PSYCHOPHYSIOLOGY

Vol. 23, No. 5
Printed in U.S.A.

Guidelines for Human Electromyographic Research

ALAN J. FRIDLUND
University of Pennsylvania

AND JOHN T. CACIOPPO
University of Iowa

ABSTRACT

Guidelines are proposed for the collection, analysis, and description of electromyographic (EMG) data. The guidelines cover technological issues in EMG recording, social aspects of EMG experimentation, and limits to inferences that can be drawn in EMG research. An atlas is proposed for facial EMG electrode placements, and standard EMG terminology is suggested.

DESCRIPTORS: Apparatus, Biofeedback, Electromyography, Electrophysiological recording, Experimental design, Facial expression, Facial muscles, Muscles, Instrumentation, Statistical analysis.

During the Fall of 1984, the Editor of *Psychophysiology*, David Shapiro, asked us to begin work on guidelines for the collection, analysis, and description of electromyographic (EMG) data. This request followed the growing use of EMG methods and a lack of existing guidelines such as those formulated for electrodermal and heart rate research (Fowles et al., 1981; Jennings et al., 1981). In order to sample broadly the EMG expertise that exists in the Society of Psychophysiological Research, we initiated during the summer of 1985 a survey of over one hundred psychophysiologists experienced in EMG. Their responses form the basis for the guidelines in this document. We thank them for contributing so thoughtfully and extensively.[1]

Our intent in advancing EMG publication guidelines is not to establish fixed standards or circumvent longstanding practices of experienced investigators. Rather, we review common problems in, and optimal methods for, the handling of EMG data in ways that reflect the behavior of experts in the field. By providing a coherent summary of expert opinion regarding current EMG practice, we hope that readability and comparability of future EMG studies will be enhanced.

EMG research has benefited considerably from recent developments in detection and computing technology. Psychophysiologists have pioneered in these developments. Psychophysiologists have also become much more sophisticated in non-technological aspects of experimentation. For this reason, we focus not only on the technical aspects of EMG recording, but also on the social aspects of EMG experiments, and on the interpretation of EMG responses. We emphasize the general psychophysiological use of EMG. We do not discuss EMG application in neurodiagnosis or rehabilitation medicine; excellent treatments are available elsewhere (cf., Basmajian & De Luca, 1985; Goodgold & Eberstein, 1977).

Physical Setting

The physical setting of EMG recording includes equipment, laboratory and computer configurations, and procedures for optimizing the quality of EMG recording. In this section, we discuss: technical aspects of noise and grounding; transducers; electrode site specification and preparation; ampli-

[1]We owe special thanks to Anton von Boxtel, Paul Fair, Stephen Fowler, Joseph Hager, and Louis Tassinary for their extended critiques and consultation. We thank all the respondents to the survey. Many provided exceptionally detailed and thoughtful comments and suggestions. We thank in particular: Kees Brunia, Alexander Dale, Roman Ferstl, Frances Graham, Mary Losch, Robert Malmo, James Raczynski, Joyce Segreto, and Noburu Sumitsuji.

This research was supported in part by NIH Biomedical Research Support Grant 2-S07-RR-07083-20 to A. J. Fridlund from the University of Pennsylvania, and by NSF grant BNS-8414853 to John T. Cacioppo.

Address requests for reprints either to Alan J. Fridlund, Department of Psychology, University of Pennsylvania, 3815 Walnut Street, Philadelphia, PA 19104; or John T. Cacioppo, Department of Psychology, University of Iowa, Iowa City, IA 52242.

fication; signal filtering, integration, and smoothing; and formats for recording and presenting data.

Noise and Grounding

The EMG signal is a quasi-random train of motor unit action potentials discharged by the contraction of striate muscle tissue. This signal train is characterized by a frequency range from several Hz to over 2 kHz, and by amplitudes ranging at the surface of the skin from fractions of a μV to several hundred μV. As a result of its amplitude and frequency characteristics, detection of high-quality EMG signals requires conscientious application of noise-reduction and grounding practices.

Recording the low-level signals encountered in EMG research usually requires that the laboratory be shielded to minimize electrical artifact. With earlier types of EMG instrumentation, a shielded compartment (i.e., a Faraday cage) was required for interference-free recording. Newer EMG equipment with better noise rejection now allows more tolerance of noise sources in the laboratory. We provide guidelines for minimizing noise from common sources, and for measuring EMG system noise levels.

Noise Sources in the EMG Laboratory. Noise in the laboratory arises from several common sources. 60-Hz noise emanates from lights and electrical transformers. Both can be shielded. Relay equipment is notorious for generating electrical noise during switching. Arc-suppression diodes and capacitors can be placed across relay coils, and in many cases, across the relay contacts themselves. Computer clock and electrical bus noise can superimpose high-frequency noise artifacts on recorded signals. Computers can be installed in shielded enclosures and connected to the AC line through commercially available surge suppressors and AC line filters. A/D converters, which are often located close to EMG equipment, can be doubly shielded and relocated far from low-level signal cables (i.e., those running from the subject to the EMG amplifiers). For maximal noise attenuation, shielded ribbon cable should be used for connecting the computer with its peripherals (e.g., printer, modem, input/output ports).

Televisions and video monitors are potent laboratory noise sources. All TVs and monitors that use cathode ray tubes generate high-frequency noise from the transformers used for CRT beam deflection. This noise can range from about 15 kHz to several hundred kHz. It is best eliminated by placing the devices at least two feet away from EMG equipment, and if necessary, in a grounded metal cabinet.

Television equipment can also be a potent source of radio-frequency (RF) noise. These RF signals can on occasion induce noise in EMG monitoring and video recording. Flat 300 Ω television cable is unsuited for most laboratory use because of its high leakage of RF energy. Coaxial cable with shielded connectors should be used exclusively for transmitting RF and video signals within the laboratory. Standard televisions leak RF energy from their antenna terminals even when no cable is connected. This RF energy can be shunted with commercially available RF filters or "traps." Using composite or direct-drive video monitors rather than standard televisions will eliminate this RF interference altogether.

Occasionally, a strong nearby radio or television transmission station can cause severe RF interference. Alerting the station in question of its spurious emissions is one course of action. In addition, RF filters can be placed at the outputs of EMG amplifiers, smoothers or integrators, and at A/D converter inputs, to attenuate the interference acceptably. Attempting to place RF filters at EMG amplifier inputs is ill-advised, since the filters are likely to degrade input impedance and general noise-rejection characteristics (i.e., common-mode rejection; see below).

Several general rules also apply in minimizing noise (see the general discussion of noise reduction in physiological recording by Bramslev, Bruun, Buchthal, Guld, and Petersen, 1967). Any noise-generating equipment should be located as far as possible from the participant and from EMG electrode cables and amplifiers. All cables carrying low-level signals (such as input signals from EMG electrodes) should be as short as possible. Cables should have a low impedance, and they should be shielded and grounded using established techniques (Strong, 1970).

Measuring System Noise. Noise in any EMG system is best tested by placing a dummy resistive load across the EMG amplifier inputs to simulate a set of electrodes placed on the participant. Fridlund and Fowler (1978) detailed how to construct this dummy load. Three 10 kΩ resistors are placed in a "triangular" configuration, with each vertex of the triangle connected to one of the three amplifier input leads (i.e., the inverting, noninverting, and "indifferent" or ground leads). The amplifier's output signal is then observed on an oscilloscope with a shielded probe at a high amplifier gain (e.g., gains from 50,000 to 100,000). Using this arrangement, noise sources can be discovered and eliminated systematically. Although many EMG amplifiers include "notch" filters to eliminate 60-Hz noise, it is

much better to minimize noise before it is amplified. This is because notch filters attenuate frequencies on either side of 60 Hz to a varying degree.

Grounding. Although modern amplifiers with high input impedances have minimized risks associated with EMG monitoring, imperfect or incorrect grounding (i.e., "ground loops") can result in 60-Hz noise and, in rare circumstances, danger to the research participant. Ground loops can be avoided by ensuring that all equipment is grounded in the laboratory *at exactly one point.* This grounding point should be a ground plane deliberately designed for the purpose. Relying on the AC line ground at the outlet box is potentially unsafe and ineffective.

The participant connected to electrodes should also be grounded *only at one point,* usually by a ground electrode or a conductive strap. To avoid a participant's becoming one path in a ground loop, all conductive surfaces such as equipment cabinets, instrument panels, etc., should be out of reach of the participant. Any experimental manipulanda should be thoroughly insulated, or better yet, constructed of nonconductive material. Strong (1970) and Bramslev et al. (1967) have also detailed biomedical grounding techniques.

Transducers

Surface Electrodes. EMG researchers in psychophysiology typically use surface pelletized silver-silver chloride (Ag-AgCl) electrodes. This surface is used in preference to stainless steel or other alloys because it generates only a small DC offset current when in contact with skin. Surface electrodes are attached to skin with double-stick adhesive collars. These electrodes detect the EMG signal through skin using a conductive paste or gel, and are most often used in a bipolar (paired electrode) configuration.

Surface EMG electrodes have several advantages. They show broad (nonselective) detection of firings of aggregates of motor units that correlate well with the overall level of contraction of muscle groups underlying and near the electrodes (Lawrence & De Luca, 1983). The poor selectivity of surface electrodes can make it difficult to pinpoint exactly which muscles are contracting. When surface electrodes are used, it is particularly inappropriate to attribute the resulting EMG signals to specific muscles (the same caution applies, albeit to a lesser extent, with needle electrodes; see below). For example, electrodes are often placed on the forehead to measure actions of the *lateral frontalis,* the muscle that raises the outer brow (e.g., Segreto-Bures & Kotses, 1982). However, this placement also detects actions of many other facial muscles, both proximal (such as the *medial frontalis,* which lifts the inner brow, and *corrugator supercilii,* which knits the brow) and distal (such as the *masseter,* which adducts the jaw). For this reason, studies using surface electrodes should refer to EMG signals as reflecting activity from sites (e.g., "forehead-site EMG" or "*medial frontalis* region") rather than muscles (e.g., "frontalis EMG").

Surface EMG electrodes are noninvasive and simple to attach. Unfortunately, their placement with adhesive collars can obstruct movement, especially when they are used to measure actions of facial muscles. The draping of the electrode wires on the subject can be distracting or restraining if not done carefully. Participants may be self-conscious about the electrodes on their faces or bodies during an experiment, and as a result they may alter their behavior (see Demand Characteristics section, below).

The size of the Ag-AgCl electrode surface (the *detection surface*) affects the detected EMG signals. Smaller Ag-AgCl surfaces are more selective, and the smaller electrode housings allow closer inter-electrode spacing with resulting higher selectivity. Differences in the frequency response of electrodes of varying sizes are typically negligible (van Boxtel, Goudswaard, & Schomaker, 1984).

Surface electrodes are manufactured in a variety of sizes. The most important size parameter is that of the Ag-AgCl detection surface which contacts the skin. Electrodes with .5 cm diameter Ag-AgCl detection surfaces and 1.5 cm diameter housings are used most commonly for limb and trunk EMG sites. Miniature electrodes with .25 cm Ag-AgCl detection surfaces and .5 cm or 1 cm housings are used most commonly for facial EMG sites.

Our respondents preferred using electrodes with 0.5 cm Ag-AgCl detection surfaces for limb and trunk EMG sites, and those with 0.25 cm Ag-AgCl detection surfaces for facial EMG sites. We recommend this usage. Our respondents indicated no clear preference for inter-electrode spacing. For purposes of standardization, we recommend *ad hoc* a 1 cm inter-electrode spacing for the 0.25 cm electrodes, and except where otherwise noted below, a 1.5 cm spacing for the 0.5 cm electrodes.

An exception to the latter guideline concerns the use of the bilateral forehead .5 cm electrode placement described by Davis (1952). This is erroneously called a "frontalis" placement in the biofeedback literature. This placement detects muscular actions throughout the head and neck (Basmajian, 1976). Using widely spaced large electrodes makes sense only if one is interested in a placement with low selectivity. We discourage using this forehead place-

ment unless the EMG signal is interpreted to reflect broad EMG activity in the head and neck. The placements described later should be used for more selective facial EMG recording.

An alternative kind of surface electrode incorporates integral integrated-circuit preamplification (Basmajian & De Luca, 1985). In addition to offering noise rejection equal to or superior to present methods, this electrode does not require pastes or gels, but rather relies on direct skin-to-metal contact. It can be constructed in a concentric configuration. This type of electrode offers obvious advantages in ease of preparation, and very possibly, EMG signal quality. However, these electrodes are not yet widely available, and experience with these electrodes is still too limited to formulate guidelines for their use.

Fine-Wire and Needle Electrodes. Fine-wire and needle electrodes are used frequently in rehabilitation medicine for diagnosis of muscle function and nerve conduction. Few of our respondents indicated experience with needle electrodes. Fine-wire electrodes (cf., Basmajian & Stecko, 1962) have been used in a few experimental psychophysiological investigations. These include studies of laryngeal movements in "covert language" tasks, and the work by Sumitsuji et al. on posed facial expressions of emotion (e.g., Sumitsuji, Matsumoto, Tanaka, Kashiwagi, & Kaneko, 1967).

Indwelling electrodes are made of platinum or stainless steel inserted through skin directly into muscle or via a 26 gauge needle carrier. Sumitsuji (personal communication, October, 1985) fashions fine-wire electrodes for facial EMG from 70–80 micrometer-diameter stainless-steel wire, insulated except for 2 mm at the tip. He inserts these manually through the hair follicle into the facial muscle, apparently without undue irritation.

Fine-wire electrodes have several advantages, especially for facial EMG recording. They do not obstruct small movements as much as surface electrodes. Many electrodes can be used simultaneously without hiding facial areas from camera view. They show extremely selective detection (i.e., they have pickup regions from one to a few motor units), and they are the method of choice when specific small muscle groups must be isolated experimentally. They are very sensitive to small levels of muscular contraction.

Fine-wire electrodes have corresponding disadvantages. Large movements of either the target muscle or adjacent muscles may dislodge them or relocate them within the muscle. Their selectivity may result in an EMG signal that is not sufficiently representative of overall muscle activity for the intended purpose. Medical consultation may be required for their implantation. Occasionally, infection can result from improper sterilization. Finally, these electrodes are typically used on laboratory personnel, and may be problematic with naive subjects.

A few respondents who described experience with both surface and indwelling recording expressed clear preference for the surface method in psychophysiological research. However, increasing interest in isolating small muscle groups electromyographically may mandate more use of indwelling recording. At this time, too few psychophysiologists have had sufficient experience to warrant guidelines for its use.

Electrode Site Specification

Agreement among researchers about electrode placements over target muscle groups is necessary to ensure that findings across studies are comparable. Establishing guidelines for standard electrode placements is a formidable task. It requires a balancing of factors such as: 1) proximity of a proposed site to underlying muscle mass with minimal intervening tissue or interfering signals (such as the electrocardiogram); 2) position of electrode relative to muscle tissue fiber size, location, and orientation (a paired electrode placement parallel to the course of the muscle fibers usually maximizes selectivity); 3) avoidance of straddling the motor-endplate region in placing differential electrodes (Tassinary, Geen, & Cacioppo, 1986); 4) ease of location of sites via anatomical landmarks that show relative uniformity across participants; 5) ease of electrode attachment to these sites without undue problems from skin folds, bony obstructions, etc.; and 6) minimizing crosstalk from adjacent sites.

Until the requisite empirical work is performed, *ad hoc* conventions about electrode placements are needed to maximize reliability if not ultimate validity. For standardizing electrode placements, most EMG researchers in psychophysiological studies have used the 35-year-old manual by Davis (1952). We recommend continued use of these placements for EMG recording only in the limb and neck regions. Despite the burgeoning literature using facial EMG to measure mood and emotion (see Fridlund & Izard, 1983), no EMG site "atlas" has been available for the facial musculature.

Relevant data are available for only three facial muscles. Tassinary et al. (1986) reviewed the anatomical data regarding the location of the *zygomatic major* and *corrugator supercilii* muscles in the face, and conducted three experiments to isolate the electrode sites that met the six criteria outlined above. The activity of each muscle was verified with visible coding using the Facial Action Coding System (Ekman & Friesen, 1978). Limited data regarding the

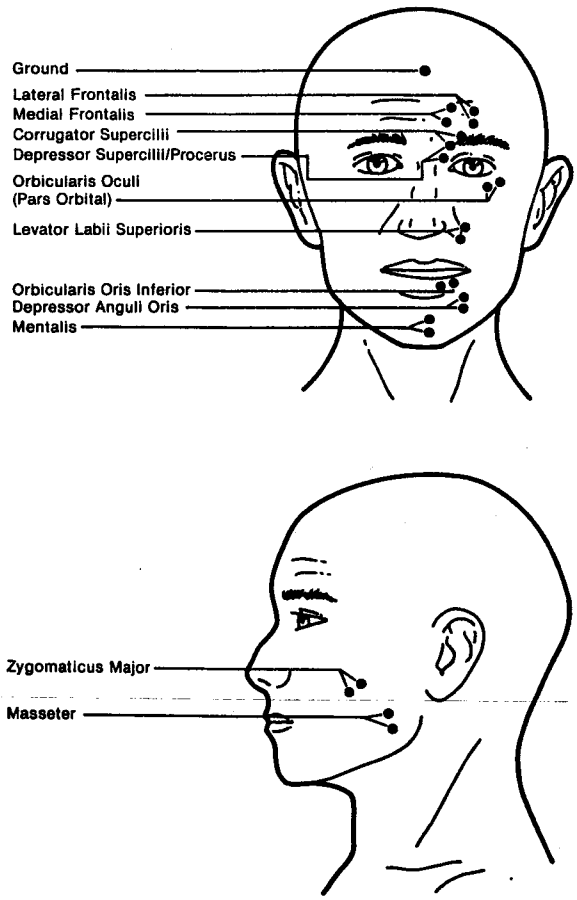

Figure 1. Atlas of EMG electrode placements for surface differential recording over major facial mimetic muscles.

Corrugator supercilii (knits the brow). One electrode is affixed directly above the brow on an imaginary vertical line that traverses the *endocanthion* (the inner commissure of the eye fissure). The second electrode is positioned 1 cm lateral to, and slightly superior to, the first on the border of the eyebrow. (Note: EMG activity may show high crosstalk with activity from *depressor supercilii* and *procerus*.)

Depressor anguli oris (lowers the upper lip outside the commissure, and depresses the angle of the mouth). One electrode is affixed 1 cm lateral to, and 1 cm inferior to, the *cheilion* (lip corner), and the second is placed 1 cm inferior to the first.

Depressor supercilii and *Procerus* (pull the brow in and down; combined placement). One electrode is affixed directly above the brow on an imaginary vertical line traversing the *endocanthion*. The second is placed at a 1 cm distance on the side of the nasal bone. (Note: EMG activity may show high crosstalk with activity from *corrugator supercilii*.)

Lateral frontalis (raises the outer and middle brow). Electrodes lie on an imaginary vertical line 1 cm lateral to the vertical that traverses the pupil of the eye (during centered gaze). The inferior electrode of the pair is affixed 1 cm above the upper border of the middle of the brow; the second electrode is placed 1 cm superior to the first.

Levator Labii Superioris and *Levator Labii Alesque Nasi* (raise the upper lip, widen nostrils; combined placement). Electrodes are placed 1 cm lateral to the baseline of the *ala nasi* (nostril). The inferior electrode is .5 cm below the *alar curvature point* (the most lateral point on the *ala nasi* baseline); the second electrode is positioned 1 cm superior and slightly lateral to the first.

Masseter (adducts the jaw). The first electrode is situated along an imaginary line extending from the *gonion* (the most lateral point on the mandibular angle, by palpation) to the *exocanthion* (the lateral commissure of the eye fissure), 2 cm from the *gonion*. The second electrode is placed 1 cm superior, and slightly medial (i.e. toward the mouth), to the first electrode.

Medial frontalis (raises the inner brow). Electrodes lie on an imaginary vertical line 1 cm medial to the vertical that traverses the *endocanthion*. The inferior electrode of the pair is affixed 1.5 cm above the upper edge of the inner brow; the second electrode is placed 1 cm superior and slightly lateral to the first.

Mentalis (raises chin and pushes lower lip upward). Electrodes are affixed .5 cm lateral to the midline. The first electrode is placed .5 cm superior to the *pogonion* (the most anterior midpoint of the chin, overlying the bony protruberance on the mandible), and the second is placed .5 cm inferior to the *pogonion*.

Orbicularis oculi, inferior orbital portion (constricts the eye fissure). The first electrode is affixed 1 cm inferior to the *exocanthion* (outer commissure of the eye fissure). The second electrode is placed 1 cm medial to, and slightly inferior to, the first, so that the electrode pair runs parallel to the lower edge of the eyelid.

Orbicularis Oris, inferior portion (mouth sphincter; contracts the lips, and compresses them together and forward). The first electrode is affixed 1 cm below the *cheilion*. The second electrode is placed 1 cm medial to, and slightly inferior to, the first, so that the electrode pair runs parallel to the lower lip border.

Zygomatic major (pulls the lip corner up and back). One electrode is placed midway along an imaginary line joining the *cheilion* and the *preauricular depression* (the bony dimple above the posterior edge of the zygomatic arch), and the second electrode is placed 1 cm inferior and medial to the first (i.e., toward the mouth) along the same imaginary line.

Ground. The ground electrode is placed at the midline approximately 3–4 cm superior to the upper borders of the inner brows.

NOTE: Anatomical landmarks are from Farkas (1981). Muscle actions are from Izard (1980). Electrode locations refer to electrode centers.

utility of alternative placements over *lateral frontalis* were provided by Williamson, Epstein, and Lombardo (1980). In Figure 1 we propose differential EMG electrode placements over the major facial mimetic muscles. Placements are based upon available data for *zygomatic major, corrugator supercilii*, and *lateral frontalis*, and are *ad hoc* for the remainder.

The placement of the ground electrode on the participant also affects noise and 60-Hz rejection in the EMG signals. As noted above, only one ground electrode should be used, and all inputs should be configured to share this ground. In general, 60 Hz is minimized by locating the ground electrode close but not directly adjacent to the EMG sites being monitored. In facial EMG recording, one electrode placed mid-forehead near the hairline works well. Some researchers attach a ground reference electrode near each EMG-electrode pair and strap these multiple grounds together. This results in a "triad" configuration at each EMG site. Use of the triad at each EMG site is usually unnecessary, and can on occasion result in excess 60-Hz noise.

Electrode Site Preparation

Every EMG researcher has a favorite method of EMG site preparation. We focus on site preparation for surface EMG detection.

Our respondents indicated no concensus in site preparation practices. Some researchers favored drying the skin with acetone (inadvisable given its putative carcinogenic properties), whereas some preferred use of a hydrating solution. Others just cleaned the target sites with alcohol-wetted swabs. Nor was there concensus on abrasion of skin to reduce inter-electrode impedance. This procedure is usually inconvenient and annoying for participants, and it is sometimes painful as well. We believe that the difference in opinion on skin abrasion reflects gradual changes in EMG technology. Nearly all texts on EMG technique recommend abrasion of skin at the electrode site in order to lower inter-electrode impedance to 5 or 10 kΩ, and many methods have been suggested for this procedure. Some of our respondents recommended rubbing the skin with fine sandpaper. Others used gritty Redux paste (Hewlett-Packard) "twirled" on the site with a cotton swab. Still others scratched the skin lightly with a sterile #26 needle. With suitable recording equipment, abrasion for low inter-electrode impedance may be unnecessary under typical recording circumstances.

The need to achieve such low inter-electrode impedances stems from the design of the amplifier. Compared to newer technologies, older amplifiers generated much more noise with high input impedances at the electrodes, and their low internal input impedances (by current standards) required a low-resistance path at the source to avoid attenuating the EMG signal significantly. The inter-electrode impedance requirement is obviated in several current amplifier designs, which use input devices such as junction field effect transistors (JFETs; see Fridlund & Fowler, 1978). These amplifiers have high input impedances, and they do not increase the noise they produce when operating at high input impedances (i.e., they show flat noise/impedance gradients). The high input impedances also cause less alteration of the frequency characteristics of the EMG signals the amplifiers detect. Fridlund, Price, and Fowler (1982) presented a circuit for an EMG amplifier with optically isolated, ultra-high-impedance JFET inputs.

This noise/impedance gradient of an EMG amplifier can be calculated by using dummy input loads of varying resistances, and measuring the noise at the amplifier outputs (see section on Minimizing Noise, above). Signal loss engendered by low amplifier input impedances can be calculated by applying a standard signal to the amplifier inputs through a voltage divider. The investigator can then determine how much signal is lost, and noise is generated, at varying inter-electrode impedance levels and determine the extent to which skin preparation is necessary.

Reduction of inter-electrode impedances to 5 or 10 kΩ is most necessary when the EMG signals to be detected are very small and the EMG amplifier is an older, noisy design. In these cases, inter-electrode impedances can be measured using simple impedance meters (see Dunseath, 1982). Merely measuring inter-electrode resistance using a volt-ohmmeter is common practice, and for most purposes is entirely sufficient. This is because the skin acts as a parallel R-C circuit, and as a result the impedance between electrodes can be no higher than the resistance (Swanson & Webster, 1974). For newer amplifiers, and for large EMG signals, skin abrasion for impedance reduction is less important and can be omitted for maximal convenience to participants. If it is omitted, investigators should nevertheless ensure that their EMG signals remain free of interference and artifact.

There are two situations, however, in which reduction of inter-electrode impedances may be important regardless of amplifier characteristics. The first is in monopolar recording. High contact impedance may result in greater susceptibility to electrical interference in noisy environments. The second is in differential recording with paired, separate electrodes, for the special case in which there may be a potent electrical noise source nearer one electrode than another (for example, a nerve stimulus delivered near an EMG electrode pair). In this special case, high inter-electrode impedance may make signal detection more vulnerable to electrical interference due to differential amplification of the nearby noise source. Noise sources more distal to

paired electrodes are usually not so problematic, since their signals are cancelled by the EMG amplifier's common-mode rejection.

With the advent of JFET amplifiers integral to differential EMG electrodes with concentric surfaces, the need for site preparation will be reduced considerably or eliminated, even in generally noisy environments and with proximal electrical noise sources. For the time being, experimenters should be aware of the factors involved and justify their procedures accordingly.

The conductive medium in EMG recording serves to stabilize the hydration and conductivity of the skin underlying the electrode. It also attenuates electrode-movement artifacts by forming a stable, well-defined contact between the skin and the electrode surface. Many brands of conductive electrode pastes and gels are available for EMG electrodes. We found no data suggesting that the various commercially available conductive media affected the quality of the detected EMG signal. Pending evidence to the contrary, we recommend selecting conductive media based on convenience and price.

Amplification

EMG signals are amplified using two methods. The first method, called single-ended or monopolar recording, employs one EMG electrode over each target site, referenced to a ground electrode in contact with an electrically neutral point on the participant's body. The second and most common method is differential or bipolar recording, in which the difference signal between paired EMG electrodes (with respect to a third, ground electrode) is amplified and carried through the signal-processing chain (Faulkenberry, 1977; Ott, 1974). Any noise present at the electrode site is likely to be common to both electrodes ("common-mode" signal) and will be rejected. This "common-mode rejection" is responsible for the superior noise and 60-Hz artifact rejection of differential amplification. Bipolar recording is also more selective (Basmajian & De Luca, 1985).

Monopolar recording is characterized by a much more general pickup region than bipolar recording. In addition, it can offer a more linear measure at intense levels of muscle contraction (see Moritani & De Vries, 1978). Our respondents, who described experience with both monopolar and bipolar recording, preferred bipolar recording in their research thus far. We therefore recommend bipolar recording as the method of choice. Monopolar recording should be used only with explicit justification.

EMG researchers typically use general-purpose differential amplifiers for detecting EMG signals, and relatively little attention has been paid to the needs of the EMG researcher in amplifier design or construction. Some researchers pay scrupulous attention to the technical specifications of their equipment. Others are constrained to use whatever equipment is available, including instrumentation designed only for the clinician or biofeedback practitioner. Often this equipment is furnished with inaccurate or meaningless specifications, and there is limited flexibility in adjusting measurement parameters such as signal gain, detection passband, and type of signal integration or smoothing.

Providing minimal specifications for EMG amplifiers is difficult, given the numerous tasks for which the amplifiers are used and the varying stringency required of their measurements. We provide general guidelines regarding technical specifications increasingly likely to be encountered in state-of-the-art EMG amplifiers. These include:

1. Input impedance—at least 100 MΩ, both differential and common-mode, shunted by 5 picofarads.

2. Common-mode rejection—at least 90dB with a 10 kΩ source imbalance.

3. Noise—no more than 1 μV (*rms*) referred to the amplifier inputs, measured with a 10 kΩ dummy input load and through a 10–1000 Hz (−3dB points, 12dB/octave slopes) bandpass filter.

4. Protected inputs—amplifiers should be protected against damage due to high-voltage input transients. The inputs should be able to withstand 150 V pk, differential or common-mode, applied for 1 second.

5. Low output impedance—no more than 10 Ω.

6. Frequency response—at least 5–10,000 Hz (+3dB), with no more than 5% total harmonic distortion. The detection passband is usually limited for practical EMG use by subsequent filtering (see below).

7. Gain—variable from 10 to 100,000. Actual gain should deviate no more than 5% from the gain setting.

Signal Filtering

Some filtering of raw EMG signals is usually performed to: 1) increase signal-to-noise ratio, 2) decrease 60-Hz and EEG/EKG artifact, and 3) reduce inter-site crosstalk. Studies have generally shown that the primary energy in the surface EMG signal lies between about 10 and 200 Hz (Hayes, 1960). Between 10 and 30 Hz, this power is due in great part to the firing rates of motor units; beyond 30 Hz the shapes of the motor unit action potentials

are more important. Since skin and other tissue act as a low-pass filter, this figure varies considerably depending upon inter-electrode spacing and distance of electrodes from underlying muscle (Lindstrom, 1970).

Because of the vagaries of semiconductor fabrication, preamplfier noise is most intrusive below 10 Hz and above 500–1000 Hz (Soderquist, 1976). Generally, attenuating the high frequencies in the EMG signal (above, for example, 1000 Hz or even 500 or 250 Hz) reduces amplifier noise but rounds the peaks of the detected motor unit action potentials. Attenuating the low frequencies (below, for example, 70–100 Hz) reduces 60-Hz, EEG, and EKG artifact, and reduces inter-site crosstalk (because of the intervening tissue's preferential transmission of low frequencies), but it also blocks a good proportion of the EMG signal.

Retaining sharp signal peaks may be critical for waveform or spectral analysis of single motor units or motor unit action potential trains, but it is less critical when overall estimates of muscle tension are desired. Use of an EMG signal passband that is too restricted may result in inaccurate appraisal of tension in fatigued muscle, since shifts in EMG spectra are observed with fatigue (Mulder & Hulstijn, 1984). There may also be implications of passband selection for discriminating "fast" vs. "slow" motor units, and for detecting proximal vs. distal motor units. An additional variable is that filters used to set the EMG passband may differ in the slopes with which they attenuate frequencies outside their range.

Thus selection of an EMG detection passband must proceed based on susceptibility to artifact, presence of amplifier noise, consideration of the amplitude of the EMG signals to be detected, and need to minimize inter-site crosstalk. We suggest a passband from 10 to 500 or 1000 Hz for wideband monitoring. If low-frequency artifact and inter-site crosstalk are problematic, then filtering out frequencies below 90 or 100 Hz is recommended. If the EMG signals to be detected are weak and some measurement nonlinearity is tolerable, then attenuating frequencies above 500 or 250 Hz is recommended. Sharp filter slopes (e.g., greater than 12dB/octave), although they are desirable in EEG research to separate signal components, are not necessary. Usually the 6dB/octave filter slopes provided by simple resistor-capacitor (RC) circuits are quite sufficient for EMG. Filters should be characterized in terms of their characteristics (e.g., second-order Butterworth; see Berlin, 1977).

If EMG signals are subjected to spectral or temporal analysis, then phase lags introduced by analog filters (including 60-Hz notch filters) complicate interpretation of EMG phase spectra and coherence estimates. Digitally filtering the signals or using special phase-corrected analog filters avoids this difficulty (see discussion by Doyle and Hyde, 1983).

Signal Integration and Smoothing

The raw or filtered EMG signal is a stochastic train of motor unit action potentials. When heard through a speaker, the raw EMG signal sounds like popcorn popping. Except in rare cases, the raw signal is unsuitable for quantification without alteration. Usually the signal is rectified (either full-wave or half-wave rectification) and passed to an integrator or smoother. An exception is in the spectral analysis of EMG signals, in which integration or smoothing has distorting effects.

"Integration" and "smoothing" are often conflated in the EMG literature. Properly speaking, integration is the temporal summation or accumulation of EMG activity. "Smoothing" is simply low-pass filtering, envelope detection, or averaging of the signal. In smoothing, there is implicit integration, but with a built-in signal decay.

Several choices of integration or smoothing have been used in EMG research (cf., Tursky, 1964). In "resetting" integration, filtered and rectified EMG accumulates until either a specified time interval elapses (time-resetting integration) or a certain integrated voltage is achieved (voltage-resetting integration). In time-resetting integration, the voltage at the integrator at time-out is sampled and used as the index of integrated EMG activity. In voltage-resetting integration, the time required for the reset indicates integrated EMG activity.

The "contour follower" is a precision rectifier (Graeme, 1975) connected to a low-pass filter. It acts as a running averager of ongoing EMG activity, by providing a varying voltage proportional to the envelope of the EMG signal. It has in the past been erroneously labeled a type of integrator, but it in fact "smoothes" the EMG signal rather than integrating (accumulating) it. Simple signal smoothers often used in prefabricated EMG biofeedback machines to reduce meter fluctuations are examples of contour followers. Precision contour followers are used frequently in psychophysiological research. Fridlund (1979) presented a circuit for a contour follower.

Integrators and contour followers usually have selectable time constants. Short integration time constants produce great sensitivity to momentary fluctuations in EMG signals. Longer time constants blur rapid fluctuations in favor of broad, slow changes in the incoming EMG signal. When measuring a rapidly fluctuating EMG signal, an integrator or contour follower with a long time constant

will not be speedy enough to register signal peaks, and the resultant output will underestimate EMG signal strength. Estimates will be more accurate with EMG signals that vary more slowly. Conversely, time constants that are too short will be too sensitive to momentary EMG fluctuations, and the economic advantages of smoothing will be sacrificed.

Time constants are best chosen after pilot research to examine the characteristics of the EMG responses in question. An FM tape recorder can be used to obtain a recording of a pilot subject's EMG activity. This activity can be replayed while adjusting the integrators or contour followers until a time constant is obtained that smoothes the EMG signal sufficiently while preserving its important phasic features. The numerical time constant can then be determined precisely by the calibration method proposed below.

We further recommend using contour followers over either voltage- or time-resetting integrators. The only advantage of the integrators is that accumulated activity is more easily read on a polygraph chart. However, they are unusable when measuring EMG signal dynamics, and their resets must be translated to voltage integrals to be comprehensible. Most psychophysiologists are now (or shortly will be) using computer data acquisition, and the direct proportional output of the contour follower allows simpler sampling routines and direct translation of EMG activity to voltages. One liability is that contour followers, since they incorporate low-pass filtering, introduce a phase shift which can distort temporal or frequency analyses of the EMG signal (see sections on Filtering and Analysis).

Modes of Recording and Presenting Data

EMG data classically were recorded and presented on polygraph charts, but computer digitizing and recording are now quite common. The process of sampling EMG signals using a computer mandates that careful choices be made about signal sampling rates, the precision of the A/D converters used, and the signal gains used to feed the A/D converters.

Sampling Rate. Some of these choices are relatively easy. For example, in EMG frequency analysis the Nyquist relation specifies that EMG signals be sampled at a rate at least twice that of the fastest EMG frequency component of interest. Filter parameters are then adjusted to guard against aliasing at the chosen sampling frequency. Unfortunately, the Nyquist relation assumes both perfect filtering and continuous sampling, and these conditions are not satisfied in the real world. A good rule of thumb is to sample at 4–8 times the highest frequency of interest to avoid aliasing and allow reconstruction of the original waveform with minimal smoothing.

Most EMG researchers digitize integrated or smoothed EMG signals and are interested only that their recordings are representative of overall EMG activity. Our respondents used sampling rates from 1 sample every several seconds to 1 kHz per channel.

Clearly the rates at which EMG signals are sampled are highly dependent upon the task and the temporal resolutions required. A sampling rate that is too high wastes computer time and storage space, and it complicates data analysis. Proper use of integrators or smoothing with contour followers can allow slow sampling rates to be representative of overall EMG levels during a measurement epoch.

There is a danger in undersampling. One cannot know the temporal dynamics of the EMG signal, and these dynamics may contain valuable information about muscular action (see section on temporal analyses, below). Fridlund, Ekman, and Oster (1986) lamented the low sampling rates typically used in facial EMG studies of emotion, because one could not determine onsets, offsets and peaks of the facial actions involved. Ekman and Fridlund (1986) speculated that anomalies in facial expressions in major depression were most likely to be seen in the temporal dynamics and not the configurations of facial actions.

Computers are becoming very fast, and computer storage very inexpensive. If finer-grained analyses of EMG data might be of interest at a later date, we urge that these data be sampled and stored at the highest practicable rates. Reduced measurements (e.g., signal means) can always be derived from high-resolution data.

Analog-to-Digital Conversion. Considerations of A/D converter precision and signal gain are more complex. Very precise A/D converters (for example, 16-bit converters, which offer a resolution of 1 part in 65,536) are expensive. However, they allow amplifier gains to be such that very weak or very strong muscle actions can be detected precisely. For example, an EMG placement over the *biceps brachii* can produce signals ranging from zero to several hundred μV. A 16-bit A/D converter can reproduce the full range of *biceps* contractions while resolving the EMG activity to fractions of a μV. With a less precise A/D converter (e.g., 8-bit converters allow resolutions of only 1 part in 256), measuring the full range of muscular contraction would reduce measurement resolution to increments of over 1 μV. This lowered measurement resolution compromises measurement of weak muscular actions, such as the kinds that often accompany imagery or cognitive tasks. Increasing the amplifier

gain could result in a resolution equal to the 16-bit converter, but the usable measurement range would be limited and stronger EMG signals would be truncated or "clipped."

Eight-bit converters are inadequate for general-purpose EMG measurements in psychophysiology. They pose too many constraints on measurement resolution and signal range. One drawback of higher-resolution A/D converters is that they require longer conversion times, which in turn place a ceiling on sampling rates. However, fast, inexpensive 10- and 12-bit converters (with resolutions of 1 part in 1024 and 4096, respectively, and conversion rates upward of 100 kHz) are now available and allow precise measurement of both weak and intense muscular contractions.

Data Storage. Once data are transduced and digitized, organizing them for storage becomes important. Our respondents indicated a variety of storage devices (e.g., magnetic tape, 8-inch and 5¼-inch diskette drives, paper copy, etc.), data formats (e.g., ASCII and binary storage, sequential and random-access files, with one or more file headers and data separators), and machines (IBM, DEC, and others).

Factors such as economy, flexibility, and readability determine how the data are organized on storage devices. The need for common word processing document formats spawned the need for document standards (e.g., IBM's DCA or Document Content Architecture). Increasing discussion of a shared scientific database, plus the emergence of standardized laboratory computer data analysis and statistical packages (e.g., ASYSTANT, BMDPC, PC SAS, SPSS/PC+, SYSTAT) make the formulation of scientific data storage formats timely.

We cannot recommend comprehensive guidelines at this time. This is for several reasons. There was no concensus regarding a proper storage format for EMG data; each laboratory developed its own system for data storage and manipulation. Second, the Compact-Disc Read-Only Memory (CD-ROM) and Write-Once Read-Mostly (CD-WORM) devices are predicted to be the standards for large-scale data interchange for the 1990's, and their data formats are not finalized at this time. Third, statistical and data-analysis packages do not at present share common file structures (most microcomputer packages do accept Lotus WKS, Visicalc DIF, and Microsoft SYLK file formats, but these are too limited for general scientific data storage). Fourth, the expected emergence of a shared database under U.S. Government auspices will strongly affect formats of data interchange, and the format of this database has not yet been determined.

We do recommend that data be translated into communicable formats for archival purposes. Whenever possible, data should be archived in standard ASCII characters, in sequential files. Responses for each psychophysiological channel should reside in separate files, with a 1-line header that summarizes the contents of the file. To whatever extent possible, data for separate experimental phases should also reside in separate files (with header lines), especially if each phase contains multiple data points.

Quantification of EMG Responses

Scaling and Measurement Units

The numbers that are assigned to EMG signals of different amplitudes depend on several factors: 1) the electrical unit chosen for description of the signal; 2) the accuracy of the amplifier's gain setting; and 3) the type of integration method used; and given the integration method, the length of the integration time constant or reset criterion. We discuss how each is determined.

Measurement Units. The electrical unit for describing the amplitudes of EMG signals is the *volt* (V). EMG amplitudes are usually rescaled most conveniently in terms of *microvolts* (μV, or 10^{-6} volt). How the amplitude of an EMG signal was measured requires further specification of the measurement unit. The motor unit action potential is bipolar and asymmetrical about electrical zero. Measurements of its amplitude are frequently made from negative to positive peaks. In this and similar instances, the amplitude should be expressed as volts or microvolts *peak-to-peak* (V or μV p–p). For waveforms measured from electrical zero to positive- or negative-going peaks (e.g., the peaks of the rectified but unsmoothed EMG signal), the appropriate unit is volts or microvolts *peak* (V or μV pk).

Most often, quantification of instantaneous amplitudes (e.g., peaks) is not required. Rather, the average amplitude of a signal (e.g., the rectified and smoothed EMG signal) is desired. Two methods are available for these average measurements: measuring either integral average voltage (V or μV avg) or root-mean-square voltage (V or μV rms). Most voltmeters and A/D converters measure integral average voltage. Special circuits (e.g., high-speed A/D converters with integral squarer/dividers; see Kitchin & Counts, 1983) are required for the root-mean-square method, but it is a superior method for measuring AC signals and should be used whenever possible (see section on analysis, below). Our respondents indicated a variety of measurement methods. Whatever method is used, units should be specified appropriately.

If contour followers are used as signal smoothers, then the time constants should be specified and the results should be expressed as integral average voltage (V or μV avg).

Time- or voltage-resetting integrators can produce cryptic readouts such as number of resets or resets per minute; these measurements can and should be restated in volt-second or microvolt-second units (V-s, or μV-s) using the calibration procedures specified below.

Amplifier Gain Accuracy. EMG amplifiers do not always operate at a gain equal to their gain settings. Whenever it is important to measure absolute signal levels accurately (e.g., in multichannel monitoring requiring comparisons across channels), investigators should calibrate EMG amplifier gain directly rather than relying on front-panel gain settings. Fridlund and Fowler (1978) offered a method for calibrating EMG amplifier gain. A 10,000:1 voltage divider is constructed from one 100 kΩ resistor and one 10 Ω resistor. Resistors should be metal film types with 1% tolerance or less. The inverting (−) amplifier input and the free end of the 10 Ω resistor are tied to ground. The junction of the two resistors is tied to the amplifier noninverting (+) input. A sine wave generator is connected to ground and to the free end of the 100 kΩ resistor. A 1 V p–p AC signal at the center of the chosen EMG filter passband is fed to the voltage divider. The amplifier's gain is set by measuring its output voltage. For example, a gain of 10,000 would produce 1 V p–p at the amplifier outputs.

Time-Constant Accuracy in Smoothing or Integration. Time constants of contour followers or integrators do not always accord with their front-panel settings. Depending upon the rapidity of change in a given EMG signal, inaccuracies in time constants can affect amplitudes of the smoothed or accumulated signals. Time constants should be calibrated precisely whenever the temporal or frequency characteristics of multiple EMG signals are compared.

To determine the time constant (degree of smoothing) of a contour follower, a low-frequency (e.g., 10-Hz) sine wave signal of 2 V p–p is applied to the contour follower inputs, and the output voltage of the contour follower is determined. The frequency of the sine wave is increased until the output of the contour follower is 3dB less (i.e., 0.707 of the original output). The time constant (in seconds) of the contour follower at its current setting is $1/(2\pi F)$, wherein F is the frequency in Hz of the sine wave at the −3dB output voltage.

To achieve a desired time constant, the sine wave is adjusted to the appropriate −3dB frequency, and the contour follower is set for the −3dB voltage output. This calibration method relies on the usual characterization of a low-pass filter by its −3dB, or "corner," frequency (Faulkenberry, 1977). As a guide to selecting a contour follower's time constant, Fridlund (1979) provided a graph showing the effects of different time constants on the EMG signal produced by phasic contraction of *biceps brachii.*

Time constants of resetting integrators are calibrated using a constant DC signal at the inputs. For example, an integrator whose time constant is 1 s will have a 1 V output after a .1 V signal is applied for 10 s. This 1 V output denotes a voltage integral of 1 V-s. The actual time constant can be calculated from the equation: $TC = V_{in} \times t/V_{out}$, wherein TC is the time constant (in seconds), V_{in} is the DC input voltage, t is the time duration of the DC input voltage (in seconds), and V_{out} is the integrator output voltage.

Signal Denoising

Noise levels in recording equipment differ across studies, and even across separate EMG channels in the same laboratory. Unequal noise levels can complicate comparisons of EMG levels, especially at very low levels of EMG activity that approach the noise floor. There are three reasons for ascertaining EMG channel noise: 1) to ensure that recording electronics are operating correctly; 2) to check the integrity of electrode placements; and 3) to make equivalent the outputs of multiple EMG channels.

Noise in recording electronics should be measured using the 10 kΩ resistor triad described previously (see Noise and Grounding section, above). Noise at the amplifier outputs (and filter, integrator, or contour follower outputs, if applicable) should vary no more than 10% across channels; a channel that exceeds this tolerance can be presumed defective. When electrodes are connected to the subject, noise across EMG channels can be assessed while the subject is at rest and target muscles are relaxed. An electrode that is loose or in poor contact with the skin will produce abnormally high noise levels or a DC signal indicating amplifier blocking. Repair of the faulty electrode contact should restore proper noise levels on the affected channel.

Numerically adjusting the EMG signals for the calculated noise levels is sometimes performed. There are two common ways to "de-noise" signals. In the first, noise levels are measured and are simply subtracted from signal levels. The problem with this procedure is that noise is regarded as additive with signal. Thus if noise is 1 μV on one channel and 2 μV on another, equating the two channels by

subtracting 1 μV from the noisier channel will result in a 1 μV inequality at all signal levels.

The second method is called "denoising in quadrature," after the quadrature detection method of FM radio transmission. This procedure recognizes that noise is orthogonal to signal. It is a geometric differencing of noise from signal that deducts noise levels from recorded amplitudes near the noise floor but leaves high signal levels relatively unchanged. The formula is $D = \sqrt{(S^2 - N^2)}$, wherein S is raw signal amplitude and N is mean raw noise amplitude, and D is the amplitude of the denoised signal.

More complex, active noise-reduction schemes (e.g., sliding passband or signal autocorrelation methods) have not to our knowledge been used for EMG measurement. Because of the quasi-random nature of the EMG signal, their value for improving EMG signal quality is unclear.

We recommend quadrature denoising over simple subtraction of noise levels. However, we advise caution in using any signal denoising. Although denoising schemes can facilitate graphical comparison of EMG signals with different baseline noise levels, we await data suggesting that such schemes make any difference in quantitative analysis of the signals.

Baselines, Score Corrections, and Standardization

Baselines. It is desirable in most EMG research to achieve a measure of response that is free from the influence of the prestimulus level. Several of our respondents noted ambiguity in the term "baseline" when applied to EMG signals. They distinguished "psychological" from "physiological" baselines. This distinction is necessary because, unlike responses such as the EEG or electrodermal response, a muscle "at rest" shows electrical silence (Basmajian & De Luca, 1985). Therefore the "physiological baseline" for any EMG site is the recording system noise floor. On these grounds, Fridlund and Izard (1983) questioned the *pro forma* baseline correction of EMG scores.

On the other hand, experimental subjects rarely show zero activity in any EMG sites, because they may be actively moving, aroused, anxious, etc. Achieving representative "psychological" baselines is the relevant task. This is sometimes done by subtracting the prestimulus mean from the stimulus-period mean (e.g., Schwartz, Fair, Salt, Mandel, & Klerman, 1976). This procedure is satisfactory if the prestimulus state will not confound the stimulus-period state. For example, if one is investigating EMG responses during "anxiety," then it may be inappropriate to subtract EMG levels for a prestimulus period when subjects may already be anxious. Such a subtraction might be more appropriate if the EMG measures of interest are unlikely to be contaminated by prestimulus behavior, e.g., finger movements in a reaction-time task.

It seems best to acquire prestimulus EMG levels that are confounded with as little task-irrelevant muscular activity as possible. This is a problem of experimental rather than statistical control (i.e., putting subjects at ease). Using a "closed-loop baseline" procedure may also be helpful (McHugo & Lanzetta, 1983). In this procedure, the experimenter (or the computer that controls the experiment) postpones task presentation until somatic activity is acceptably low. Extraneous muscular activity is thus minimized prior to the recording interval of interest and a purer task-specific effect is obtained.

Other Score Corrections. EMG researchers, like other investigators in psychophysiology, have attempted to use change scores, range-corrected scores, and standard scores in an attempt to achieve a metric common to all somatic sites, and one which allows easier comparisons across subjects. The experimental circumstances under which it would be possible and useful to achieve such a metric have not been given sufficient thought in the EMG literature. For example, standardizing EMG scores has often been used in an attempt to reduce individual variability and site variability in EMG activity. Yet it can be shown mathematically that score standardization can obscure or misrepresent treatment effects (see section on Drawing Inferences from EMG Data, below).

Psychophysiological signals whose phasic amplitudes are dependent upon their prestimulus tonic levels (e.g., electrodermal response) are often corrected in accordance with the "Law of Initial Values" (Wilder, 1962; Lykken, Rose, Luther, & Maley, 1966). Because the physiological baseline for EMG signals is always zero, the rationale for baseline corrections of EMG signals is weak at best.

Thus the utility of *pro forma* covariance analyses, baseline corrections, or range corrections of EMG signals has yet to be demonstrated systematically. Fridlund, Schwartz, and Fowler (1984) performed the only study that directly compared baseline-corrected and range-corrected with uncorrected EMG signals. They found that corrected EMG scores did not improve the ability to discriminate emotions within subjects. Between-subjects studies are called for which test whether baseline and other corrections are useful. We suggest that researchers who use corrected scores also furnish analyses based on uncorrected scores. This procedure will allow investigators to ascertain when specific types of corrections are most useful.

Analysis of EMG Data

EMG activity unfolds over time, and like most other psychophysiological responses, the raw signal

is too complex to analyze without considerable data reduction. Fridlund and Izard (1983) introduced the term "parameter extraction," derived from mathematical models of feature extraction and pattern recognition (cf., Duda & Hart, 1973), to describe the selection of quantitative features of the EMG motor unit action potential train. It is these features that are subject to inferential statistical analysis. They include the EMG signal's amplitude, temporality, and frequency.

EMG Amplitude Measures

Most psychophysiological research using EMG has focused on some variation of EMG signal amplitude as the dependent measure. The raw EMG signal is time- and force-dependent, and it varies in a quasi-random fashion around the electrical zero point. Recording EMG signals with AC-coupled amplifiers (or DC amplifiers with zero offsets) ensures that the average value will be zero. Simple averaging of the raw EMG signal is thus uninformative.

Counting or averaging the EMG signal's peaks, or tallying its directional changes or zero crossings, are relatively easy methods to implement. They are useful for gauging gross differences in EMG activity, provided sampling rates are high enough (Grieve & Cavanaugh, 1973; Willison, 1963). These parameters do not vary linearly with contraction, and at high ranges of muscular contraction they are unreliable. In some cases, nonlinearity with level of contraction is irrelevant. For example, reflexes are often quantified using peak-to-peak (or peak rectified) EMG amplitude and onset latency (e.g., Brunia, 1983; Clarkson & Berg, 1984; Silverstein & Graham, 1978). We advise using raw EMG signal peaks, directional changes, or zero crossings, only if explicit attention is paid to their unreliable relation to degree of contraction.

Lippold (1967, p. 257) maintained that the integrated EMG (IEMG) signal represents overall muscular contraction more accurately than a simple amplitude. Subsequent research has used the term IEMG to refer to several different processing techniques, and has revealed that Lippold's assertion holds for all of them (cf. Winter, Rau, Kadefors, Broman, & De Luca, 1980). Four of the most common processing techniques are: 1) the mean of the full-wave rectified, unsmoothed EMG signal; 2) the mean of the rectified EMG signal, smoothed using a contour follower (see section on integration above); 3) the rectified EMG signal as accumulated in an integrator (voltage- or time-resetting); and 4) root mean square (rms) EMG.

The rms parameter has been used rarely in psychophysiology, due to the relative simplicity of average voltage measurement (see section on measurement units, above). The rms measure performs the square root on squared EMG samples across a predetermined measurement window. Basmajian and De Luca (1985) maintain that rms measurement of EMG activity provides a more accurate index of the underlying physiological events than measures of mean amplitude. RMS measurements should be described in units of V or μV rms. We describe the relationship between rms and mean amplitude measures below.

Temporal Domain

Measures of integrated EMG amplitudes, although representative of overall muscular contraction, are insensitive to the distribution of amplitudes and to their unfolding over time. Cacioppo, Marshall-Goodell, and Dorfman (1983) outlined a moment-based (moment, as in statistical moments) procedure that represents, more fully than mean EMG amplitude, the amplitude characteristics of integrated (or rectified) EMG and the associated patterns of muscular contraction (see Cacioppo et al., 1983; Cacioppo, Petty, & Morris, 1985).

Cacioppo and Dorfman (1986) recently extended this work and presented a more systematic and comprehensive moment-based method of "topographical analysis." This method can be used to represent the amplitude, temporal, or frequency characteristics of any non-negative bounded (NB) waveforms (e.g., raw, rectified or integrated EMG, or EMG power spectra). Within topographical analysis, NB waveforms can be represented by categorization of their moments. Even moments provide a multidimensional indicant of dispersion about a specified reference point, and odd moments similarly indicate waveform asymmetry (Cacioppo & Dorfman, 1986). For example, the first moment of the amplitudes about zero is equivalent to an average voltage estimate of EMG amplitude, and the second moment is equivalent to rms EMG. Topographical analysis can combine information provided in the rms measures with that in the average estimates, and it allows rigorous comparisons among waveforms. Whether these more comprehensive analyses are generally useful in EMG studies remains to be established.

Our respondents suggested the derivation of EMG gradients as one other method for studying changes in EMG activity over time. This procedure derives from a series of mean rectified EMG (or IEMG) measures. Components of the gradient can be calculated using one of the procedures outlined previously. Investigators should report both the epoch during which EMG activity is averaged in forming the gradients, and the specific method by

which each component of the gradient is calculated. Because EMG gradients are constituted from a series of average EMG measures, they are employed in investigations of tonic rather than phasic EMG activity.

Frequency Domain

With the advent of high-speed laboratory computers and equally fast analog-to-digital conversion, and using efficient Fast Fourier Transform (FFT) algorithms (Brigham, 1974), the frequency-domain analysis of EMG signals is now practical. However, only one of our respondents regularly performed EMG frequency analyses. Current practice in experimental psychophysiological research is exemplified in a recent study of the effects of electrode characteristics on the EMG signal by van Boxtel et al. (1984). Each 1-min EMG recording was partitioned into 30 sample records of 2 s duration. EMG activity was sampled at a rate of 1024 Hz, and the EMG signals were subjected to low-pass (anti-aliasing) filtering at 500 Hz. Each 2-s record was 20% tapered (10% at each end) using a cosine window (Bloomfield, 1976), and power spectra for 0–512 Hz were computed using the FFT. To decrease random error in spectral estimates, power spectra were averaged across the 30 sample records. Finally, the spectra were normalized, averaged across subjects, and the median frequency was computed for the resulting averages.

References abound on the technology and utility of frequency analyses for investigating periodic physiological waveforms such as the EEG. However, use of frequency analyses for EMG data is still at an early stage. Most efforts have consisted of methodological investigations of EMG signal parameters. Since the EMG signal is by nature quasi-random and largely aperiodic, it is unclear what substantive contribution such analyses can make to psychological phenomena.

We nonetheless offer several general recommendations. EMG should be sampled at least 4–8 times as fast as the highest frequency of interest, and sharp anti-aliasing filtering should be used. Samples should be selected such that stationarity assumptions are met (see Sugimoto, Ishii, Iwata, & Suzumura, 1977). Data should be tapered at each end (e.g., using a split-cosine bell, with a 10% taper at each end) to avoid spectral leakage, and the tapering method should be specified. Windowing the resulting periodograms and averaging across epochs and subjects whenever possible will reduce error in spectral estimates. The window type (e.g., Hamming, Parzen, rectangular) should be specified as well. More specific guidelines await further research.

Social Context of EMG Experiments

The psychophysiology experiment, whether laboratory or field study, can involve not only powerful treatment manipulations (e.g., Ax, 1953), but also unintended apprehension, distraction, and artifact. Although laboratory artifacts emerging from subject-experimenter interaction are well-known (e.g., Rosenthal & Rosnow, 1969), Gale and Smith's (1980) survey revealed little systematic attention by psychophysiologists, and responses to our survey suggested a similar picture.

Inattention to subject-experimenter effects may be a remnant of the belief that, unlike verbal and overt behavior, physiological measures are objective and bias-free (see Cooper, 1959). The vulnerability of physiological responses to instructional sets (Sternbach, 1966), intentional distortion (Honts & Hodes, 1982a, 1982b), and social biases (Tognacci & Cook, 1975) vitiates this notion. Nowhere is this vulnerability more apparent or troublesome than in research on skeletomotor activity (Cacioppo, Petty, & Marshall-Goodell, 1985; Fridlund & Izard, 1983). In this section, we review potential artifacts and suggest procedures for assessing or preventing them.

Subjects and Experimenters

Psychophysiological assessment is mostly noninvasive but can be psychologically intrusive. The psychophysiological experiment may be unique in that an extensive period of engagement with the subject is often required before the experimental task begins. Conversation about and attachment of "electrodes," the presence of electronic gadgetry and signal cables, and the obvious scrutiny of experimenters, all complicate capturing the psychological processes of interest in EMG research.

What do you say to subjects before the experiment begins? It is reasonable to assume that subjects' responding will be affected by the experimenters' demeanor and the content of the conversation, but we know of no research that assesses their effects systematically. As Gale and Baker (1981) noted, "In psychophysiological studies, experimenter-subject interactions are particularly important since the procedures may involve bodily contact, partial removal of clothing, skin abrasion, touching, and application and removal of electrodes" (p. 373). Subjects are often made anxious in the process.

Our respondents suggested a few simple procedures for reducing participant anxiety. Prospective subjects can be shown the laboratory and briefed about the experiment before they consent to participate. They can even be run through a mock experiment. Some respondents reported that they used

soothing music or brief progressive relaxation (e.g., Goldfried & Davison, 1976) to calm subjects.[2]

The "atmosphere" and furnishings in the laboratory's subject room can affect subjects' comfort before and during the experiment. The subject room should be a comfortable temperature. The lighting should not be too bright, both because subjects may be less anxious in low light levels and because they will make fewer muscular responses (squinting, brow-knitting) that may contaminate EMG recordings. Carpeting, living-room furniture, incandescent lamps, and walls painted in pleasant pastels and appointed with tasteful art, are preferable to steel cabinetry, fluorescent lamps, and linoleum floors. Instrument and electrode-attachment panels should have as few switches, blinking lights, and meters as possible; they can be made of wood rather than metal.

Experimenters and laboratory assistants should be trained to achieve rapport with subjects in the same way novice clinicians train in the psychometric setting (cf., Cacioppo et al., 1985; Gale & Smith, 1980). Most respondents suggested using modeling and role-playing to teach experimenters to be friendly and professional, and to be straightforward and relaxed about necessary touching. Experimenters should be as adept interpersonally as technically. In describing EMG recording technique, neutral words (e.g., recording discs) should supplant anxiety-provoking ones (electrodes). The subject should have a chance to handle a recording electrode, and if possible, play a part in attaching his or her own.

There was no consensus among respondents about the sex of experimenter in relation to sex of subject. Some respondents used only same-sex experimenters, but this introduces a confound when the sex of the subject is a factor. We prefer either varying the sex of the experimenter and coding it for subsequent analysis, or to utilize male-female coexperimenter teams, whenever subjects of both sexes are being tested. Analyses of the factors of sex of experimenter and/or subject have not always been reported. Until more is known about these factors, we suggest that they be analyzed and reported whenever they are varied.

Finally, subjects generally need to avoid unnecessary shifts in posture or limb movement to minimize EMG activity irrelevant to the experimental task. Providing a comfortable chair and tailoring tasks to minimize extraneous movement are superior to instructions or artificial restraints on subjects' actions.

Observation and Coaction Effects

Observation by, or the presence of others, tends to facilitate performance on simple tasks and impair performance on complex ones (Geen & Gange, 1977; Moore & Baron, 1983; Zajonc, 1965). Observation may inhibit facial behavior or alter it dramatically (see review by Fridlund, Ekman, & Oster, 1986). Although few EMG studies have tested two subjects simultaneously, several have involved participants who interacted on tasks that were purportedly cooperative or competitive (e.g., Englis, Vaughan, & Lanzetta, 1982).

More often, the chief interaction is directly between subject and experimenter. Our respondents' laboratories differed widely in their physical layouts and the methods used to monitor subjects. In some laboratories, subjects are placed in the same room as the experimenter(s). In other labs, subjects are placed in a separate room and are monitored through a one-way mirror or a conspicuously placed camera. In still others, subjects are placed alone in a room while believing (correctly or not) that they are not being observed.

In the laboratory, subjects should be made to feel comfortable and involved. Instead, they often feel either over-scrutinized or deserted entirely. There are several methods for minimizing these reactions. Cacioppo, Petty, and Marshall-Goodell (1984) suggested using a cover story (see also Fridlund and Izard, 1983)[3], an interesting task, separate recording and subject rooms, unobtrusive visual observation (e.g., using a hidden camera), and multiple practice trials.[4] These minimize subjects' feel-

[2]Of course, the dispositional and situational antecedents of apprehension and its effects on EMG activity are of considerable interest (see Fridlund, Hatfield, Cottam, & Fowler, 1986).

[3]Using a cover story does not mean that subjects are deceived or victimized by an elaborate ruse. The goal is to reduce the subject's self-consciousness while the investigator maintains careful control over the experimental tasks. "Cover story" refers here to any explanation of the study that deviates from the investigator's own. For example, explaining the "purpose" of a study at a superficial level would constitute a cover story.

[4]Our suggesting the use of multiple practice trials is based on data collected by Beverly Marshall-Goodell and the second author showing that effects of another's presence on orienting and startle are most apparent at the beginning of a series of trials. Additionally, including multiple practice trials minimizes both the effects of practice and habituation, and any initial confusion and apprehension, during experimental tasks. Practice trials are of course contraindicated when the focus of the study is presence of others, learning, habituation, confusion, or apprehension.

ing that they are in a fishbowl. To minimize their feeling deserted, several of our respondents emphasized the importance of assuring subjects that they can beckon the experimenter at will. Most human consent forms carry the proviso that subjects can withdraw from the experiment at any time. A corollary is that subjects should be able to communicate with the experimenter at any time, using a two-way audio intercom at minimum.

Evaluation Apprehension

Related to subjects' belief that their thoughts and behavior are being monitored is Rosenthal's (1966) argument that subjects are apprehensive about being evaluated by experimenters. This "evaluation apprehension" is likely to be exacerbated by the presence of high-tech gadgetry and experimenters who are both socially skilled and technically proficient (e.g., see the description of the bogus pipeline by Jones and Sigall, 1971). This apprehension is of special concern in EMG studies for two reasons. First, widespread muscle activation characterizes anxious individuals (Fridlund, Hatfield, Cottam, & Fowler, 1986), complicating the detection of low-level EMG responses across measurement conditions, particularly when one condition arouses more apprehension than another.

Second, evaluation apprehension can also induce participants to behave in an especially customary or socially desirable manner. For instance, in the case of facial EMG studies of emotion, cultural display rules—customs for managing facial behavior in social situations (Ekman, 1972; Ekman & Friesen, 1971)—can make the EMG data more reflective of social propriety than task-specific emotion. To minimize evaluation apprehension, subjects can be informed that there are no correct responses to experimental tasks or questions, and that previous subjects have given a wide range of responses. Experimenters can also inform subjects that the study focuses on an endpoint over which subjects have little reason to be concerned and have no control, such as involuntary neurophysiological activity (Cacioppo et al., 1984; Fridlund & Izard, 1983).

Demand Characteristics

A related laboratory artifact has been noted by Orne (1962), who has argued that many subjects try to discern the true purpose of the research and shape their behavior accordingly. Contemporary subjects cagily expect psychologists to use cover stories and deceptions in their research, and the equally crafty experimenter must try to ensure that the covers and deceptions are intact until the subjects' data are collected. Whenever subjects can discern the experimental hypotheses, then demand characteristics are confounded with the experimental manipulations.

That subjects can so easily manipulate their muscular behavior makes EMG studies particularly susceptible to demand-characteristics confounds. Fridlund and Izard (1983) argued that many facial EMG studies of emotion are plagued by such confounds. They reasoned that placing multiple electrodes on a person's face can make the person acutely aware of his or her facial expressions. Subjects who desired to please (or frustrate) the experimenter or to "contribute to science" might make (or inhibit) faces accordingly. Although recent studies whose designs minimized experimental demand still found that subtle emotions could be discriminated (Cacioppo et al., 1984; Cacioppo, Petty, Losch, & Kim, 1986; Fridlund et al., 1984), demand confounds are an ever-present hazard.

Fridlund and Izard (1983) proposed a variety of procedures for minimizing and assessing effects of experimental demand in EMG studies. They include: 1) use of dummy electrode placements over bodily areas irrelevant to the experimental tasks; 2) cover stories to the effect that brain waves and the like are being measured rather than EMG; 3) challenging subjects to guess the purposes of the experiment at its conclusion and separately analyzing the data from those who guess correctly; and 4) using explicit counterdemand instructions. Counterdemand instructions rely on subjects' conformity to neutralize their intuitions about how they should react in the experiment. For example, in a facial EMG study of emotion, subjects may be told that "we've found that the best subjects are the ones who are the least self-conscious about how they're doing."

Additional techniques for reducing demand include: 5) giving subjects peripheral experimental hypotheses; 6) designing the laboratory setting to minimize subjects' perceptions of being scrutinized (see previous section); 7) whenever possible, using tasks sufficiently absorbing that subjects are oblivious to role behavior; and 8) reducing perceived status differences in subjects and experimenters through trust and rapport. Any deception should be disclosed fully to subjects at the earliest possible time.

As we suggested at the outset of this section, "the nature of the interaction between the experimenter and subject is both a fount of potential biases in psychophysiological research and the source of their solutions" (Cacioppo et al., 1985, p. 288).

Experimenter Bias

Because the interaction between the experimenter and participant is relatively intimate and extended in EMG research, greater experimenter bias

can develop during the interaction. Rosenthal (1966) has maintained that an experimenter's desires are transmitted to participants by means of unintentional, mostly nonverbal cues (e.g., facial expressions, tone of voice, length of time spent explaining certain points). Experimenter biases in EMG studies may be especially important when tasks involve emotion and social interaction. Double-blind testing procedures are one solution, but they are costly. In addition, experimenters can be kept uninformed about the nature of the experimental treatment to which a subject will be exposed until they complete their contact with the subject. Finally, critical experimental instructions and follow-ups can be automated. Although our respondents indicated little experience with these procedures, we believe that such procedures should be considered whenever possible.

Drawing Inferences from EMG Data

EMG responses are not linked invariantly to specific psychological or behavioral states. Thus, the context in which these responses are observed is paramount when validly interpreting their meaning. Cook and Campbell (1976) outlined four classes of experimental validity: 1) statistical conclusion validity—whether there are reliable differences among conditions; 2) internal validity—whether the treatment was necessary to produce the observed effect; 3) external validity—whether the observed effect generalizes to other subjects, times, and settings; and 4) construct validity—whether the treatments and observed effect reflect the theoretical constructs of interest. Cacioppo et al. (1985) discussed how all four types bear on psychophysiological experiments. We focus presently on threats to statistical conclusion validity and construct validity in EMG experiments.

Statistical Conclusion Validity

There are no set methods for analyzing EMG data, and thus reportable results are quite dependent upon the statistical tests used. Muller, Otto, and Benignus (1983) and McHugo and Lanzetta (1983) provided informed discussions about data-analytic paths in psychophysiological experiments. Among the issues they covered were: experiment-wise error rates, cross-validation of results from data-snooping techniques, nonparametric tests, between- vs. within-subjects analyses, and univariate vs. multivariate tests. We focus on the last two.

Between vs. Within-Subjects Analyses. There are large differences in EMG responding among individuals, and testing each individual is costly. Thus it is often desirable to examine treatment effects within rather than between subjects. McHugo and Lanzetta (1983) posed two different ways of examining within-subjects treatment effects. One involves repeatedly presenting similar trials to allow pooling of changes over time. The second exposes each subject to multiple experimental conditions so that the same subjects appear in both experimental and control cells. Both procedures reduce error variance, increase generalizability, and improve repeatability. Both procedures can be used in the same study. The former is limited when EMG responses are expected to change across trials due to motor learning, practice effects, habituation, etc. The latter is limited when experimental treatments are characterized by sensitization or carryover effects (see Greenwald, 1976).

There are no accepted metrics for comparing EMG sites within or between individuals. Some respondents reported dealing with between-subjects differences in EMG responding by standardizing their EMG measures. Unfortunately, this procedure has limitations that are often unrecognized. To illustrate, let T_i represent a within-subjects treatment (e.g., treatments that evoke happiness, sadness, and anger), and S_j represent a particular subject. Mean EMG measures are presented in the left columns of Table 1, and the corresponding standardized EMG measures are in the other two sections.[5]

Even though standardization was within subjects, the order of the treatment means $T_1 - T_3$ and the intervals between individual data points within

[5]We thank Donald D. Dorfman for his insightful comments regarding the limitations of standard scores. The data provided in Table 1 are his.

Table 1

Hypothetical data showing hazards of EMG score standardization

Subjects	Raw Scores in Hypothetical Study 1 (T_1-T_2) and Study 2 (T_1-T_3)					Standard Scores in Hypothetical Study 1				Standard Scores in Hypothetical Study 2				
	T_1	T_2	T_3	$\bar{X}$	SD	T_1	T_2	$\bar{X}$	SD	T_1	T_2	T_3	$\bar{X}$	SD
S_1	3	2	1	2.00	1.00	.707	−.707	0.0	1.00	1	0	−1	0.00	1.00
S_2	1	2	10	4.33	4.93	−.707	.707	0.0	1.00	−.675	−.473	1.15	0.00	1.00
S_3	1	2	10	4.33	4.93	−.707	.707	0.0	1.00	−.675	−.473	1.15	0.00	1.00
$\bar{X}$	1.67	2.00	7.00			−.236	.236			−.120	−.320	0.43		

subjects were changed by standardization. If one had used only T_1 and T_2 in this study, both untransformed and standard scores would have indicated that $T_2 > T_1$ (see middle columns of Table 1). If this study were then replicated perfectly (i.e., the same raw data were obtained in response to T_1 and T_2), but treatment T_3 was added, then the untransformed scores for T_1 and T_2 would be unchanged (by definition), whereas the standardized EMG measures would now indicate that $T_1 > T_2$ (right, Table 1). In other words, despite the second "perfect" replication, the use of standard EMG scores to remove any large individual differences would lead to opposite conclusions in the two studies. It is simple to demonstrate the same limitation when using standard EMG scores to obtain comparability among recording sites.

Standardization is not subject to the above limitation when treatments are certain to have evoked the full range of subjects' responding. However, it is rarely the case in most psychophysiological research that EMG maxima (i.e., the EMG signal at a muscle's *maximal voluntary contraction*, or MVC) are obtained, and obtaining such maxima is not trivial (cf., van Boxtel, Goudswaard, & Janssen, 1983). Hence, we recommend as the most judicious strategy examining both raw and standardized treatment means and reporting any difference in ordering. Alternatively, if maxima can be approximated, then EMG responses can be expressed as proportions of those maxima.

Univariate vs. Multivariate Analyses. Multivariate procedures have several advantages over univariate analyses. At the very least, they provide protection against Type I errors due to conducting multiple univariate tests on related measures. They also allow assessment of the configurations of responding among several dependent measures, a particularly valuable attribute for studying response patterns associated with stress or emotion (Fridlund & Izard, 1983; Fridlund et al., 1984).

There are two major disadvantages of multivariate procedures. First, they can require large numbers of cases (e.g., subjects), typically 8–10 cases per variable per treatment group. Second, the results of the analyses can depend heavily upon the particular set of variables in the analysis (Cacioppo et al., 1985). This occurs especially in procedures such as multiple regression, factor and principal-component analyses, or discriminant analysis, which weight variables to achieve a solution. Including or deleting another psychophysiological measure can lead to changes in the weighting of each measure in the multivariate analysis. The derived weights can be particularly unstable when the psychophysiological measures are highly correlated, a situation in which variables can serve a suppressor or moderator influence on the solutions. This instability can vitiate any theoretical interpretations about the importance of individual variables in accounting for an effect.

Instability in weights in a multivariate analysis is less of a problem when: 1) obtaining a multivariate effect (e.g., assessing whether or not there is a difference among treatment groups using MANOVA) is sufficient without regard for the dependent variable weights that accounted for it; 2) cross-validation on new data establishes the robustness of the multivariate solution; and 3) the directions of the univariate effects corroborate the multivariate solution.

Using stepwise regression or discriminant analysis procedures in a shotgun approach is unacceptable, except as an exploratory tool when there is no guiding theory (see Muller et al., 1983). Variables found to be "significant" in stepwise procedures are suspect unless they are shown to be important in cross-validation. We also agree with Wilkinson (1985), who states, "For a given set of data, an automated stepwise program cannot necessarily find a) the 'best' fitting model, b) the 'real' model, or c) alternative 'plausible' models. Furthermore, the *order* variables enter or leave a stepwise program is usually of no theoretical significance. You are *always* better off thinking about *why* a model could generate your data and then testing it . . ." (p. 196).

Construct Validity and Manipulation Checks

Whether experimental treatments actually operate as intended, and whether the dependent measures (e.g., EMG responses) actually sample the intended behavior, are questions of construct validity. For example, an investigator may want to know, "Does mood affect facial EMG?". Testing such a hypothesis successfully first depends upon constructing an operational definition of "mood." Second, whether EMG changes are specific to the face or reflect general somatic activity may be theoretically crucial. As a case in point, McGuigan (1970) noted that experiments on perioral EMG activity during "silent language processing" were more informative when perioral EMG was contrasted with activity from nonoral sites, and when EMG responses evoked by silent language tasks were compared to those of nonlanguage tasks. McGuigan's suggestion is an example of the double dissociation design widely used in physiological psychology, (Teuber, 1955), and we recommend its use wherever possible.

Crucial experiments are unfortunately not always possible or definitive (see Petty & Brock, 1981).

Our respondents reported dealing with problems of construct validity in many ways, ranging from limiting their explanatory constructs to the physiological level, to using multitrait-multimethod matrices. Nonetheless, there was general agreement that experimental treatments used in the typical EMG study are complex and may influence subjects in a variety of ways. It is therefore possible, even likely, that treatment effects are due to more than the intended manipulation, and that EMG responses are derivatives of more than the theoretical construct of interest.

One way of addressing the problem of uncertainty about treatment effects is to use a variety of manipulations thought to tap the same construct (i.e., multiple operationalization). For the question, "Does mood affect facial EMG?", mood could be varied in numerous ways (e.g., self-referent "Velten"-type statements, good vs. bad weather, giving money to subjects). Congruence of effects on EMG responses would provide evidence that "mood" was indeed an influence instead of just self-reflection, weather or money; inconsistencies, on the other hand, would raise questions about the purity of the manipulated construct.

We also recommend that investigators provide independent evidence for the efficacy of their experimental manipulations. For instance, one may wish to distinguish between deliberate and spontaneous actions (e.g., eyeblinks). Self-report measures can provide independent evidence that the treatments operated as intended, because for deliberate actions people can usually report a prior intention to act.

Whether or not a manipulation check is included should not depend upon whether the subject can report its psychological impact. Nonverbal measures are preferable when they, rather than verbal reports, vary reliably as a function of the treatment (e.g., see Ekman, Levenson, & Friesen, 1983).

Finally, EMG responses may reflect functions that are unrelated to the experimental treatments (e.g., blinking, swallowing, parapraxes). We recommend videotaping subjects and using the tapes during data reduction to help eliminate those data confounded by unwanted behavior. This procedure enhances the construct validity of the extracted measures. However, the criteria used for defining "unwanted behavior" should be specified, and the numbers of deletions across conditions should be compared statistically to ensure that deletions are unrelated to the experimental treatments. If significant differences are observed across conditions, then selection bias in the EMG responses that are retained threatens the construct validity of the measures.

Integrating EMG with Other Response Systems

Psychophysiologists have long been concerned with the relationships among multiple response systems. In past research, experimenters have examined these relationships by calculating correlations or by examining interactions in treatment effects across response systems (e.g., heart rate and EMG both tend to decline during the forewarning period of a simple reaction-time task). More recently, Porges and colleagues (e.g., Porges, McCabe, & Yongue, 1982) have used time-series analyses to examine the interactions between respiratory and cardiac rhythms.

The most important concern in relating EMG to other responses is their differential amplitude-time courses. EMG is a stochastic pulse train that can change value nearly instantaneously. Integration or smoothing can alter the rate of change of the EMG signal drastically. If recording parameters are not set appropriately or calibrated precisely (see sections on gain accuracy and time constants), then correlations or coherences of EMG with other variables may produce results that are more reflective of instrument settings than muscular activity. Pilot research with simulated signals can assure that the desired temporal features of EMG and other responses will be unobscured by signal processing or averaging. For example, Fridlund, Fowler, and Pritchard (1980) assessed whether a "general tension factor" was operating across limb and head EMG sites in a biofeedback task. A pseudo-session with a .1 Hz sine wave applied to all EMG channels verified that a general factor, if present in the musculature, would emerge in the data analysis.

EMG and Inferences about Pathology

Aside from EMG's common use in neurodiagnosis and rehabilitation medicine to test nerve and muscle function, EMG is often used as a dependent measure in assessment or treatment of pathology. The types of pathology studied with EMG have included depression, anxiety disorders, muscle-contraction and migraine headache, and essential hypertension.

Most frequently, elevated EMG activity from a bilateral forehead site (often called a *"frontalis"* site, but not to be confused with the unilateral, *lateral frontalis* site proposed earlier) is taken as pathognomonic of anxiety, tension, stress or fear. Reductions in activity in this site, and presumably the *frontales*, are taken as a sign of improvement, or are assumed to indicate relaxation over the whole body. Alexander and Smith (1979) listed the assumptions concealed by this use of the forehead site: 1) that EMG activity from a single muscle could

indicate general muscular tension; 2) that learned tension reduction in a single muscle would evoke tension reduction in others; 3) that reports of relaxation were critically dependent on tension reduction in a key muscle; 4) that EMG activity from a key muscle, or group of muscles, correlated with autonomic nervous system activity.

Evidence collected over the last decade suggests that: 1) there is little evidence for a "general tonus" in the striate musculature measurable in one muscle (Fridlund, Cottam, & Fowler, 1982), even in anxious individuals (Fridlund, Hatfield, Cottam, & Fowler, 1986); 2) EMG activity from the *frontalis* site does not show high correlations with activity from other muscles (Alexander, 1975; Freedman & Papsdorf, 1976; Fridlund et al., 1980; Glaus & Kotses, 1977, 1979; Sagberg & Kveim, 1981; Shedivy & Kleinman, 1977; Whatmore, Whatmore, & Fisher, 1981); 3) *frontalis* site EMG activity does not univocally reflect general arousal (Burish & Horn, 1979) or tension-related symptomatology (Alexander & Smith, 1979).

The *"frontalis"* is actually two muscles. The *lateral frontalis* merely lifts the middle and outer brow; the *medial frontalis* lifts the inner brow (Fridlund, Ekman, & Oster, 1986). We know of no data that support the uniquity of *lateral frontalis*. As we noted earlier, a bilateral forehead EMG site detects chiefly activity from the *frontales*, but it also detects broad muscular activity in the head and neck. Activity from this site will reflect not only brow-raising but also chewing, jaw-clenching, brow-knitting, etc. None of these acts has been demonstrated to be reliably pathognomonic, or reflective of the course or successful treatment of any disorder. Clinical inferences based on EMG activity in the *frontales* or any other muscles must be made with caution.

The preceding discussion does not mitigate the possibility of idiosyncratic muscular contractions that relate to symptomatology (cf., Malmo, 1975). Such relations must be determined empirically.

Terminology

Inconsistent terminology plagues the EMG field and creates confusion. The International Society of Electrophysiological Kinesiology recently adopted standard terminology for research in electromyography (Winter et al., 1980). We recommend the adoption of this terminology for all submissions to *Psychophysiology*. A glossary is reprinted in the Appendix.

REFERENCES

Alexander, A.B. (1975). An experimental test of assumptions relating to the use of electromyographic biofeedback as a general relaxation technique. *Psychophysiology, 12*, 656–662.

Alexander, A.B., & Smith, D.D. (1979). Clinical applications of EMG biofeedback. In R.J. Gatchel & K.P. Price (Eds.), *Clinical applications of biofeedback: Appraisal and status* (pp. 112–133). New York: Pergamon.

Ax, A.F. (1953). The physiological differentiation between fear and anger in humans. *Psychosomatic Medicine, 15*, 433–442.

Basmajian, J.V. (1976). Facts vs. myths in EMG biofeedback. *Biofeedback and Self-Regulation, 1*, 369–371.

Basmajian, J.V., & De Luca, C.J. (1985). *Muscles alive: Their functions as revealed by electromyography* (5th ed.). Baltimore: Williams & Wilkins.

Basmajian, J.V., & Stecko, G.A. (1962). A new bipolar indwelling electrode for electromyography. *Journal of Applied Physiology, 17*, 849.

Berlin, H.M. (1977). *Design of active filters.* Indianapolis: Sams.

Bloomfield, P. (1976). *Fourier analysis of time series: An introduction.* New York: Wiley.

Bramslev, G.R., Bruun, G., Buchthal, F., Guld, C., & Peterson, H.S. (1967). Reduction of electrical interference in measurements of bioelectrical potentials in a hospital. *Acta Polytechnica Scandinavia, Electrical Engineering Series, 15*, 37.

Brigham, E.O. (1974). *The fast Fourier transform.* Englewood Cliffs, NJ: Prentice-Hall.

Brunia, C.H.M. (1983). Motor preparation: Changes in amplitude of Achilles tendon reflexes during a fixed foreperiod of one second. *Psychophysiology, 20*, 658–664.

Burish, T.G., & Horn, P.W. (1979). An evaluation of frontal EMG as an index of general arousal. *Behavior Therapy, 10*, 137–147.

Cacioppo, J.T., & Dorfman, D.D. (1985). Topographical analysis of non-negative bounded waveforms: Application to psychophysiological data [Abstract]. *Psychophysiology, 22*, 577.

Cacioppo, J.T., Marshall-Goodell, B., & Dorfman, D.D. (1983). Skeletomuscular patterning: Topographical analysis of the integrated electromyogram. *Psychophysiology, 20*, 269–283.

Cacioppo, J.T., Petty, R.E., Losch, M.E., & Kim, H.S. (1986). Electromyographic activity over facial muscle regions can differentiate the valence and intensity of affective reactions. *Journal of Personality and Social Psychology, 50*, 260–268.

Cacioppo, J.T., Petty, R.E., & Marshall-Goodell, B. (1984). Electromyographic specificity during simple physical and attitudinal tasks: Location and topographical features of integrated EMG responses. *Biological Psychology, 18*, 85–121.

Cacioppo, J.T., Petty, R.E., & Marshall-Goodell, B. (1985). Physical, social, and inferential elements of psychophysiological measurement. In P. Karoly (Ed.), *Measurement strategies in health psychology* (Vol. 1, pp. 263–300). New York: Wiley.

Cacioppo, J.T., Petty, R.E., & Morris, K.J. (1985). Se-

mantic, evaluative, and self-referent processing: Memory, cognitive effort, and somatovisceral activity. *Psychophysiology, 22*, 371–384.

Clarkson, M.G., & Berg, W.K. (1984). Bioelectric and potentiometric measures of eyeblink amplitude in reflex modification paradigms. *Psychophysiology, 21*, 237–241.

Cook, T.D., & Campbell, D.T. (1976). The design and conduct of quasi-experiments and true experiments in field settings. In M. Dunnette (Ed.), *Handbook of industrial and organizational psychology*. Chicago: Rand McNally.

Cooper, J.D. (1959). Emotion and prejudice. *Science, 130*, 314–318.

Davis, J.F. (1952). *Manual of surface electromyography*. Montreal: Laboratory for Psychological Studies, Allan Memorial Institute of Psychiatry.

Doyle, D.J., & Hyde, M.L. (1983). Digital inverse filtering methodology for physiological signals. *Psychophysiology, 20*, 591–596.

Duda, R.O., & Hart, P.E. (1973). *Pattern analysis and scene classification*. New York: Wiley.

Dunseath, W.J.R. (1981). A low-cost precision impedance meter. *Psychophysiology, 19*, 117–119.

Ekman, P. (1972). Universal and cultural differences in facial expressions of emotion. In In J. Cole (Ed.), *Nebraska symposium on motivation, 1971* (Vol. 19, pp. 207–283). Lincoln: University of Nebraska Press.

Ekman, P., & Fridlund, A.J. (1986). Assessment of facial behavior in Major Affective Disorder. In J.D. Maser (Ed.), *Expressive behavior in depression*. Hillsdale, NJ: Erlbaum.

Ekman, P., & Friesen, W.V. (1971). Constants across cultures in the face and emotion. *Journal of Personality and Social Psychology, 17*, 124–129.

Ekman, P., & Friesen, W.V. (1978). *The facial action coding system*. Palo Alto: Consulting Psychologists Press.

Ekman, P., Levenson, R.W., & Friesen, W.V. (1983). Autonomic nervous system activity distinguishes among emotions. *Science, 221*, 1208–1210.

Englis, B.G., Vaughan, K.B., & Lanzetta, J.T. (1982). Conditioning of counter-empathetic emotional responses. *Journal of Experimental Social Psychology, 18*, 375–391.

Farkas, L.G. (1981). *Anthropometry of the head and face in medicine*. New York: Elsevier.

Faulkenberry, L.M. (1977). *An introduction to operational amplifiers*. New York: Wiley.

Fowles, D.C., Christie, M.J., Edelberg, R., Grings, W.W., Lykken, D.T., & Venables, P.H. (1981). Publication recommendations for electrodermal measurements. *Psychophysiology, 18*, 232–239.

Freedman, R., & Papsdorf, J. (1976). Generalization of frontal EMG biofeedback training to other muscles [Abstract]. *Biofeedback and Self-Regulation, 1*, 333.

Fridlund, A.J., Cottam, G.L., & Fowler, S.C. (1982). In search of the general tension factor: Tensional patterning during auditory stimulation. *Psychophysiology, 19*, 136–145.

Fridlund, A.J. (1979). Contour-following integrator for dynamic tracking of electromyographic data. *Psychophysiology, 16*, 491–493.

Fridlund, A.J., Ekman, P., & Oster, H. (1986). Facial expressions of emotion. In A. Siegman & S. Feldstein (Eds.), *Nonverbal behavior and communication* (pp. 143–223). Hillsdale, NJ: Erlbaum.

Fridlund, A.J., & Fowler, S.C. (1978). An eight-channel computer-controlled scanning electromyograph. *Behavior Research Methods & Instrumentation, 10*, 652–662.

Fridlund, A.J., Fowler, S.C., & Pritchard, D.A. (1980). Striate muscle tensional patterning in frontalis EMG biofeedback. *Psychophysiology, 17*, 47–55.

Fridlund, A.J., Hatfield, M.E., Cottam, G.L., & Fowler, S.C. (1986). Anxiety and striate-muscle activation: Evidence from electromyographic pattern analysis. *Journal of Abnormal Psychology, 95*, 228–236.

Fridlund, A.J., & Izard, C.E. (1983). Electromyographic studies of facial expressions of emotions and patterns of emotion. In J.T. Cacioppo & R.E. Petty (Eds.), *Social psychophysiology: A sourcebook* (pp. 243–286). New York: Guilford Press.

Fridlund, A.J., Price, A.W., & Fowler, S.C. (1982). Low-noise, optically isolated electromyographic preamplifier. *Psychophysiology, 19*, 701–705.

Fridlund, A.J., Schwartz, G.E., & Fowler, S.C. (1984). Pattern recognition of self-reported emotional state from multiple-site facial EMG activity during affective imagery. *Psychophysiology, 21*, 622–637.

Gale, A., & Baker, S. (1981). In vivo or in vitro? Some effects of laboratory environments, with particular reference to the psychophysiology experiment. In M.J. Christie & P.G. Mellet (Eds.), *Foundations of psychosomatics*. Chichester: Wiley.

Gale, A., & Smith, D. (1980). On setting up a psychophysiological laboratory. In I. Martin & P.H. Venables (Eds.), *Techniques in psychophysiology* (pp. 565–582). Chichester: Wiley.

Geen, R.G., & Gange, J.J. (1977). Drive theory of social facilitation: Twelve years of theory and research. *Psychological Bulletin, 84*, 1267–1288.

Glaus, K.D., & Kotses, H. (1977). Generalization of frontalis muscle tension. *Biofeedback and Self-Regulation, 2*, 307–308.

Glaus, K.D., & Kotses, H. (1979). Generalization of frontalis muscle tension: A closer look. *Psychophysiology, 16*, 513–519.

Goldfried, M.R., & Davison, G.C. (1976). *Clinical behavior therapy*. New York: Holt, Rinehart, & Winston.

Goodgold, J., & Eberstein, A. (1977). *Electrodiagnosis of neuromuscular diseases*. Baltimore: Williams & Wilkins.

Graeme, J.G. (1975). *A simplified precision rectifier with variable gain*. Application Note AN-75. Tucson, AZ: Burr-Brown Research Corporation.

Greenwald, A.G. (1976). Within-subject designs: To use or not to use? *Psychological Bulletin, 83*, 314–320.

Grieve, D.W., & Cavanaugh, P.R. (1973). The quantitative analysis of phasic electromyograms. In J.E. Desmedt (Ed.), *New developments in electromyography and clinical neurophysiology* (Vol. 2, pp. 487–496). Basel: Karger.

Hayes, K.J. (1960). Wave analyses of tissue noise and muscle action potentials. *Journal of Applied Physiology, 15*, 749–752.

Honts, C.R., & Hodes, R.L. (1982a). The effects of mul-

tiple physical countermeasures on the detection of deception [Abstract]. *Psychophysiology, 19*, 564–565.

Honts, C.R., & Hodes, R.L. (1982b). The effects of simple physical countermeasures on the detection of deception [Abstract]. *Psychophysiology, 19*, 564.

Izard, C.E. (1980). *The maximally discriminative facial movement coding system (MAX).* Newark, DE: Instructional Resources Center, University of Delaware.

Jennings, J.R., Berg, W.K., Hutcheson, J.S., Obrist, P., Porges, S., & Turpin, G. (1981). Publication guidelines for heart rate studies in man. *Psychophysiology, 18*, 226–231.

Jones, E.E., & Sigall, H. (1971). The bogus pipeline: A new paradigm for measuring affect and attitude. *Psychological Bulletin, 76*, 349–364.

Kitchin, C., & Counts, L. (1983). *RMS to DC conversion application guide.* Norwall, MA: Analog Devices, Inc.

Lawrence, J.H., & De Luca, C.J. (1983). Myoelectric signal vs. force relationship in different human muscles. *Journal of Applied Physiology, 54*, 1653–1659.

Lindstrom, L.R. (1970). *On the frequency spectrum of EMG signals.* Technical Report - Research Laboratory of Medical Electronics, Chalmers Institute of Technology, Goteborg, Sweden.

Lippold, O.C.J. (1967). Electromyography. In P.H. Venables & I. Martin (Eds.), *Manual of psychophysiological methods* (pp. 245–298). New York: Wiley.

Lykken, D.T., Rose, R., Luther, B., & Maley, M. (1966). Correcting psychophysiological measures for individual differences in range. *Psychological Bulletin, 66*, 481–484.

Malmo, R.B. (1975). *On emotions, needs, and our archaic brains.* New York: Holt, Rinehart, & Winston.

McGuigan, F.J. (1970). Covert oral behavior during the silent performance of language tasks. *Psychological Bulletin, 74*, 309–326.

McHugo, G., & Lanzetta, J.T. (1983). Methodological decisions in social psychophysiology. In J.T. Cacioppo & R.E. Petty (Eds.), *Social psychophysiology: A sourcebook* (pp. 243–286). New York: Guilford Press.

Moore, D.L., & Baron, R.S. (1983). Social facilitation: A psychophysiological analysis. In J.T. Cacioppo & R.E. Petty (Eds.), *Social psychophysiology: A sourcebook* (pp. 434–466). New York: Guilford Press.

Moritani, T., & De Vries, H.A. (1978). Reexamination of the relationship between the surface integrated electromyogram (IEMG) and the force of isometric contraction. *American Journal of Physical Medicine, 57*, 263–277.

Mulder, T., & Hulstijn, W. (1984). The effect of fatigue and repetition of the task on the surface electromyographic signal. *Psychophysiology, 21*, 528–534.

Muller, K.E., Otto, D.A., & Benignus, V.A. (1983). Design and analysis issues and strategies in psychophysiological research. *Psychophysiology, 20*, 212–218.

Orne, M.T. (1962). On the social psychology of the psychological experiment: With particular reference to demand characteristics and their implications. *American Psychologist, 17*, 776–783.

Ott, W.E. (1974). *Instrumentation amplifiers: Versatile differential input gain blocks.* Application Note AN-75. Tucson, AZ: Burr-Brown Research Corporation.

Petty, R.E., & Brock, T.C. (1981). Thought disruption and persuasion: Assessing the validity of attitude change experiments. In R.E. Petty, T.M. Ostrom, & T.C. Brock (Eds.), *Cognitive responses in persuasion* (pp. 55–80). Hillsdale, NJ: Erlbaum.

Porges, S.W., McCabe, P.M., & Yongue, B.G. (1982). Respiratory heart-rate interactions: Psychophysiological implications for pathophysiology and behavior. In J.T. Cacioppo & R.E. Petty (Eds.), *Perspectives in cardiovascular psychophysiology* (pp. 223–264). New York: Guilford Press.

Rosenthal, R. (1966). *Experimenter effects in behavior research.* New York: Appleton-Century-Crofts.

Rosenthal, R., & Rosnow, R. (Eds.) (1969). *Artifact in behavioral research.* New York: Academic Press.

Sagberg, F., & Kveim, K.B. (1981). Simultaneous EMGs from six sites during muscular relaxation: A comparison between forearm and forehead feedback. *Psychophysiology, 18*, 424–431.

Schwartz, G.E., Fair, P.L., Salt, P., Mandel, M.R., & Klerman, G.L. (1976). Facial muscle patterning to affective imagery in depressed and nondepressed subjects. *Science, 192*, 489–491.

Segreto-Bures, J., & Kotses, H. (1982). The experimenter expectancy effects in frontal EMG conditioning. *Psychophysiology, 19*, 467–471.

Shedivy, D.I., & Kleinman, K.M. (1977). Lack of correlation between frontalis EMG and either neck EMG or verbal ratings of tension. *Psychophysiology, 14*, 182–186.

Silverstein, L.D., & Graham, F.K. (1978). Eyeblink EMG: A miniature eyelid electrode for recording from orbicularis oculi. *Psychophysiology, 15*, 377–379.

Soderquist, D. (1976). Minimization of noise in operational amplifier applications. Application Note AN-15. In *Linear and conversion I.C. products* (pp. 15-36–15-45). Santa Clara, CA: Precision Monolithics, Inc.

Sternbach, R.A. (1966). *Principles of psychophysiology.* New York: Academic Press.

Strong, P. (1970). *Biophysical measurements.* Beaverton, OR: Tektronix, Inc.

Sugimoto, H., Ishii, N., Iwata, A., & Suzumura, N. (1977). Stationarity and normality test for biomedical data. *Computer Programs in Biomedicine, 7*, 293–304.

Sumitsuji, N., Matsumoto, K., Tanaka, M., Kashiwagi, T., & Kaneko, Z. (1967). Electromyographic investigation of the facial muscles. *Electromyography, 7*, 77–96.

Swanson, D.K., & Webster, J.G. (1974). A model for skin-electrode impedance. In H.A. Miller & D.C. Harrison (Eds.), *Biomedical electrode technology: Theory and practice* (pp. 117–128). New York: Academic Press.

Tassinary, L., Geen, R., & Cacioppo, J.T. (1986). Optimizing surface electrode placements for facial EMG recording: Guidelines for recording from the *corrugator supercilii* and *zygomaticus major* muscle regions [Abstract]. *Psychophysiology, 23*, 466.

Teuber, H.L. (1955). Physiological psychology. *Annual Review of Psychology, 6*, 267–294.

Tognacci, L.N., & Cook, S. (1975). Conditioned autonomic responses as bidirectional indicators of racial attitude. *Journal of Personality and Social Psychology, 31*, 137–144.

Tursky, B. (1964). Integrators as measuring devices of

bioelectric output. *Clinical Pharmacology and Therapeutics, 5*, 887–892.

van Boxtel, A., Goudswaard, P., & Janssen, K. (1983). Absolute and proportional resting EMG levels in muscle contraction and migraine headache patients. *Headache, 23*, 215–222.

van Boxtel, A., Goudswaard, P., & Schomaker, L.R.B. (1984). Amplitude and bandwidth of the frontalis surface EMG: Effects of electrode parameters. *Psychophysiology, 21*, 699–707.

Whatmore, G.B., Whatmore, N.J., & Fisher, L.D. (1981). Is frontalis activity a reliable indicator of the activity in other skeletal muscles? *Biofeedback and Self-Regulation, 6*, 305–314.

Wilder, J. (1962). Basimetric approach (law of initial value) to biological rhythms. *Annals of the New York Academy of Sciences, 68*, 1211–1220.

Wilkinson, L. (1985). *SYSTAT: The system for statistics.* Evanston, IL: Systat, Inc.

Williamson, D.A., Epstein, L.H., & Lombardo, T.W. (1980). EMG measurement as a function of electrode placement and level of EMG. *Psychophysiology, 17*, 279–282.

Willison, R.G. (1963). A method for measuring motor unit activity in human muscle. *Journal of Physiology, 168*, 35–36.

Winter, D.A., Rau, G., Kadefors, R., Broman, H., & De Luca, C.J. (1980). *Units, terms, and standards in the reporting of EMG research.* Report by the Ad Hoc Committee of the International Society of Electrophysiological Kinesiology.

Zajonc, R.B. (1965). Social facilitation. *Science, 149*, 269–314.

(Manuscript received June 4, 1986; accepted for publication July 25, 1986)