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Robotic Arm Use by Very Young Motorically Disabled Children

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This paper reports on a study carried out to determine if very young children would interact with a small computer-controlled robotic arm. Six disabled and three normal children were used in the study. All children were less than 38 months in age. The arm was trained to carry out movements on activation of a single switch by the child. Fifty percent of the disabled children and 100% of the normal children did interact with the arm and use it as a tool to obtain objects out of reach. Possible relationships between the use of the arm and developmental levels in various areas are discussed.

Key Words: Cognitive development—Motoric disability—Robotic arm—Tool use—Very young children.

The microcomputer has been used to aid in the development of human interaction skills in two ways: as a contingency controlling system and as a monitor of the child's performance (1). In the former capacity, the computer can allow simple gross body movements to serve as controlling actions, and the computer can provide a wide variety of environmental effects when the child does perform a purposeful movement. The second role for the microcomputer is as a monitoring system to log the degree of interaction and learning that is taking place. Monitoring the child's performance helps to measure a child's progress toward specific learning goals.

The physical manipulation of objects is a major contributing factor in the development of cognitive and language skills in the very young child (2). It is also well established that the child is an active learner and that development requires an interactive process between the child and the environment (3). Infants and very young children face a critical task in learning to recognize the relationships between their actions and environmental effects of these actions (4). In developing an understanding of these relationships, the young child learns to initiate and exert control over both social and nonsocial aspects of their environment.

The direct manipulation of objects by robotic systems controlled by the child is an attractive contingent result in a computer-controlled and switch-activated system for very young children. As a first step in this process, we have developed a system that allows control of a small robotic arm by a single switch activation. The initial question addressed by our research is whether a very young child will interact with a robotic arm, and whether that interaction will involve using the arm as a tool. This paper describes our initial study designed to answer this question.

Brinker and Lewis (5) used the concept of co-occurrences (the provision of a contingent result when the child carries out a purposeful action) to foster the development of interaction skills in infants and very young children. They implemented this approach using a microcomputer to provide both contingency control and monitoring (6). Their approach was based on arranging events to be consistently controlled by an infant's behaviors such that the infant could be led to the belief that the world was controllable. The infant learned about both social and nonsocial environments through controlled interaction. Brinker and Lewis' rationale for this use of microcomputers with handicapped infants was based on the view that many handicapped infants can be at risk for deprivation of contingency experiences by virtue of a limited repertoire of movements. Two major factors are of importance. (a) Because most early handicapping conditions have a considerable motor component, the

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infant may not be able to engage the environment due to the lack of required movements. (b) The infant's acquisition of a generalized expectancy of competence is found in a social environment.

Brinker and Lewis used switch activation by the infant to control graphics, toys, and tape recordings of songs or voices. They collected data on the number of switch activations and observable behaviors (e.g., facial expressions, reaching for a toy) of the infant. The computer was programmed to modify contingencies based on the switch activation frequency. The number of switch hits as a function of time was displayed at the end of each session for various contingencies. This display was used to show parents how the child was interacting with the system. These data showed that children as young as 3 months would develop purposeful movements to cause the contingent result.

Behrmann and Lahm (7) used similar contingencies, and they also collected data representative of the degree of interaction that the child had with the system. Others have used preschool computer programs (e.g., cause and effect, sequencing) that provide interesting graphics or sounds on activation by a switch. Many of these intervention programs concentrate on the provision of interesting results from switch activation, but they do not monitor the child's responses.

The work reported here differs from the use of robotic systems as manipulative prostheses for persons with disabilities (8). Manipulative applications are typically directed to older individuals, and they do not generally consider either the cognitive demands or the cognitive benefits that might result from robotic arm use. Howell et al. (9) have discussed the cognitive use of robotic aids, but no data are yet available from their project.

EXPERIMENTAL SYSTEM

Our system consists of an Apple IIe microcomputer, a Minimover-5 robotic arm (10), and a "guidance unit" used to train the arm to make specific movements (11). These system components were chosen because the Apple IIe is widely available in special education settings, and the robotic arm is relatively inexpensive (about $1,500). The anatomy of the arm consists of five main structures: a stationary base, a body, an upper arm, a forearm, and a two-fingered gripper. This arm is anthropomorphic (about half adult human scale), and it moves in a smooth human-like manner. The arm can rotate about its base, flex and extend at the elbow and shoulder, extend, flex, supinate, and pronate the wrist, and open and close the gripper. All these functions are under computer control. The guidance unit, which employs a six-degree-of-freedom joystick, allows training of the arm by moving the joystick in the desired direction of arm movement, and it is therefore intuitively simple for a teacher, therapist, or parent to train a specific movement that is of interest to the child. In order to make use of this system for our application, software was developed that allowed three basic activities: (a) training the arm for a specific movement; (b) allowing the child to play back the movement by hitting a single switch; and (c) monitoring the child's behavior while the arm is being used to complete a task.

The trainer program uses either the guidance unit or a series of text commands to train the arm. With the guidance unit, the teacher, therapist, or parent moves the arm in the desired direction by moving the joystick. Joystick position controls the direction of the arm. For example, a forward movement of the joystick moves the arm in that direction; pulling up on the joystick raises the arm, and so on. Closing the gripper (two "fingers") on the arm is accomplished by rotating a knob on the top of the joystick. In the text training mode, commands such as "100 forward" can be typed in. This command will move the arm forward 1 inch. Commands such as this can also be combined to form a complete task (e.g., "get the cracker"). Details of the trainer program are described by Cook et al. (11).

Once a movement has been trained, it is given a name and stored on disk. This movement can then be loaded into the computer at a later time and played back. Based on a careful evaluation, we have found this system to be easy for a therapist, teacher, or parent to use (12). One may construct complex tasks that are meaningful to young children. Typical tasks are bringing a cracker within reach of the child and tipping a cup to reveal its contents.

The playback program allows two modes: single hit and continuous. In single hit, the entire movement is played back when the switch is hit once. In the continuous mode, the movement is played back step-by-step as long as the switch is depressed, and the arm stops when the switch is released. The system also has provisions for the control of toys, a tape recorder, and computer graphics.

Our monitoring software is based on principles developed by Brinker and Lewis (6), in which specific computer keys can be labeled to code behaviors that the child demonstrates. For example, we monitored behaviors such as "looks at arm," "looks at switch," "restless," and so on. The specific behaviors to be monitored can be adjusted for each child. The time at which a key is pressed by the observer (indicating that a behavior occurred) is also recorded by the computer program. In addition, we monitor the time at

TABLE 1. Subjects

Subject	Age (months)	Diagnosis[a]	Test results/developmental age (months)[b]
L.P.	20	SE, CP, QUAD, ATH	EIDP: Cognitive 9–11
K.T.	38[c]	SE, ASYMM, SPAS DIPL	EIDP: Cognitive >12–15 Gross motor 6–7
B.J.	35[d]	SPAS, QUAD, DD, low visual acuity, SEIZ, cortical atrophy	EIDP: Gross motor 3–5 RZ: Exploration of environment 7–9
J.M.	35	MICRO, SEIZ, gastrostomy, hydronephrosis, arhtrogryposis	EIDP: Cognitive 6 Gross motor 5–6
C.B.	18	SPAS, QUAD, MICRO, DD	EIDP: Cognitive 5 Gross motor 3–5
A.P.	8	CHROM ANOM[e]	EIDP: Cognitive 5–6 Gross motor 3–5

[a]SE, static encephalopathy; CP, cerebral palsy; QUAD, quadriplegic; ATH, athetoid; SPAS, spastic; DIPL, diplegia; SEIZ, seizure activity; MICRO, microcephalic; DD, developmental disability; CHROM ANOM, chromosomal anomaly; ASYMM, asymmetric.
[b]EIDP, developmental programming for infants and young children scales; RZ, Reynell-Zinkin developmental scales for young visually handicapped children (see text for description of tests).
[c]Gestational age, 35 months.
[d]Gestational age, 33.5 months.
[e]Unbalanced translocation resulting in partial Trisomy 17q and partial Monosomy 14q.

which each press of the arm control switch occurs. All of these data may be collected for either the robotic arm experiments or for experiments using toys or graphics as the contingency. These data allowed us to determine if the child was interacting with the arm and to determine the nature of that interaction (e.g., using it as a tool).

The monitoring software also allows generation of plots of switch activation and observed behaviors as a function of time. Details of this software are presented by Hoseit (13).

SUBJECTS

The experimental evaluations were carried out at the Placer Infant Development Program in Roseville, CA, an early intervention program for children from birth to 36 months. Children in this program have developmental delays and/or disabilities or are at risk of developing such delays. Parents participate in the program with their children on a regular basis. The program utilizes an interdisciplinary team of staff consisting of infant/parent educators, occupational therapists, physical therapists, speech-language pathologists, and a clinical psychologist. Developmental assessments are provided, and developmental and therapeutic activities are conducted to promote development (enhance strengths, remediate weaknesses, and support parents).

The subjects were six developmentally delayed children with chronological ages less than 38 months and three able-bodied children 6, 11, and 18 months of age. To determine the cognitive developmental level of the subjects, the Developmental Programming for Infants and Young Children (EIDP) test was used (14). The EIDP, a criterion-referenced infant assessment measure for infants in the 0–36-month range, consists of six subscales that evaluate perceptual/fine motor, cognition, language, social/emotional, self-care, and gross motor abilities (15). The six scales include 274 milestones giving a profile of developmental functioning. The inter-rater reliability of this test ranges from 0.80 to 0.97 (mean, 0.89), and the test–retest reliability is 0.93–0.97. The Reynell-Zinkin Developmental scales (16) were used in place of the EIDP cognitive scales for one subject (B.J.) who demonstrated low visual acuity.

The chronological ages, diagnoses, and developmental levels for the disabled subjects are shown in Table 1. The subjects represent a variety of disabilities and skill levels. The test results shown in Table 1 were obtained by the staff of the Infant Program who are trained in the administration of the developmental scales used. The developmental levels shown in Table 1 must be considered as ranges rather than exact values.

DATA COLLECTION

Each experimental session began with an initial interview with the program staff and parent regarding the child's developmental level, objects of interest to the child, and what actions of the robotic arm were most likely to be of interest to the child. In each case, the parent and/or staff were able to suggest robotic arm movements based on tasks in which the child typically engaged. The arm was trained to carry out these tasks, and the movements were stored on disk.

In order to determine the child's understanding of means-end causality, simple battery-powered and switch-activated toys or computer graphics were used to establish this skill. The switch was placed in front of the child together with the toy or computer screen, and the use of the switch to control the toy or computer was demonstrated. When the child then activated the switch and attended to the result, we concluded that he was associating the two events (switch closure and result). We also used this procedure to determine the best switch for the child to use and the best switch location for access by the child. All of the subjects in this study were successful in this task.

Robotic arm use began with a familiarization period, during which we played with the child and determined what the general reaction to the robotic arm was. Initially, the single hit mode was used. When the child pressed the switch, an entire task was carried out by the robotic arm. The child was shown that pressing the switch caused the robotic arm to move. This task was identical to that with the toy, except that the robotic arm was used. All of the subjects used the switch to play back a task movement in the single hit mode.

The experimental phase was meant to determine if the child would use the robotic arm as a "tool" to retrieve an object out of reach. For this purpose, we used the continuous playback mode. The switch was placed in front of the child, and an object to be retrieved by the arm was placed in view of the child but out of reach. The switch was presented to the child, and her actions were recorded. The child was required to press the switch continuously to continue the task movement. The monitoring program kept track of the switch activations, and the child's behaviors (e.g., looks at switch, looks at arm, restless) were assigned to number keys on the computer keyboard. An observer recorded the occurrences of these behaviors by pressing the assigned numeric key. Two types of data were displayed at the conclusion of each session: the number of switch activations as a function of elapsed time, and the time relationship between switch activations and the observed behaviors described. In all cases, a parent and staff member were present together with the experimenters. The child was verbally prompted to hit the switch, and in some cases, was physically prompted ("hand over hand") as well. The frequency of prompts was reduced during the latter part of each experimental session.

RESULTS

Figure 1 illustrates how the data were collected and analyzed. Data are shown for three subjects, one of whom did use the arm as a tool in the continuous playback task, one who did not (both disabled), and one normal subject. These three example plots represent the three classes of results obtained, and similar plots were developed for the other subjects and contingencies. In this figure, the horizontal line on each plot represents switch closure. The vertical axis is the time (in seconds) before (negative numbers—below the vertical line) and after (positive numbers—above the vertical line) the switch was pressed. The horizontal axis is elapsed "time" in switch closures. Behaviors are plotted at the time they were observed relative to switch activation, and they are coded by unique symbols. The proximity of a behavior to the activation of a switch is thus indicated by its relationship to the horizontal line. Behaviors occurring near the time of switch closure are plotted close to the line (e.g., "looks at contingency" and "looks at switch" for subject B.D. in Fig. 1), and those occurring well before or long after switch closure appear far from the horizontal line (e.g., "shows interest" for subject C.A. in Fig. 1).

We used two criteria to determine if the child was interacting with the robotic arm: correspondence and repeatability. Applying a "correspondence criterion" (reflecting temporal proximity), we concluded that a behavior was related to switch activation if it occurred within 5 s before or after the switch was pressed. This time frame was arbitrary but consistent with the view that responses occurring within 3–5 s are the most motivational for young children (17). This $\pm$5-s window bracketed the activation of the switch to allow determination of behaviors that occurred just prior to hitting the switch and those that occurred just after hitting it. Thus, if the child looked at the switch, then pressed the switch, then watched the arm move, all within the time window specified, we concluded that he was correlating switch activation with arm control. The second criterion used was termed a "repeatability criterion." In this case, we determined the number of times within an experimental session that the correspondence criterion was met as a percentage of the total number of times the switch was pressed. A large percentage indicated that the child was intentionally activating the switch to cause arm movement, while a low percentage indicated more random switch activation.

Applying these criteria to the sample data in Fig. 1, we would conclude that subject C.B. (top trace) had little or no interest in the robotic arm or the switch. Subject L.P. (middle plot in Fig. 1) would be viewed as interacting, since she almost always looked at the

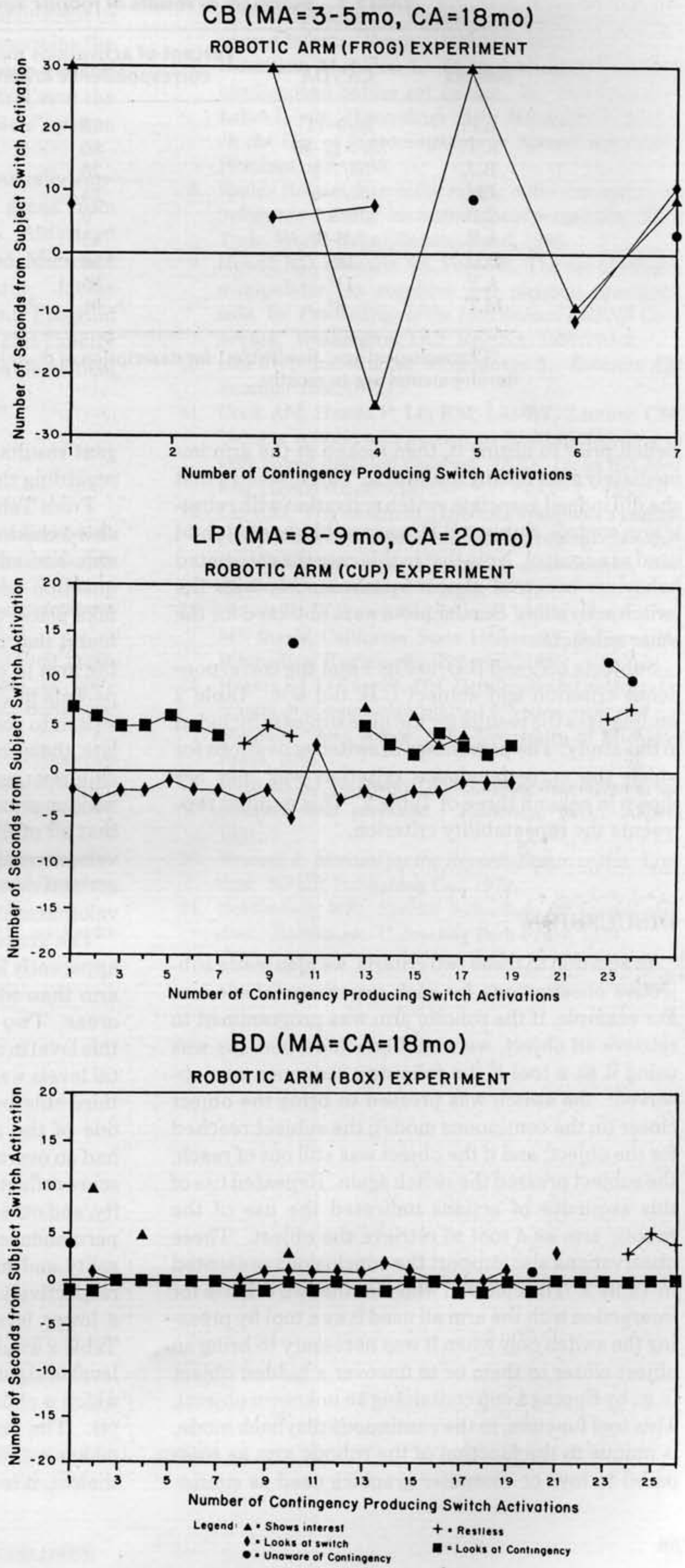

FIG. 1. Sample data collected from three of the subjects during the robotic arm experiments. Similar data were obtained for other subjects and contingent results. The horizontal line represents switch activation. The vertical scale is the number of seconds before (negative) or after (positive) switch activation. Observed behaviors are coded with unique symbols and plotted at the time they occurred before or after switch activation.

TABLE 2. Summary of results of robotic arm experiments

Subject	CA[a]/DA	Percent of activations meeting correspondence criterion	Tool use of robotic arm?
L.P.	20/9–11	73	Yes
K.T.	38/>12–16	80	Yes
B.J.	35/7–9	75	Yes
J.M.	36/3–6	25	No
C.B.	18/5.5	0	No
A.P.	8/5–6	45	No
B.D.	18[a]	96	Yes
A.Y.	11[a]	85	Yes
M.T.	6[a]	91	Yes

[a]Chronological age. See Table 1 for description of disabled children. DA, cognitive developmental age in months.

switch prior to hitting it, then looked at the arm immediately after hitting the switch. This indicates that she did indeed associate switch activation with robotic arm control. Subject B.D. was an able-bodied child used as a control. Note that in this case the associated behaviors occurred almost synchronously with the switch activation. Similar plots were obtained for the other subjects.

Subjects L.P. and B.D. in Fig. 1 met the correspondence criterion and subject C.B. did not. Table 2 summarizes the results for the nine subjects included in this study. The percentage of switch activations for which the correspondence criterion was met are shown in column three of Table 2. This number represents the repeatability criterion.

DISCUSSION

In addition to these two criteria, we also made subjective observations for each experimental session. For example, if the robotic arm was programmed to retrieve an object, we would conclude that she was using it as a tool if the following sequence was observed: the switch was pressed to bring the object closer (in the continuous mode); the subject reached for the object; and if the object was still out of reach, the subject pressed the switch again. Repeated use of this sequence of actions indicated the use of the robotic arm as a tool to retrieve the object. These observations also support the conclusions presented in Table 2. The children who met the two criteria for interaction with the arm all used it as a tool by pressing the switch only when it was necessary to bring an object closer to them or to uncover a hidden object (e.g., by tipping a cup containing an unknown object). This tool function, in the continuous playback mode, is unique to the function of the robotic arm as compared to toys or computer graphics used as contingent results, and it provides additional information regarding the child's skills.

From Table 2, it can be seen that three of the disabled children did use the arm as a tool, and all of the able-bodied children did also. Since our original question was whether or not this interaction would take place, this result is of interest in itself. We also found that none of the children appeared fearful of the arm (a concern expressed by program staff and parents prior to the study), and all were able to use a switch to control contingencies. It is tempting to relate these results to other characteristics of these children, particularly their developmental levels in various areas. Comparison of Tables 1 and 2 shows that all of the disabled children with a cognitive developmental age of 7–9 months and greater did interact and meet both criteria, and those below this developmental level in this category did not.

The gross motor and fine motor skill levels were apparently less related to success in using the robotic arm than were the levels in cognitive and language areas. Two of the able-bodied subjects were above this level in chronological age (although developmental levels were not assessed for these children). The third able-bodied child (M.T.) was 6 months old, and one of the noninteracting disabled children (J.M.) had an overall cognitive level of 6 months. This latter score reflects object permanence, means–end causality, and other factors. As shown in Table 1, her object permanence score alone was 7 months, but her causality and means–end scores were 2 and 5 months, respectively. Thus, she may have been functioning at a lower level than her cumulative score shown in Table 2 would indicate. The 6-month developmental level is significant for a child, since it is the point at which a child will work for a toy that is out of reach (4). The small sample size included in this study makes it difficult to draw general conclusions. Nevertheless, it is clear that very young children will use a robotic arm to accomplish tasks that are of interest to them. Further research is under way to determine the degree to which these children will develop general manipulative skills when given more control over the robotic arm than the single switch "playback" system described here.

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