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Sensory Feedback and the Impaired Motor System

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A group design study was carried out using regulated feedback to enhance functional recovery in stroke patients. Patients trained on three computerized tasks aimed at improving guided limb motion in the hemiplegic arm. The therapeutic group was able to make use of the sensory feedback to outperform the control group in each of the three tasks. The therapeutic group also showed an adaptation of the improved performance on the three tasks. Further investigation is required to demonstrate that such sensory feedback training results in a corresponding improvement in activities of daily living skills.

INTRODUCTION

The fundamental motor rehabilitation issue is the manner in which the therapeutic process can exploit the ability of the central nervous system to elicit modifications in performance. The central nervous system exhibits a remarkable plasticity of function. Under normal conditions, motoric activities can be significantly altered, particularly in the presence of sensory signals conveying information concerning the error in performance.[1] In an impaired system, however, the ability to translate error signals into modified performance may be affected, and hence plasticity may be reduced. Functional recovery is aided by nonspecific factors, that is, random sensory experiences encountered during daily life do contribute to improved performance. Nonetheless, substantial improvement will most likely require specific factors, as manifested by meaningful and regulated feedback within a task-oriented context.[2]

The goal of this study was to enhance functional recovery of the hemiplegic arm in a group of stroke patients, by means of feedback that is specific to the impairment, meaningful to the patient, and regulated by the performance. The motor theme selected was guided limb motion, or more specifically, accessing targets in space with endpoint

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accuracy.[3] Relevant tasks were designed that encompassed the fundamental components involved in the activity of reaching. These components included spatial and temporal motor accuracy with stationary and moving targets, and temporal perceptual accuracy with moving and sometimes occluded targets.

A microcomputer-based system, called the Rehabilitation Workstation (Fig. 1), was used to present the tasks to the patient, and to provide the patient with appropriate and timely feedback concerning his performance. This was accomplished by using input sensors to measure the actual performance of the patient, and then translating the behavior into useful information for the patient. The error and quality of performance were fed back to the patient, along with sensory stimuli to induce improvement in future performance.

The hypothesis was that regular training on the Workstation tasks, with the accompanying feedback and motivational elements, would result in significant improvement in task performance.[4] Since the tasks were specifically designed to simulate functional reaching, verification of the hypothesis would encourage further investigation to demonstrate formally that the improvement showed a transfer to functional activities, as evidenced in activities of daily living skills.

METHODS

Subjects

Twelve hemiplegic patients were recruited for this study. The patients ranged in age from 45 to 70 years, and included both sexes. Each patient had experienced only one stroke, and that occurred between 6 and 24 months prior to the start of the study. A computed tomography scan or a neurological assessment, as interpreted by a physiatrist, demonstrated a unilateral insult. Incontinence, unilateral visual neglect, and visual acuity more than 20/40 with correction as tested monocularly precluded admission to the study.

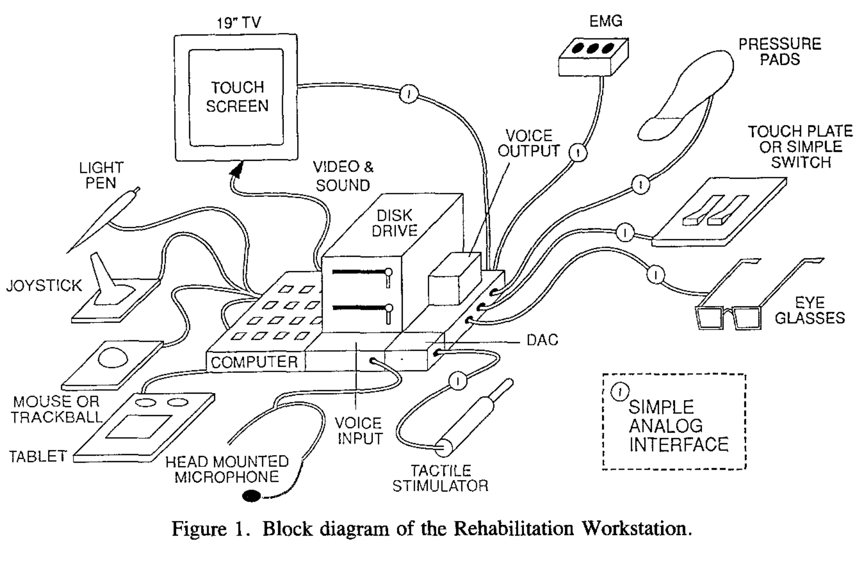

Figure 1. Block diagram of the Rehabilitation Workstation.

Cognitive or perceptual deficits that would interfere with comprehension of the tasks, as evaluated by an occupational therapist, also disallowed accrual.

The patients had no other treatment intervention, such as pharmacological management or occupational or physical therapy, for 8 weeks prior to the study and throughout the duration of the study. Each patient was pronounced medically stable by the clinical staff at the beginning of testing.

Instrumentation

The system used in this experiment was based on a Radio Shack color computer, and an ordinary 19 in. color television set. Two input devices, a touchplate and a touchscreen, were used. The output devices were the television set and a programmable voice unit.[5]

The touchplate consisted of two copper rectangles inlaid in a movable flat wooden surface. The plate operated as a simple binary switch, detecting whether or not the subject's hand was bridging the two copper rectangles. By means of the computer timer, the time of change from one state to the other was also detected. This sensor was used to calculate temporal perceptual accuracy, that is, the difference in time between the actual and perceived occurrence of an event. The touchplate was also used to monitor the maintenance of a standard initial position for the subject's hand prior to the start of each task trial.

The touchscreen measured 19 in. diagonally and fit over the face of the television set. The touchscreen recorded the horizontal and vertical coordinates of points that were touched, and in conjunction with the computer timer, the time at which the points were touched. This sensor enabled the calculation of spatial endpoint accuracy, that is, the distance between the desired and the actual point of touch; it also permitted the calculation of temporal endpoint accuracy, that is, the difference between the desired and the actual time of touch.

The television screen was used to present visual output consisting of objects of different size, shape, color, and content, and with various motion attributes. Tones of different pitch, frequency, and volume, as well as concatenations of these tones and sound effects, were also provided through the television monitor. The voice unit consisted of a programmable module that could speak syllables, words, and sentences. This was used to present additional auditory output at selected times during the tasks.

Tasks

Three tasks were designed, to be presented and performed with the Workstation. Each task contained a fundamental component of guided limb motion which must be mastered in order to access spatial targets successfully. Task I was directed toward improving spatial accuracy in reaching for stationary targets.[6] Task II was concerned with the perceptual facet of guided limb motion, and required the accurate prediction of the appearance of a moving target at a prescribed point after the target had disappeared for a period of time. This second task was prompted by the observation that in many functional reaching tasks the target or the limb is occluded during portions of the reach and the nervous system is required to do a nonvisual monitoring of the target or limb motion in order to calculate the parameter values for successful access.[7] Task III was concerned with the element of timing, and involved exercise in placing the hand at a designated location so that it coincided temporally with the arrival of a moving target at that location.[8]

Each of the three tasks had two versions, namely, training and testing. During the training version, the subject was given feedback that enabled him to evaluate his performance, as well as motivational and reward factors. During the testing version, the identical task was presented, but the subject was given no indication whatsoever as to the quality of his performance.

Each version of each task also had five levels of difficulty associated with it. When the subject performed successfully at one level according to a predetermined criterion, he proceeded to the next level in which certain parameters were changed to make the task more difficult. The identification and variation of the difficulty parameters were based either on well-accepted principles of rehabilitation or on the results of companion studies carried out during this experiment.

A scoring system was devised for each of the tasks, so that a quantitative measure of performance could be derived for each task trial. The subject was given 0, 1, 3, or 5 points for each execution of each trial, depending on how well he accomplished the primary focus of the task. He was then given a cumulative score for each session which took into account the individual trials as well as the level of difficulty.

Task I. For Task I, the subject was seated in front of the television set, at a distance which enabled him to reach the screen with full arm extension. The task began with the subject placing the hand of his hemiplegic arm in a standard position on the touchplate, which was situated at the midline in front of him at waist level. A star one inch in diameter then appeared on the screen at shoulder level but in a random horizontal location. The subject was instructed to touch the star as close to its center as possible using the hemiplegic arm, without regard to the speed of the action.[9] Scoring was based on the spatial error, that is, the distance between the center of the target and the actual touch.

Feedback consisted of the appearance of a small circle at the actual point of touch, together with 0, 1, 3, or 5 tones indicating the performance score. In this way, the subject received an immediate gross assessment of the quality of his performance through the auditory response, and finer visual information with which to compare his actual touch to the required touch. The subject was thus given an error signal which he could use to improve future performance. After every five task trials, the output voice unit of the Workstation announced the total score for those five trials. Audio-visual rewards were also given, in proportion to the degree of success.

The level of difficulty for Task I was increased by physically moving the television set from the side contralateral to the hemiplegia to the ipsilateral side in five successive stages. It is a verified fact that it is considerably more difficult to extend the hemiplegic arm in the ipsilateral direction than in the contralateral direction.[10]

Task II. Task II was a prediction task and required no movement of the hemiplegic arm. The task began by having the subject maintain an initial position as described in Task I, but with the unaffected hand on the touchplate. The task commenced with the appearance on the television screen of a target and a path composed of horizontal and vertical segments. The target then began moving at a constant velocity along the path to a destination point marked somewhere on the path. At some point along the path the target disappeared. The subject was instructed to continue monitoring the motion of the target nonvisually, and then respond by unbridging the two rectangles of the touchplate when he thought the target was at the destination point. Preliminary investigations showed that unbridging the rectangles was one of the fastest motor responses that this population could make. Thus, the motor component of the response was minimized. The scoring depended on the temporal error, specifically, on the difference between the time that the target would have arrived at the destination had it continued visibly at its constant velocity and the perceived time of arrival as given by the subject's response.

Feedback consisted of the reappearance of the target, now stationary at the point on the path where it actually was at the time of the subject's response. This provided a graphic illustration of whether the response was too early or too late, as well as an analog indicator of the amount of error. A number of tones also sounded to indicate the numerical performance score. Thus, the subject was given a visual means of understanding the exact magnitude and direction of his temporal error, and an auditory signal to use as a quick comparator for his attempts. The voice unit and reward system added motivational elements to the task.

The levels of difficulty for this task were determined from a study of normal subjects exposed to the task. The task was presented with the target moving at different constant velocities, with different distances between the starting point and the destination point, with different total durations from the start of the motion to the actual arrival of the target at its destination, and with different points at which the target disappeared. An analysis of variance of the resulting performances of the subjects indicated that, while velocity and duration contributed somewhat to the difficulty of the task in that slower velocities and longer durations made the task more difficult, the overwhelming parameter was the ratio of visual to nonvisual monitoring. Hence, the levels for Task II in this study, in ascending order of difficulty, were characterized by trials in which the ratio of the path length over which the target was visible to the path length between the point of target disappearance and the destination point became smaller.

Task III. For Task III, the subject was seated as in Task I. The task began with the appearance of a target and a fixed, marked destination at the same vertical level on the television screen. The destination was contralateral to the hemiplegic side, that is, at the location that was easiest for arm extension. The target then began moving toward the destination. The subject was instructed to touch the destination point on the screen, using the hemiplegic arm, at the exact time of arrival of the target at that point, with only minimal regard for spatial accuracy. Scoring was based on the temporal error, as given by the distance between the target and the destination at the time of touch, or equivalently by the difference between the time of arrival and the time of touch.

Feedback consisted of the halting of the target in place at the time of touch and of tones indicating the score. The subject could then study the target's spatial location relative to the destination in order to correct his strategy for making future touches that were temporally coincident with the target. As in the other two tasks, the voice unit and reward system were activated by successful performance.

The level of difficulty was increased by starting the target at positions that were closer to the destination point thus decreasing the distance traveled, and by increasing the velocity of the target. The net effect was a dual decrease in the total time interval during which arm movement could take place. More importantly, the velocity increase also resulted progressively shorter time intervals during which points could be scored, since the scoring scheme was based on the distance of the jogger from the destination. Hence, as the levels became more difficult, less time was allowed for arm movement, and shorter time periods were given for fine-tuning the endpoint component.

Experimental Design

The experiment was a matched-pair group design, consisting of six hemiplegic patients in the therapeutic group and six in the control group. Two screening sessions were held for each subject to evaluate additional eligibility requirements, aimed at identifying subjects who possessed approximately the same initial capability of performing the tasks. To assure further the equivalence of the two groups, the 12 subjects were matched into 6 pairs. The matching was based on an independent clinical evaluation of their motor and cognitive states, using standard test instruments.[11] The members of each pair were then randomly assigned to either the therapeutic or control group.

Each of the 12 subjects was tested three times a week over a 4-week period, for a total of 12 sessions. Testing consisted of five trials of the testing version of each of the three tasks. On the first testing day, the subject performed at the easiest level of difficulty. Successful performance at a level was defined as the accrual of a predetermined number of points on two separate occasions. When the subject exhibited successful performance at one level of a task, he proceeded at the following session to be tested at the next more difficult level of that task. Successful performance and progress were regarded independently for each of the three tasks.

Subjects in the therapeutic group only were given a training session immediately following each testing session. The training session consisted of 20 trials of the training version of each of the three tasks. Training on each task was administered at a level of difficulty one higher than the highest level mastered by the subject during testing on that task.

Thus, the therapeutic group was given considerable exposure to specific, regulated feedback in each of the tasks, and the control group was given no feedback. At the conclusion of the sessions, a comparison of the two groups was made to determine whether an impaired nervous system is able to integrate specific sensory information in such a way as to induce greater improvement in motor performance than that brought about by nonspecific factors.[12]

Reliability of the Tasks

The results of the two sessions of screening for the twelve subjects accepted into the study were used as the basis for a test-retest reliability study. The reliability coefficients for the three tasks were as follows:

Task I	$r = 0.8038$	$(p < 0.01)$
Task II	$r = 0.6552$	$(p < 0.05)$
Task III	$r = 0.8353$	$(p < 0.01)$

These results indicate that a score of a person drawn from the population under study on the first day of screening provides information for the prediction of his score on the same task one day later. In short, the data indicate that each task is reliable for this population.

RESULTS

Two distinct though related measures, bearing on the relative performance of the two groups during the 12-session testing period, were available. One was raw data, representing exact error per trial, recorded for each of five trials per session for each task. Error was measured in screen pixels for Task I and in seconds for Tasks II and III. The second measure was average points per session, based on a point system designed in part to serve as an easily understood benchmark by which progression to higher levels of difficulty in each task was determined. The point system has the advantage over raw data of uniform applicability to the three tasks, so that a measure of overall achievement across the tasks is available from the sum of points scored on each of the tasks. Furthermore, it has built-in difficulty and reward factors: bonus points were awarded for each successful passage to a higher level of difficulty; more points were awarded for a quality of performance at a high level of difficulty for a task than for the same quality achieved at a lower level of difficulty for the same task. On the other hand, an advantage of the raw data is that it gives accurate weight to trials in which the error is particularly large, in contrast to the more simplistic awarding of 0 points for such trials. In analyzing the data, it was decided to compare the groups on a task-by-task basis using raw data and to arrive at an overall comparison of the groups, across the three tasks, by employing point score results.

Analysis of variance (ANOVA) was used to analyze the raw data from each of the tasks and the point scores summed across tasks. The design of the experiment in all four cases was the same, 2×12 factorial (with independent variables G = groups and S = sessions) in a randomized block design, with the six matched pairs of subjects constituting six blocks.

Every point of view from which the data were analyzed led to the same conclusion, namely, a highly significant superiority in performance by the members of the therapeutic group.

Raw Data

The performance of the therapeutic group, based on lower mean error per trial, was superior in each of the three tasks to that of the control group, as shown in Table 1.

The differences between the two groups indicated in Table 1 are significant with $p < 0.01$ for all three tasks. The F ratios for the variable G for the respective tasks are 7.54, 30.56, and 8.29, each exceeding the critical value $F(1,115) = 6.87$. The variable S was

Table 1. Average Error per Trial

	Task I (pixels)	Task II (sec)	Task III (sec)
Therapeutic	14.79 ± 22.03	1.47 ± 1.30	0.43 ± 1.07
Control	21.49 ± 28.94	2.57 ± 2.70	0.74 ± 1.86

insignificant for all three tasks, as was group-session interaction. As might be expected, block effects were highly significant ($p < 0.01$) in all three cases.

Point System

The results of the 12 sessions of testing as reflected by the point system, incorporating reward factors for acquisitions of higher levels of difficulty, show highly significant superiority for the therapeutic group. In particular, the therapeutic group scored a higher average number of points per five-trial session, over $6 \times 12 = 72$ sessions per group, than the control group in all three tasks, as Table 2 indicates.

Analysis of the sum of average point scores per session across the three tasks (e.g., the first data item is the sum of the 3-point scores across the three tasks for the first subject in the first group at the first session) reveals that the sum of average point scores per session of 98.23 ± 77.32 for the therapeutic group is significantly higher (F ratio = 29.41, $p < 0.01$) than the control group's corresponding score of 63.85 ± 67.90. In this analysis, the factor "sessions" was significant ($p < 0.05$) and block effect was again highly significant ($p < 0.01$); group-session interaction was insignificant.

DISCUSSION

In addition to the formal results presented, there is a considerable amount of other evidence, both quantitative and qualitative, to lend further support to the study's major conclusion. There is also evidence from the data in the study to support the validity of two related hypotheses. First, there is information which implies that training with specific, regulated sensory feedback brings about *adaptation* of enhanced performance on behavioral motor tasks such as the three Workstation tasks. Second, there is a corpus of evidence that such training shows a *transference* to functional skills.

Major Conclusion

The major conclusion of the study is that the therapeutic group was able to make use of the sensory feedback conveyed during the training program to demonstrate significantly better performance in the Workstation tasks than the control group. There is additional tangential information that supports and strengthens this major conclusion.

Quantitative Information. To consider the comparative achievement of the two groups in greater detail, we present Tables 3 and 4 which give information about performance within individual matched pairs. Table 3 contains total point scores of each of the 12 subjects, viewed within their respective blocks on each of the three tasks. Table 4 gives

Table 2. Average Point Scores per Session

Task	Therapeutic	Control
I	31.43 ± 32.72	24.79 ± 32.43
II	27.72 ± 17.88	17.92 ± 18.13
III	39.08 ± 37.43	21.14 ± 25.18

Table 3. Point Totals

	Task I		Task II		Task III		Total	
Pair	Ther	Cont	Ther	Cont	Ther	Cont	Ther	Cont
1	77	413	261	93	341	577	679	1083
2	621	102	77	41	400	56	1098	199
3	941	996	521	501	1120	657	2582	2124
4	131	120	339	124	117	57	587	301
5	102	48	258	97	79	43	439	183
6	391	107	540	434	757	134	1688	657

information about the relative success of the two groups in acquiring levels of difficulty. Table 3 reveals that, for the tasks taken separately, the member of the therapeutic group scored more points on a task than the corresponding control group person on 15 of 18 possible comparisons. Looking at the sum of points across the three tasks, the member of the therapeutic group scored a higher number of points within five of the six blocks. In reference to Table 4, the members of the therapeutic group made a larger number of acquisitions of levels than the control group subjects on each of the three tasks, and within four of the five blocks on which a difference was recorded.

As indicated under Experimental Design, matched pairing of subjects was based on independent clinical evaluation of their motor and cognitive states. Subjects within blocks were then assigned randomly to the therapeutic and control groups. Pairings and assignments to the two groups were not made with reference to any direct measure of predisposition toward competence in any of the three tasks, or on the three tasks taken collectively, and in fact were made under the assumption that there were no such predispositions. There is actual data available to verify that these predispositions did not exist. A part of the screening process for eligibility for the study was testing, at the lowest level of difficulty, in each of the three tasks on 2 separate days. (These results were the basis of the reliability study reported on earlier.) The data from this screening process, if strongly skewed in favor of the therapeutic group, would seriously detract from the attribution of that group's superior testing results to training, ascribing some of the superiority instead to a predisposition in the subjects. The screening data, however, showed that the groups were quite comparable. By no measure, using either point scores or raw data, was there a statistically significant superiority for either group in screening scores on any of the three tasks. Indeed, an analysis of the screening scores for the tasks

Table 4. Acquisition of Levels

	Between groups within three tasks						
	Task I		Task II		Task III		Total
Therapeutic	9		7		13		29
Control	6		5		6		17
	Between groups within six matched pairs						
	Pair 1	Pair 2	Pair 3	Pair 4	Pair 5	Pair 6	Total
Therapeutic	3	5	12	2	0	7	29
Control	5	0	9	1	0	2	17

by means of a Wilcoxin rank sum test yielded nearly equal rank sums for both groups. This is in sharp contrast to the significant advantage earned by the therapeutic group in all three tasks during the later training and testing period.

Further information in a similar vein, bearing now on the relationship between screening and testing performance within individual subjects, was obtained by calculating a ratio of mean raw score, i.e., average error, per trial for testing to mean raw score per trial for screening. A ratio below 1 indicated improved performance whereas a ratio above 1 signaled deterioration. Since both screening sessions took place at the easiest level and the raw scores were frequently obtained from higher levels (particularly for the therapeutic group), this ratio does not strictly measure improvement or deterioration; rather, it understates improvement. Nonetheless, it is another useful vehicle for comparing the two groups. For the therapeutic group, based on three tasks per subject for six subjects, improvement occurred in 13 of 18 cases; the corresponding number for the control group was 9 of 18. The list of 36 ratios was analyzed by means of the Wilcoxin rank sum test. On an individual task basis, the therapeutic group had a larger rank sum on all three tasks, by margins of 42–36, 44–34, and 53–25 for Tasks I, II, and III, respectively. Analyzing the 36 ratios across the three tasks, the rank sum of the therapeutic group was 392, as opposed to 274 for the control group ($p < 0.05$).

It is important to emphasize that any superiority in testing displayed by the therapeutic group, based on raw data, is all the more impressive when the generally higher levels of difficulty in the tasks, not recognized in the raw data, at which they tended to be tested (recall Table 4) is taken into account. This remark pertains not only to the preceding paragraph but also to the results reported in Table 1 and the discussion of those results.

Finally, in addition to promoting greater accuracy, it appears that training with feedback also encouraged a more consistent performance. One indication of this is the uniformly lower standard deviation in Table 1 for the therapeutic group, compared to the control group. These numbers were high in all cases due to large differences in performance among individual subjects, a major reason in turn for employment of a block design.

Qualitative Remarks. There are noteworthy items relating to individual subjects and to individual matched pairs in the study. Pairing 2 (see Table 3) is of particular interest because both subjects in that block were rated by the therapists as "very good" in their affected arm movement, but relatively weak in their cognitive abilities. Considering the wide margin by which the subject in this block who received training outperformed his control group counterpart in all three tasks, a margin not foreshadowed by the results of their screening, it appears that the feedback and motivational features of the training had their greatest significance for this pair of subjects. This result seems to highlight the value of training with feedback as a motivational and instructional tool for stroke patients with cognitive defects.

In pairing 3, the control group subject outscored his counterpart in screening on all three tasks, but was outscored in testing in Tasks II and III. Even in Task I, where this control group subject compiled marginally more points, the subject in the therapeutic group had a superior average raw score, i.e., average error in pixels per trial, and attained the fifth, and highest, level of difficulty as compared to only the fourth level attained by the control group subject.

Adaptation

The six subjects in the therapeutic group returned on three separate occasions following the training program in order to determine whether they were able to maintain the improvement derived from the training sessions. These follow-up sessions were held immediately after, 4 weeks after, and 8 weeks after the end of training, and were performed at the highest level attained during training. Comparisons were made between the results of two sets of tests: (1) the two screening sessions and the first testing session (performances before any training took place); and (2) the three follow-up sessions.

The following numerical results emerged. In the 18 cases consisting of the cumulative scores on each of the three tasks for each of the six subjects, 13 of the 18 were higher in follow-up than in screening. Also, each subject performed better in more tasks during follow-up than during screening; specifically, five subjects presented higher scores in two of the three tasks during follow-up and one presented higher scores in all three tasks during follow-up. Regarding the three tasks as a whole, four subjects did better on Tasks I and II in follow-up than in screening, and five subjects did better in Task III in follow-up than in screening. These results illustrate that, in general, the subjects in the therapeutic group maintained a higher quality of performance after training than that which they exhibited initially before entering the program. It must be noted, however, that there was a monotonic, though slight, deterioration of performance from one follow-up session to the next. It is again important to emphasize that these adaptation results are even more impressive considering that the follow-up scores were achieved at higher levels of difficulty than the screening scores.

Functional Transference

Ideally, in any rehabilitative intervention, one would like to see the improvement demonstrated within the therapy environment transferred to functional skills. Specifically, in the present study, a natural question occurs as to whether Workstation training translates to a general statement regarding improved functional abilities, such as dressing and other self-care activities. Although it was beyond the scope of this study to prove formally that this functional transference occurred, there were several indicators that in fact it did take place.

Because the Workstation is automated and programmable, it enabled the precise control over the stimulus as well as the flexibility in presentation that is required in order to simulate functional tasks without having to resort to contrived experimental procedures. The three tasks were specifically constructed so as to reflect functional reaching activities, and require functional reaching skills. Thus, the formal results of the study, which showed that there was enhancement of performance on the three tasks, strongly suggest that this enhancement should also be observed in activities of daily living.

Also compelling are the anecdotal compilations on patients who were in the therapeutic group. These were obtained from patient self-reports, family reports, logs of the personnel involved in the training, and observations of health professionals not connected with the study. Virtually all of the patients displayed looser shoulder rotations throughout the training program, and this is a fundamental goal for stroke patients. Two patients gave unsolicited reports of improved functional use of the arm since the beginning of the training program. One other patient, who had shown no change in arm function for some time under conventional therapy, exhibited noticeable improvement of arm function during training, as commented upon by family members and a former therapist. Secondary functional effects were documented as well. For example, one patient reported more hand flexibility as a result of the finger extension required to score accurate touches on the screen. In another case, the therapist who was administering the training noted a postural improvement in one of the patients as a result of progressing through the levels of Task I, in which more and more seating stabilization is demanded in order to achieve success as the reaching becomes more ipsilateral.

The above commentaries indicate that a formal study of functional transference of the behavioral improvement is warranted. The patients in the current study were given the Klein-Bell test, an activities of daily living measure, before and after the training program. This test, however, was far too gross to reveal any of the functional changes cited above that appear to have taken place. Future studies will very likely involve a longer training period in order to produce quantifiable changes, and a more sensitive instrument for rating functional performance indices.

CONCLUSION

The major hypothesis of the study, that is, that specific and regulated feedback can be used by a population of stroke patients to improve performance on fundamental behavioral components of guided limb motion, has been proved statistically. Secondary propositions, namely, that this improvement is adaptive and that it translates into improvement in functional skills, have been given credence through additional quantitative results and anecdotal observations.

In conclusion, a scheme for enhancing recovery of function in an impaired motor system has been presented. This scheme relies upon the inherent plasticity of the central nervous system. It suggests, however, that nonspecific tactics are insufficient to repair a dysfunctional system. The realization of significant modifications demands the utilization of specific feedback presented to sensory systems capable of participating in the restorative process.

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