Augmented Auditory Information in the Control of Upper-Limb Prostheses

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The present study compared the effects of augmented auditory information on the linear positioning performance of individuals with natural or prosthetic limbs. Subjects were ten male volunteers, five of whom had above-elbow amputations and had used their prosthetic devices for an average of 8.3 years. The other five subjects were selected from a volunteer pool. Movements were made and measured on a standard linear slide whose cursor had a pulsing infrared diode attached opposite the subject. An infrared camera and microprocessor translated diode movement into a corresponding change in voltage. The voltage was simultaneously applied to an audio device which supplied the augmented feedback. The movement of the cursor by the subject was paralleled by a linearly-related change in audible frequency (Hz). The subjects performed 15 trials at each of three retentions (immediate, 15-sec filled, and 15 sec unfilled), both with and without the augmented feedback, for a total of 90 trials. The results of group x feedback x retention intervals analysis of variance on absolute and variable error indicated both a group x retention and a group x feedback interaction. Subjects using a prosthetic limb to produce the movement were less accurate and more variable than the "normal" subjects when augmented feedback was not concurrent with response.

KEY WORDS: Amputees; Feedback; Movement; Prosthesis

Theorists in motor behavior1-6 have developed hypotheses dealing with the processes needed to transform sensory input into internal movement representations. While these memorial representations have been proposed to take the form of a perceptual trace,1 schema,6 or a spatial coordinate system,4 theorists agree that movement control depends on the coding of direct and/or integrated sensory information into memory.2,5

Indeed, a variety of information sources aid in the development of an accurate internal representation of a movement. Visual and auditory information as well as proprioceptive information arising from the actual movement may be used. Of major concern is the sensory information available from kinesthesia (joint and muscle afferents) because these receptors transmit information indicating joint position, tension, and velocity.

Normal individuals are thought to rely on the kinesthetic receptors for the control and/or evaluation of movement. However, amputees who wear the traditional cable-operated prostheses have no opportunity to store or utilize kinesthetic information from the prosthetic limb, even though such information may be received indirectly in a gross fashion through the body movement used to cause movement in the device. Indeed, even those who use myoelectrically-controlled devices, with limb output controlled by bioelectricity generated by voluntary muscular contraction, are given little feedback about the joint position of the prosthesis by the signals. It appears that vision must be heavily relied upon in monitoring and use of either control system. The addition of information (augmented feedback), other than vision, which could be coded centrally should aid the amputee significantly in improving distance and location reproduction. Such information may be redundant for nonamputees having the capability of using direct afferent feedback in reproducing movements. Excessive feedback for the nonamputees could act as noise, decreasing the amount of attention given to the more relevant, for them, kinesthetic information. Additional electronically-assisted feedback may augment the development of an internal representation of the movement for the amputees because no direct afferent information comes into competition with the processing of the auditory information.

Purposes of the present study were: (1) to compare the performance of subjects having normal afferent pathways with that of amputees in whom such pathways directly from the moving limb are absent; and (2) to determine if the augmented auditory feedback influences performance and/or has access to central processing in memory.

METHOD

Subjects. The study involved ten male student volunteers from Texas A&M University, ranging in age from 20 to 31. Five individuals had left above-elbow amputations and had used their cable-operated prostheses for a mean of 8.3 (range 7 to 11) years. The other five subjects were nonamputees randomly selected from a volunteer pool. All subjects had no other diagnosed performance limitations.

Design. The experiment involved a $2 \times 2 \times 3$ (group $\times$ feedback $\times$ retention interval) factorial design with repeated measures on the last two factors. The three retention intervals used were immediate reproduction, 15 seconds rest, and a 15-second filled interval. Subjects received 12 movement distances ranging from 30 to 85cm in 5cm increments, repeated over retention intervals and feedback conditions. Thirty trials were performed in each of the two feedback conditions, ten trials at each of the three retention intervals, for a total of 60 trials, with five trials at each preselected distance. The order of presentation for the factors was randomly determined with

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the restriction that each feedback condition and retention interval contain five trials.

Procedure. Subjects received written instructions concerning the experiment, after which they were blindfolded, led to the testing area, and seated in front of a linear track apparatus such that the midline of the body was in line with the midrange of the left to right movements. The experimenter placed the subject's hand or prosthetic device, elbow unit locked, on the movement cursor, and presented the total possible movement range. On each trial, the subject moved the cursor from left to right along the horizontal track until striking a stop placed by the experimenter at a preselected point. During the augmented feedback trials, the movement of the cursor was accompanied by an audible tone that increased in intensity and pitch as the distance from the starting point increased. The instrumentation consisted of a standard linear slide to which a pulsing infrared diode was attached to the movement cursor opposite the subject. An infracamera and microprocessor translated the movement of the diode into a corresponding change in voltage, which was fed to a device (audio VCO) providing the augmented auditory feedback. Thus, the movement of the cursor by the subject was paralleled by a linearly related change in audible frequency (Hz) (fig 1).

The subject returned his hand or prosthetic device to the starting point while the experimenter returned the cursor during the retention interval. Reproduction movements were undertaken either immediately, after a 15-second rest interval, or after a 15-second filled interval of vocal counting backward by three. Work by Laabs shows that, by comparing recall accuracy after brief retention intervals with immediate recall, inferences can be made concerning the access of movement cues to central processing. When recall accuracy is maintained over an unfilled retention interval (as compared with immediate recall) but declines after a filled retention interval (filled with interpolated activity) it is assumed that the subject was able to process (rehearse) relevant movement cues. However, decreases in recall accuracy after both filled and unfilled retention intervals suggest that the subject was not effective in coding/processing the available cues. This technique permits the isolation of movement cues that have access to central processing from those that are ineffectively processed/rehearsed and thus spontaneously decayed.

RESULTS AND DISCUSSION

Augmented auditory feedback appeared to facilitate immediate recall, the amputee group repositioning more accurately than the normal group (fig 2). However, the influence of the augmented auditory feedback after either a 15-second unfilled or filled retention interval appeared to depend upon both the group and the retention interval (filled or unfilled). Indeed, a group x feedback x retention interval analysis of variance with repeated measures on the last two factors indicated an interaction of all factors $f(2,16)=3.44$, $p<0.05$ as well as main effects of feedback $f(1,8)=44.54$, $p<0.01$ and retention intervals $f(2,16)=15.88$, $p<0.01$. The analysis also indicated group x retention interval $f(2,16)=3.8$, $p<0.05$ and group x feedback $f(2,16)=23$, $p<0.01$ interactions.

Augmented auditory information appeared to facilitate the immediate reproduction of a simple linear movement. However, while the amputee group appeared to process the auditory information centrally, this was not the case for the nonamputee subjects. This conclusion is supported by the finding that the amputee group maintained some residual influence from the auditory information over a 15-second unfilled retention interval that was lost when processing was blocked, as in the 15-second filled interval. No residual effect was evidenced in the nonamputee group after a 15-second unfilled retention interval, indicating that the nonamputee subjects could not, or

Fig 1—Subject performing task on apparatus.

Fig 2—Experimental relationships among groups, retention intervals, and accuracy.
chose not to utilize the augmented auditory information. Perhaps, in the nonamputee subjects, the auditory information was blocked from processing because this information had to compete with more customary kinesthetic information, while the amputee subjects were free to process this information.

The fact that the amputees were able to code the auditory information into a form that enhanced movement reproduction suggests the need for a series of future studies to determine the effects of this information in the training of recent amputees on the nonvisual use of their prosthetic limbs. For example, the use of electronic auditory biofeedback in the initial stages of training, with the gradual reduction of this augmented information, could perhaps lead to permanent changes in the skill of manipulating the device without overdependence on vision.

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References

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