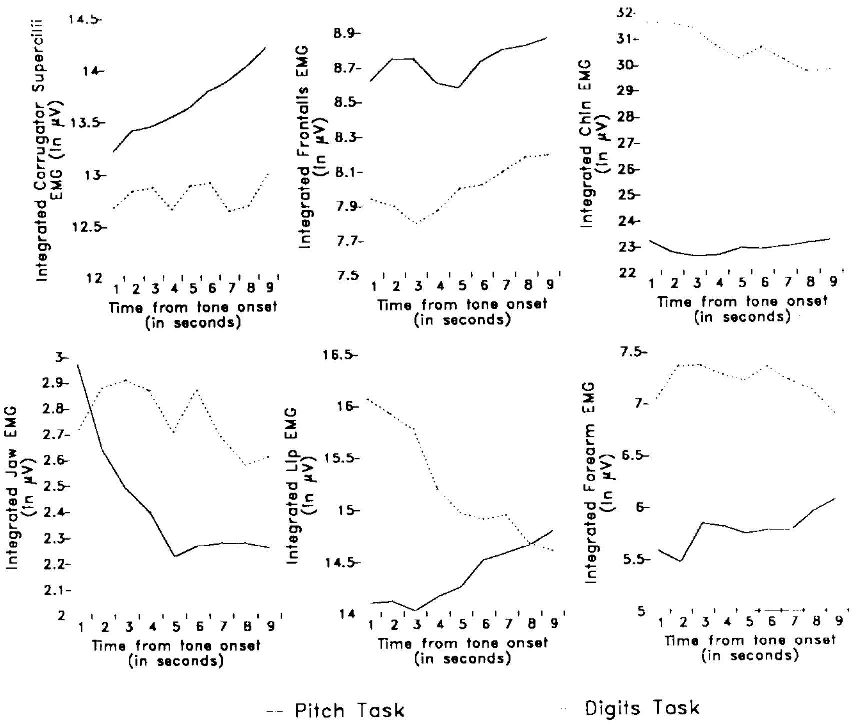

Fig. 6. Mean integrated EMG (in average μV) as a function of time relative to tone onset for both tasks at each muscle location (collapsing over difficulty levels).

the digits task contrasted with an increasing trend for the pitch task (see figure 6).

It can also be seen in figure 6 that the pitch task was accompanied by a strictly monotonic, positive gradient in *corrugator* tension, as compared to the lack of a clear trend for the digits task. On the other hand, a sharp decline can be seen in jaw tension for the pitch task, contrasted again with an inconsistent trend during the digits task.

Discussion

The results confirmed Hypothesis 1 by demonstrating that the pitch discrimination task satisfied the basic heart rate requirements of a sensory (i.e., environmental) intake condition. Heart rate: (a) decreased monotonically as the difficulty of the auditory discrimination increased; (b) declined within trials; and (c) recovered partially after the subject presumably heard the tone change in pitch. Moreover, the decline in heart rate over trials with no pitch change was steeper than the mild decline for digits trials.

On the other hand, Hypothesis 2 was not confirmed: heart rate did not rise significantly as the difficulty of the digits task increased, and actually declined slightly within trials. These negative results suggest that the manipulation of the difficulty levels did not sufficiently affect mental effort on the digits task, even though performance was affected. Our digits task may have been less demanding than the one used by Kahneman et al. (1969). It may be necessary to provide more explicit cues or reinforcements to evoke shifts in mental effort for the kind of digits task used in the present study.

The results support Hypothesis 3. The principal muscle tension difference between the two tasks is the much greater chin tension produced by digit retention. It seems reasonable to attribute the greater chin tension to the subvocalization subjects reported for the digits task. However, chin tension did not vary significantly with difficulty levels for the digits task, so this explanation must be offered cautiously. It is possible that the increase in chin tension for the digits task is related to greater general somatic activation (including postural adjustments, etc.) as suggested in a review by Obrist (1981), though Haagh and Brunia (1984) have demonstrated that considerable tension increases can occur in a variety of muscles without resulting in increased chin tension.

Hypothesis 4 was only partially confirmed. Muscle tension did not change with the difficulty levels of the digits task for any of the muscle areas studied. This lack of EMG results is consistent with the negative results found for heart rate, and again suggests that mental effort was not effectively manipulated by changing the length of the digits string. On the other hand, both *corrugator* and *frontalis* tension increased significantly with the difficulty of the auditory discriminations. Though the decrease in jaw tension only approached significance, the fact that the decrease was monotonic over the three difficulty levels, and confirms a previous result by Holloway and Parsons (1972), argues that this result merits further study.

It should be noted, however, that pairwise comparisons between difficulty levels of the pitch task revealed that the heart rate change and the muscle tension changes for *frontalis* and jaw were not near significance between the moderate and hard levels of difficulty. Furthermore, the increase in *corrugator* tension was dramatic from moderate to hard, but not between easy and moderate levels of difficulty. The changes between the easy and moderate levels suggest increased somatic inhibition accompanied by decreased heart rate, lowered jaw tension (probably to aid hearing), and increased *frontalis* tension due, perhaps, to the tendency to raise the eyebrows in order to widen the eyes, and thus permit more sensory stimulation (i.e., environmental intake).

The only notable change between the moderate and hard levels of difficulty was an increase in *corrugator* tension, consistent with Darwin's (1872) view that eyebrow lowering accompanies any discrimination that is particularly difficult. Note that we found increased facial muscle tension despite the fact that these increases may produce auricular contractions that could actually reduce auditory sensitivity (Djupesland, 1965; Salomon and Starr, 1963).

That facial tension changes occur in opposite directions for different facial muscles in the same task is inconsistent with Brunia's (1984) prediction of a general reduction of facial muscle tension representing a "quieting in this communication system". Our results are more analogous to the "directional fractionation" found for autonomic responses during environmental intake tasks (Lacey, 1967). Rising tension in the brow and forehead muscle region is consistent with, and may actually enhance, increased arousal and alertness. On the other hand, falling tension in the jaw muscles is consistent with somatic inhibition and may form part of the overall response to reduce internal noise. That the muscular changes associated with the expression of "interest" have functional significance is consistent with the general concept behind the classic motor theories of attention (e.g., Pillsbury, 1908; Ribot, 1889). Such motor theories predict that muscle tension changes will accompany (and, in some cases, aid) any effort at shifting or maintaining the focus of attention.

The directional fractionation of facial tension responses found in the present study was recently confirmed in a study based on a simple reaction time task (Damen, van Boxtel, and Brunia, 1989). *Corrugator* (and for some conditions, *frontalis*) tension increased during the foreperiod, while the tension in other muscles, notably those elevating the jaw, decreased.

Because the tone did not always change at the same point within a trial of the pitch task, nor did it change at all for half the trials, it was possible to observe tension gradients under conditions of sustained auditory attention. These tension gradients differed from those found for the digits task, confirming Hypothesis 5. The tension gradients for both lip and arm went in opposite directions for the two tasks. Moreover, the pitch task was associated with a monotonic rise in *corrugator* tension over time along with a monotonic decline in jaw tension, whereas there were no consistent gradients for these muscle areas during the digits task.

Consistent with Hypothesis 6, and similar to the results for heart rate, *corrugator* tension exhibited a gradient reversal on trials during which the pitch of the tone noticeably changed, namely the easy trials, for which the subjects were presumably confident in their detection of the pitch change. If brow tension reflects cognitive or mental effort in general, then the present results are consistent with hypotheses of early motor theories, that the effects of mental effort can be observed in terms of muscle responses even in a very simple sensory attention task.

The chief purpose of the present study was to investigate the changes in muscle tension that accompany the relatively "pure" (i. e., unconfounded with higher-order cognitive processing) mental effort associated with a very simple (although not always easy) sensory discrimination task. A meaningful pattern of heart rate and muscle tension changes was found that differed from that observed in a digit retention task. The principal finding was that whereas tension in the *corrugator* and *frontalis* regions increased with the difficulty of the auditory discriminations, jaw tension decreased. These results were paralleled by the observed monotonically positive tension gradient over time for *corrugator*, and the monotonically negative gradient for jaw tension. It has long been known that muscle tension changes, especially in the brow and forehead areas, accompany effortful mental tasks. The present results demonstrate that such muscle tension changes occur even for a simple sensory task that minimizes cognitive load. Whereas previous studies involving sensory intake emphasized tension decreases (mainly in the chin area), the present study found both increases and decreases in tension as a function of muscle location.

The muscle tension changes for *corrugator*, *frontalis*, and the jaw area coincide with expectations based on the facial expression that has been observed to accompany auditory attention. Moreover, markedly reduced *corrugator* tension immediately after relatively noticeable changes in the pitch of the tone, suggests that this muscle area may, at least in part, reflect attention to the tone, and not just the more general (e.g., affective or attitudinal) aspects of the task situation. In summary, the results of the present study underscore the usefulness of EMG measures as indicators of the processes involved in sensory attention, and point to the need to record from multiple muscle locations before drawing general conclusions about the role of the skeletal muscle system even in relatively simple cognitive processes.

Acknowledgements

The research reported in this article was supported in part by NIMH Grants MH40747 and MH43454 and by NIMH Research Scientist Development Award (MH00875) to Richard J. Davidson, and by NIMH post-doctoral fellowship F32-MH08889-01 to Barry H. Cohen.

We gratefully acknowledge the assistance of Jeffrey Howard in preparing stimuli and running subjects, and Jeffrey Henriques in the preparation of the figures.

References

Bartoshuk, A.K. (1956). EMG gradients and EEG amplitude during motivated listening. *Canadian Journal of Psychology, 10,* 156–164.

Brunia, C.H.M. (1984). Facilitation and inhibition in the motor system: An interrelationship with cardiac deceleration? In M.G.H. Coles, J.R. Jennings, and J.A. Stern (Eds.), *Psychophysiological perspectives: Festschrift for Beatrice and John Lacey* (pp. 199–215). New York: Van Nostrand Reinhold.

Cacioppo, J.T., and Petty, R.E. (1981). Electromyographic specificity during covert information processing. *Psychophysiology, 18,* 518–523.

Cacioppo, J.T., Petty, R.E., and Morris, K.J. (1985). Semantic, evaluative, and self-referent processing: Memory, cognitive effort, and somatovisceral activity. *Psychophysiology, 22,* 371–384.

Clites, M.S. (1936). Certain somatic activities in relation to successful and unsuccessful problem solving. Part III. *Journal of Experimental Psychology, 19,* 172–192.

Cohen, B.H. (1983). *Electromyographic patterns associated with cognition and affect.* Unpublished doctoral dissertation, New York University.

Cohen, B.H. (1986). The motor theory of voluntary thinking. In R.J. Davidson, G.E. Schwartz, and D. Shapiro (Eds.), *Consciousness and self-regulation, Vol. 4* (pp. 19–54). New York: Plenum Press.

Coles, M.G.H. (1974). Physiological activity and detection: The effects of attentional requirements and the prediction of performance. *Biological Psychology,* 2, 113–125.

Damen, E.J.P., van Boxtel, A., and Brunia, C.H.M. (1989, October). *Heart rate and amplitude of facial and jaw EMG activity during the foreperiod of a simple reaction time task.* Paper presented at the annual meeting of the Society for Psychophysiological Research, New Orleans.

Darwin, C.R. (1872). *The expression of emotions in man and animal.* London: John Murray.

Davis, C.M., Brickett, P., Stern, R.M., and Kimball, W.H. (1978). Tension in the two frontales: Electrode placement and artifact in the recording of forehead EMG. *Psychophysiology, 15,* 591–593.

Davis, J.F. (1959). *Manual of surface electromyography.* WADE Technical Report, 59–184. Ohio: Wright Air Development Center.

Davis, R.C. (1939) Patterns of muscular activity during mental work and their constancy. *Journal of Experimental Psychology, 24,* 451–465.

Djupesland, G. (1965). Electromyography of the tympanic muscles in man. *International Audiology, 4*(1), 34–41.

Fridlund, A.J., and Cacioppo, J.T. (1986). Guidelines for human electromyographic research. *Psychophysiology, 23,* 567–589.

Haagh, S.A.V.M., and Brunia, C.H.M. (1984). Cardiac-somatic coupling during the foreperiod in a simple reaction-time task. *Psychological Research, 46,* 3–13.

Hadley, J.M. (1941). Some relationships between electrical signs of central and peripheral activity. II. During "mental work". *Journal of Experimental Psychology, 28,* 53–62.

Hass, H. (1970). *The human animal: The mystery of man's behavior.* New York: G.P. Putnam's Sons.

Holloway, F.A., and Parsons, O.A. (1972). Physiological concomitants of reaction time performance in normal and brain-damaged subjects. *Psychophysiology, 9,* 189–198.

Howell, D.C. (1987). *Statistical Methods for Psychology* (2nd ed.). Boston: Duxbury Press.

Huynh, H., and Feldt, L.S. (1976). Estimation of the Box correction for degrees of freedom from sample data in the randomized block and split plot designs. *Journal of Educational Statistics, 1,* 69–82.

Izard, C.E. (1977). *Human Emotions*. New York: Plenum Press.

Kahneman, D., Tursky, B., Shapiro, D., and Crider, A. (1969). Pupillary, heart rate, and skin resistance changes during a mental task. *Journal of Experimental Psychology, 79*, 164–167.

Lacey, J.I. (1967). Somatic response patterning and stress: Some revision of activation theory. In M.H. Appley and R. Trumball (Eds.), *Psychological stress: Issues in research* (pp. 14–44). New York: Appleton-Century-Crofts.

Locke, J.L., and Fehr, F.S. (1970). Subvocal rehearsal as a form of speech. *Journal of Verbal Learning and Verbal Behavior, 9*, 495–498.

MacNeilage, P.F. (1966). Changes in electroencephalograms and other physiological measures during serial mental performance. *Psychophysiology, 2*, 344–353.

McGuigan, F.J., and Rodier, W.I., III. (1968). Effects of auditory stimulation on covert oral behavior during silent reading. *Journal of Experimental Psychology, 76*, 649–655.

McGuigan, F.J., and Winstead, Jr., C.L. (1974). Discriminative relationship between covert oral behavior and the phonemic system in internal information processing. *Journal of Experimental Psychology, 103*, 885–890.

Obrist, P.A. (1981). *Cardiovascular psychophysiology: A perspective*. New York: Plenum Press.

Obrist, P.A., Webb, R.A., and Sutterer, J.R. (1969). Heart rate and somatic changes during aversive conditioning and a simple reaction time task. *Psychophysiology, 5*, 696–723.

Pillsbury, W.B. (1908). *Attention*. New York: Macmillan.

Ribot, T.A. (1889). *The psychology of attention*. New York: Humboldt.

Salomon, G. and Starr, A. (1963). Electromyography of middle ear in man during motor activities. *Acta Neurologica Scandinavia, 39*, 161–168.

Salzen, E. (1981) Perception of emotion in faces. In G. Davies, H. Ellis, and J. Shepherd (Eds.), *Perceiving and Remembering Faces* (pp. 133–169). New York: Academic Press.

SAS Institute, Inc. (1982). *SAS User's Guide: Statistics, 1982 Edition*. Cary, North Carolina: SAS Institute, Inc.

Schnore, M.M. (1959). Individual patterns of physiological activity as a function of task differences and degree of arousal. *Journal of Experimental Psychology, 58*, 117–128.

Smith, C.A. (1989). Dimensions of appraisal and physiological response in emotion. *Journal of Personality and Social Psychology, 56*, 339–353.

Snodgrass, J.G., and Corwin J. (1988). Pragmatics of measuring recognition memory: Applications to dementia and amnesia. *Journal of Experimental Psychology: General, 117*, 34–50.

Tomkins, S.S. (1962). *Affect, imagery, consciousness. Vol. 1: The positive affects*. New York: Springer.

Travis, L.E., and Kennedy, J.L. (1949). Prediction and automatic control of alertness: III. Calibration of the alertness indicator and further results. *Journal of Comparative and Physiological Psychology, 42*, 45–57.

Vaughn, A.O., and McDaniel, J.W. (1969). Electromyographic gradients during complex visual discrimination learning. *Psychonomic Science, 16*, 203–204.

Wallerstein, H. (1954). An electromyographic study of attentive listening. *Canadian Journal of Psychology, 8*, 228–238.