Errorless learning using haptic guidance: research in cognitive rehabilitation following stroke

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ABSTRACT

This paper presents an approach to rehabilitation of cognitive deficits following stroke using haptic guided errorless learning with an active force feedback (AFF) joystick and computer. While errorless learning (EL) is a proven method of teaching new information to individuals with memory problems, its effectiveness with other types of cognitive and perceptual motor deficits has not been explored. We investigated the effectiveness of haptic guided EL compared to trial and error (errorful: EF) learning on a perceptual motor task with twelve patients who had visuoperceptual deficits following stroke. Individual and group results are discussed.

1. INTRODUCTION

1.1 Cognitive Deficits Following Stroke

Cognitive deficits are a well known problem associated with many disabling conditions, such a traumatic brain injury, stroke, and other neurological disorders. The incidence of cognitive deficits following stroke has been estimated to be greater than 35% (Tatemichi et al, 1994). Impairment in global cognitive functions, attention, and psychomotor performance are significantly impaired in ischemic stroke patients regardless of the normal effects of aging (Elwan et al, 1994). Cognitive impairments following stroke result in poorer rehabilitation outcomes (Jeffrey & Good, 1995; Kwa et al, 1996), decreased quality of life (Riddoch et al, 1995), and increased incidence of depression (Lacritz & Cullum, 1998; Starkenstein and Robinson, 1989, 1990), with post stroke depression having been found to impair cognitive functioning (Lacritz & Cullum, 1998) and to be associated with poorer social functioning (Clark & Smith, 1998).

Their presence may be less obvious, but potentially as disabling, in conditions such as multiple sclerosis, drug and alcohol related disorders, and psychotic disorders such as schizophrenia. Regardless of the cause, cognitive deficits pose problems to the rehabilitation process. Examining some of the potential cognitive problems resulting from stroke is illustrative. Stroke can cause impairments of comprehension, memory, visual recognition, attention, and sequencing of actions that can have profound effects on physical functioning. To benefit from physical rehabilitation patients must be able to understand the therapist's commands, remember instructions, recognize physical objects in the environment, attend equally to both sides of space, maintain arousal levels sufficiently to co-operate throughout a treatment session and continue to utilize what the therapist has taught in their everyday lives (Riddoch et al, 1995). If the aim of rehabilitation is to optimize treatment outcomes then all factors influencing these outcomes need to be addressed, including cognitive impairments, in designing effective systems for intervention.

1.2 Haptic Guidance in Rehabilitation Robotics

Traditionally, the use of haptic guidance in the field of rehabilitation robotics has focused on physical disabilities where robotic guidance is used as a substitute for absent or diminished motor function. More recently there has been increased interest in robotic aides for motor rehabilitation (van Vliet & Wing, 1991).

For example, Krebs et al (1998), using robot-guided rehabilitation (a robotic arm) with stroke patients, demonstrated that robot-guided therapy does not have adverse effects, patients do tolerate the procedure, and brain recovery may be aided in the process. In their experimental paradigm, power assistance was used to enhance movements being made by the patient.

The broad aim of our work is the development of clinical applications of haptic guided errorless learning and evaluation of its effectiveness with cognitive problems in addition to memory. In the paradigm we describe, haptic guidance provided by a 'robot' was used for cognitive rehabilitation to retrain diminished function following non-progressive brain injury. We combined EL, a proven method of teaching new information to individuals with memory problems, and an AFF joystick capable of preventing errors from being made during learning. Haptic guidance used for cognitive retraining offers potentially a new area for rehabilitation robotics, relevant to perceptual motor skills, assisted by EL.

1.3 Errorless Learning

Errorless learning involves preventing or minimizing errors from being made during early learning trials, especially the initial trials. The foundations of EL were established in studies by Terrace (1963) who disputed the general acceptance of responding to non-reinforcing stimuli (errors) as a necessary condition for discrimination learning to occur. In his experiments pigeons were trained to respond to a stimulus correlated with reinforcement (correct or error free choice), a red typewriter key, and not respond to a stimulus correlated with non-reinforcement (incorrect or errorful choice), a green typewriter key—a discrimination pigeons would find difficult to make. One group of birds was trained under errorless conditions in which fading in of the "error" key color was done early in training and while the pigeon's head was turned away, making it difficult to respond. The other groups were trained in more traditional methods including no progressive key color changes and late introduction of the "error" key color. One interesting observation during these experiments was that pigeons in the errorless group showed behavior that was less agitated during the test phase than the other training groups.

Memory for material learned errorlessly has most often been attributed to implicit memory processes. Baddeley and Wilson (1994) proposed that one of the major functions of explicit memory is the elimination of learning errors. Explicit memory is facilitated by devoting full attention to the material to be remembered. In contrast, responses based on implicit memory are dependent upon emitting the strongest response. If erroneous responses are allowed to occur they are then strengthened across repeated learning trials. For EL to be successful the procedures need to be "foolproof," with learning tasks kept simple, guessing discouraged, and correct responses provided before the individual has a chance to make an error. A variety of techniques have been employed to prevent errors from being made during the learning process. For example, "forward chaining" involves learning the first step of the task correctly before the second and subsequent steps are taught. "Backward chaining" takes a reverse approach in which all steps of the task are completed with prompts followed by gradually withdrawing prompts from the last step then subsequent steps in reverse order of their occurrence in the task. "Vanishing cues" is similar to backward chaining in that cues or prompts are progressively removed.

Beginning in the early 1990's these EL techniques were successfully applied to the memory rehabilitation of individuals with brain injury and were found to be superior to EF learning (Baddeley & Wilson, 1994; Wilson et al, 1994; Wilson & Evans, 1996). While individuals with intact cognitive abilities are able to learn from their mistakes, research in the field of cognitive rehabilitation with memory impairments has demonstrated that conscious awareness during learning is important for error correction to occur. For many individuals with brain injury this conscious awareness, or explicit memory of the event, is diminished or unavailable. The initial response is typically unconsciously remembered and repeated, regardless of whether it is a correct response.

In a series of single case studies comparing EF and EL with amnesic participants, EL consistently resulted in superior performance, including assisting a stroke patient to learn the names of people (Wilson et al, 1994). In a subsequent study (Evans et al, 2000) in which nine different experiments were completed with amnesics, EL was found to be the superior method for tasks and situations dependent upon retrieval of implicit memory, however, tasks requiring the explicit recall of novel associations were remembered more successfully with the EF technique. We hypothesized that perceptual motor deficits following stroke would be more responsive to rehabilitation approaches relying on implicit memory.

Errorless learning has also been used in physical rehabilitation. Biomechanical control of the environment has been shown to prevent learning incorrect movements (Butler & Major, 1992). For example, only one segmental joint may be targeted for training while the remaining involved joints are kept immobilized. This type of targeted learning of motor control is analogous to the 'chaining' procedures previously described. An added benefit of EL is the resilience to increased cognitive demands. Masters, MacMahon, and Pall (in press) found, when Parkinson's patients were trained errorlessly using physical guidance in a simple motor task, hammering, there was no difference between the EL and EF groups once the guidance was removed. This result was expected as the training did not influence the neurotransmitter disturbances in the basal ganglia that characterize Parkinson's Disease. However, under dual task conditions carried out post-training, the EF group's performance became significantly worse, while the EL group's performance was unchanged. The implication from this study of the effect of EL motor learning for stroke patients is the added benefit of being able to simultaneously engage physically and cognitively demanding tasks such as walking using a hemiparetic limb while carrying on normal conversation.

2. METHOD

Hypothesis: EL training, using a haptic feedback joystick, will result in faster and more direct movements to targets in a visuospatial training task for stroke patients with visual perceptual deficits.

2.1 Participants

In this 18 month project, funded by the British Stroke Association, 12 independently living, community based male and female participants, 12 months or more post-cerebrovascular accident, ranging in age from 38 to 83, from the United Kingdom were recruited. Recruitment took place through a variety of sources including geriatricians in local health authorities, Stroke Clubs (community based support groups), and the University of Birmingham, School of Psychology patient panel volunteers. No patient was refused entry into the study on the basis of nature or severity of deficits, and severity of deficits was not stratified across groups.

2.2 Sample

All individuals in the study had evidence of some form of visuospatial processing difficulties, however, the number and severity of deficits ranged from minor visual memory problems to profound impairments across all neuropsychological measures of interest.

2.3 Assignment

Participants were pseudo-randomly assigned to either the EF training first group (group 1) or EL training first group (group 2) based on alternating the training type as each individual completed the pre-test phase. In the original assignment, six patients were allocated to each group, however two patients in group 2 did not complete the experimental paradigm and two patients in group 1 showed only minor visual memory problems, with no other visuospatial deficits.

2.4 Apparatus

2.4.1 Equipment description & operation. The equipment used in this study, a joystick and electronic gearbox unit, act as an input device to a standard desktop computer via an interface device. Users are able to interact with the computer by moving the joystick which controls an onscreen cross cursor, '+', capable of being moved around the entire screen domain. Users are able to move between stimuli displayed on screen and make selections by pressing a button on the top of the joystick. The joystick moves in a pitch and roll two dimensional plane. Any movement of the joystick generates a corresponding cursor movement on screen. Moving the joystick forward moves the cursor up, moving backward moves the cursor down, and side-to-side movements produce corresponding left or right cursor movements on screen. Operation of the joystick makes it possible to intercept targets appearing at any x/y coordinate on the computer screen. The interface programming allows for two modes of joystick operational control, EL and EF, which are set by the experimenter. Additionally, other parameter settings are available that allow for visual and auditory knowledge of results (KR), setting error margins, and selecting stimulus materials. The user moves the joystick to find a particular target on screen and makes a selection by pressing the button on the joystick. See Fig. 1.

2.5.2 Errorless or guided mode. In the guided or EL mode the system defines a 'force field valley' within which the joystick may be moved, which prevents movement to incorrect targets on the screen. The joystick does not move the user to the correct target but facilitates target acquisition by generating force field resistance against movements in any trajectory other than a straight-line path to the correct target. This sensory information comes in the form of haptic sensation (touch) via force resistance from the joystick whenever the user attempts to move it in an incorrect direction, thus allowing the user to sense the joystick's path of least resistance. By preventing movement to incorrect targets the joystick facilitates EL.

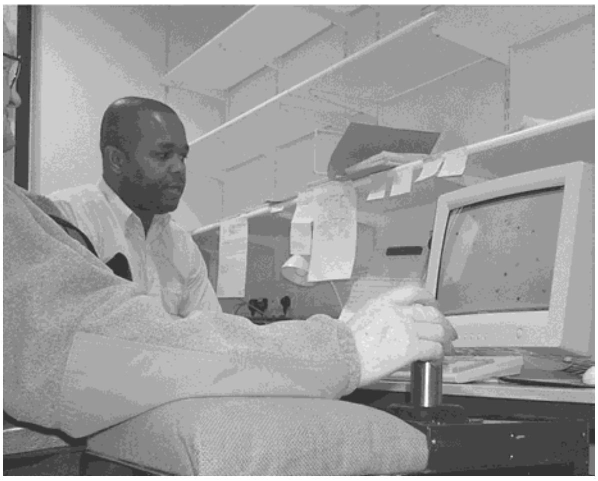


Figure 1. *AFF Joystick and computer display.*

2.5.3 Errorful or non-guided mode. In the non-guided or EF mode the joystick's force feedback parameters are switched off allowing for unrestricted movement. In this mode of operation, target acquisition is dependent upon the user's ability to manipulate the joystick thus allowing for trial-and-error, EF, learning.

2.6 Procedure

2.6.1 Neuropsychological Testing. Prior to beginning the experimental training, a comprehensive neuropsychological battery was administered to each patient. Measures relevant to visuospatial abilities were examined to determine appropriateness for the experimental task. These measures included: two subtests from the WAIS-R (Wechsler, 1981), Block Design (BD) and Digit Symbol (DSy); two from the WMS-R (Wechsler, 1987), Visual Reproduction Immediate (VR-I) and Delayed (VR-II); the six conventional subtests of the Behavioural Inattention Test (BIT) (Robertson et al, 1994); Map Search subtest (MS) from the Test of Everyday Attention (TEA) (Wilson et al, 1987) ; and Trail Making Test A and B (TMT-A & B) (Army Individual Test Battery, 1944).

2.6.2 Training. Each individual received both EF and EL training in order of presentation according to group assignment, which included similar but different visuospatial processing content in the two training conditions. Training occurred for one hour per day, one day per week, for four weeks in each training condition. Between the two types of training were three weeks in which the patient came in one day per week for repeat administration of the initial baseline tasks.

Training to improve visuospatial skills employed letter/number trail-making in which the patient was presented with an array of characters, either letters of the alphabet or numbers, which appeared among star-shaped distracters on the computer screen. These letters or numbers were to be marked in sequential order. There were gaps in the target strings (e.g. A,B,D,F,H,L,M) such that the individual needed to maintain in working memory the previously marked target while locating the next in order. Graphical displays for the tasks were created using bit maps developed within MS Paint. During each block of stimulus presentations patients moved the on-screen cursor between stimuli displayed on the computer screen making their target selections by depressing the button on top of the joystick. Visual and auditory KR was provided on each stimulus item. All participants used their unimpaired ipsilesional upper extremity to move the joystick.

3. RESULTS

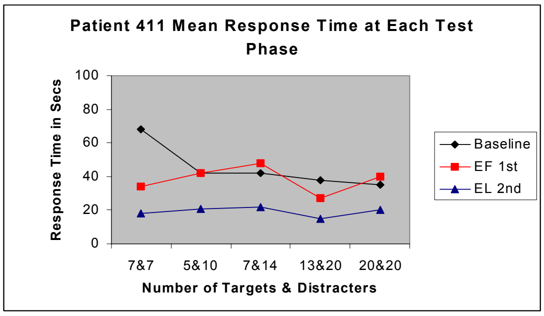
3.1 Data Analysis

In the data analysis, each patient's results were treated as a separate experiment in a single case series. Results were analyzed for two aspects of data collection: 1) response speed—the time from first button press at the beginning of each trial to final button press on last target of that trial, and 2) perpendicular distance—

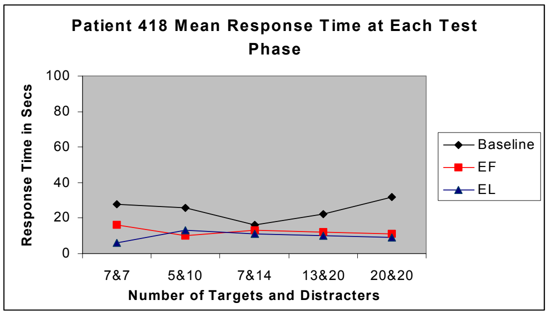
the maximum deviation from the straight line path in the trajectory from start location to target for each target in a trial. While accuracy data were collected this information proved to be uninformative for either omitted targets or target acquisition. Both time and perpendicular distance from the straight line trajectory offered more useful information about improvements in visual scanning. Data were collected at three test phases: 1) pre-training, 2) at the end of training period one, which was also prior to beginning training period two, and 3) following training period two. At each test phase task parameters progressed across five combinations of targets (T) and distracters (D): 7 T—7 D, 5 T—10 D, 7 T—14 D, 13 T—20 D, and 20 T—20 D.

3.2 *Individual Analyses*

Graphs 1 and 2 below show the response time performance of two patients who, on entry into the project, showed significant deficits in performance on all visuospatial neuropsychological measures. Both showed evidence of profound impairment on visual memory and processing speed measures. On paper and pencil letter-trailmaking both were unable to maintain the set-shifting involved in Trails B, showing obvious sequencing confusion. Patient 411 received EF training first and patient 418 received EL training first in order. For both, phase of training showed a significant main effect on response speed in favor of the EL training, and approached significance on trajectory for patient 418. EL training resulted in a significant improvement in response speed that was maintained across all levels of difficulty, compared to pre-training performance. Training also produced more consistent trajectories across all levels for patient 418 but had no effect on the variability of the trajectories for patient 411.



Graph 1: Patient 411's mean response time on visuospatial task at baseline, following EF training presented 1st, and following EL training presented 2nd.



Graph 2: Patient 418's mean response time on visuospatial task at baseline, following EL training presented 1st, and following EF training presented 2nd.

3.3 *Group Analysis*

A group analysis was carried out comparing group 1 with group 2. The informative value of this analysis was limited by small sample size, unequal group sizes at completion, and heterogeneity of groups. Left versus right visual field presentation of targets and line bisection analyses for the visual scanning study did not reveal differences between the two groups.

Taking a frequency count approach, four of the participants in group 1 and one in group 2 showed significant improvement in response speed as a result of training, with only one showing a definite advantage following the EL method. The others who benefited from training showed no advantage for either method. There was very little gain in straightness of trajectories following either type of training, and for one individual (411) performance was worse following both training types, despite his gains on overall response speed as a result of training. Only one individual's variability of trajectories benefited from training, which became more consistent at all levels of difficulty following both training modes.

From a clinical standpoint, since participating in training, one individual resumed painting as a hobby which she had been unable to do post-stroke. Another participant, a retired engineering technician with unilateral spatial neglect, was able to reduce his response speed to targets, regardless of visual field presentation, by half. The patient with the most profound visuospatial deficits, who during EF training evidenced difficulty maintaining attention and was observed to go to sleep on occasion when unable to find the target, showed immediate improvement in response speed at the more complex distracter levels as a result of training. The change in clinical picture for some participants suggests there are as yet unmeasured gains from participation in this training paradigm.

4. CONCLUSIONS

In conclusion, in our group analysis we failed to support the hypothesis that EL training, using a haptic guidance joystick, would result in faster and more direct movements to targets in a visuospatial training task for stroke patients with visual perceptual deficits. There were individual gains from this approach, as noted above, suggesting that the concept of using EL integrated with haptic guidance can benefit some patients, but not all. This result many be a function of the task design in which the gaps in the number or letter sequence required maintaining the last character before the gap in working memory until the next character is located. Working memory, as a component of the explicit memory system, would not be influenced by a training task based upon implicit memory approaches. The training task may have required recall of novel associations which has been shown to be remembered more successfully with the EF technique (Evans et al, 2000). Another factor which may have influenced the outcome is the frequency and duration of training. A once per week training schedule may not have been frequent enough for the participants to maintain gains achieved during individual training sessions across the span between training sessions.

Completion of this initial experiment in the use of haptic guidance for EL in cognitive rehabilitation has provided a wealth of information for designing subsequent rehabilitation training experiments using robotic guidance. Based on this initial study, we conclude that patients need to be carefully stratified among experimental and control groups for age, severity of stroke, and severity of neuropsychological deficits. Additionally, the training tasks need to be carefully matched to the deficits of each patient. Finally, the schedule for duration and intensity of training needs to be examined to ensure that enough training, appropriate to individual needs, is delivered.

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