Tangible user interfaces: tools to examine, assess and treat dynamic constructional processes in children with developmental coordination disorders

S Jacoby[1,2], N Josman[1,3], D Jacoby[1,4], M Koike[5,6], Y Itoh[5,7], N Kawai[5,8], Y Kitamura[5,9], E Sharlin[10] and P L Weiss[1,11]

[1]Department of Occupational Therapy, University of Haifa, Haifa, ISRAEL

[5]Human Interface Engineering Laboratory, Graduate School of Information Science and Technology, Osaka University, Osaka, JAPAN

[10]Interactions Laboratory, Department of Computer Science, University of Calgary, Calgary, Alberta, CANADA

[2]*sigalj1@012.net.il,* [3]*naomij@research.haifa.ac.il,* [4]*dojacoby@cisco.com,*
[6]*koike.minori@ist.osaka-u.ac.jp,* [7]*itoh@ist.osaka-u.ac.jp,* [8]*kawai.norifumi@ist.osaka-u.ac.jp*
[9]*kitamura@ist.osaka-u.ac.jp,* [10]*ehud@cpsc.ucalgary.ca,* [11]*tamar@research.haifa.ac.il*

[1]*hw.haifa.ac.il/occupa/LIRT,* [5]*www-human.ist.osaka-u.ac.jp/*
[10]*pages.cpsc.ucalgary.ca/~ehud/*

ABSTRACT

Tangible User Interfaces (TUIs) are a subset of human-computer interfaces that try to capture more of the users' innate ability of handling physical objects in the real world. The TUI known as ActiveCube is a set of graspable plastic cubes which allow the user to physically attach or detach cubes by connecting or disconnecting their faces. Each cube is essentially a small computer which powers up and communicates with its neighbours upon connection to a neighbouring cube. When users assemble a physical shape using the system they also connect a network topology which allows ActiveCube to digitize and track the exact 3D geometry of the physical structure formed. From the user's perspective, ActiveCube is a very powerful tool; the 3D shape being built with it physically is tracked in the virtual domain in real-time. ActiveCube's use as a concrete, ecologically valid tool to understand dynamic functional processes underlying constructional ability in either typically developed children or in children with neurological pathology has not yet been explored. The objective of this paper is to describe the ActiveCube interface designed for assessing and treating children with Developmental Coordination Disorder (DCD). In our pilot study, six male children, aged 6 to 7 years, three with DCD and three who are typically developed were tested. The children's task was to successively use the ActiveCubes to construct 3D structures in a "matching" strategy known as "Perspective Matching". The usability results showed that all the participating children enjoyed the tasks, were motivated and maintained a high level of alertness while using the ActiveCubes. More than 80% of them found the tasks to be easy or moderate. "Similarity" data from single subjects has been used to show differences in constructional ability between children with DCD and those who are typically developed. This automated ActiveCube three-dimensional (3D) constructional paradigm has promise for the assessment and treatment of children with DCD.

1. INTRODUCTION

Tangible User Interfaces (TUIs) are a subset of human-computer interfaces that try to capture more of the users' innate ability of handling physical objects in the real world. Ullmer and Ishii (2001) define TUIs as "devices that give physical form to digital information, employing physical artefacts as representations and controls of the computational data". We highlight a subset of TUIs which we call spatial TUIs: interfaces that mediate interaction with shape, space and structure. We believe efficient spatial TUIs offer intuitive spatial mapping between their physical and digital qualities, unify input and output space and enable intuitive trail-and-error activity (Shalin et al, 2004). The highly interactive and spatial nature of TUIs, as well as their current relatively large size, motivated several research efforts that mapped TUI applications to children games and playing activity. Triangles are flat TUIs which allow interactive construction of 2D shapes. Triangles were used for creating interactive narrative of a nonlinear story, allowing the users to control the story's progress as well as parts of its content by physically manipulating, connecting and disconnecting the Triangles (Gorbet et al, 1998).

An example of a spatial TUI that supports 3-dimensional (3D) construction is the ActiveCube system (Kitamura et al, 2001), shown in Figure 1. ActiveCube is a set of graspable plastic cubes (the current version dimensions are 5 cm per edge) which allow the user to physically attach or detach cubes by connecting or disconnecting their faces. Each cube is essentially a small computer which powers up and communicates with its neighbours upon connection to an adjacent cube. When users assemble a physical shape using the system they also connect a network topology which allows ActiveCube to digitize and track online the exact 3D geometry of the physical structure formed. From the user's perspective, ActiveCube is a very powerful tool; the 3D shape being built with it physically is tracked in the virtual domain in real-time.

Figure 1. *The ActiveCube system showing connections to run with a laptop computer.*

ActiveCube supports a rich variety of onboard input and output devices. For example, cubes can be equipped with a gyroscopic sensor which tracks the structure's 3D orientation. Cubes can also be equipped with a light source that can be switched to illuminate them, as well as with touch sensors, vibrators, a motorized propeller and a variety of other sensors and actuators. The current ActiveCube implementation links to a host PC through a tethered cube, or base cube, which controls the network and is the first cube of each apparatus constructed with the system (Watanabe et al, 2004).

The ActiveCube TUIs have been used as the basis for the development of Cognitive Cubes, a system that investigates adult spatial cognitive ability (Sharlin, et al., 2002). The system projected a 3D virtual prototype on a large screen and the participant was asked to construct the virtual prototype using the ActiveCube physical blocks. As the participant progressed the system extracted in real-time the geometry of the structure and analyzed the similarity between the physical construction and the virtual prototype. Testing showed that Cognitive Cubes were sensitive to age as well as to dementia (Sharlin et al, 2002).

ActiveCube has also been used to explore how human subjects use this novel computer interface to interact with narrative software. TSU.MI.KI is a novel toy based on the ActiveCube TUI (Itoh et al, 2004), practically a technological enhancement of the Japanese classic tsumiki (a traditional set of wooden blocks). TSU.MI.KI allows children to actively move through a story space by physically interacting with a set of physical cubes. The TSU.MI.KI player is confronted with several tasks through a story narrative displayed on a computer screen. In order to confront the story puzzles and challenges the child needs to play with their TSU.MI.KI "magical cubes". TSU.MI.KI extracts in real-time the shapes the user attempts to construct, for example when confronted with a river the user can build a bridge, a ship or a plane from the cubes and the system will follow with a matching virtual plane model and a corresponding narrative in the story space. Furthermore, in TSU.MI.KI the physical set of ActiveCubes with its sensors and actuators becomes physical controllers of virtual story entities, for example when the user manipulates the physical plane she constructed the virtual plane will follow its tracked movements while the physical plane vibrates and rotates its propeller.

To date, the use of the ActiveCube system as a concrete, ecologically valid tool to understand dynamic functional processes underlying constructional ability in either typically developed children or in children with neurological pathology has not yet been explored. Developmental Coordination Disorder (DCD) is a marked impairment in the development of motor coordination that significantly interferes with academic achievement or activities of daily living (American Psychiatric Association, 1994). The motor coordination of children with DCD is substantially below that expected given the child's chronological age and measured intelligence. Older children may display difficulties with the motor aspects of assembling puzzles, building models, playing ball, and printing or writing. The task of construction embraces two broad classes of activities: drawing and building or assembling (Fisher & Loring, 2004). Constructional activity entails spatial perception with a motor response (Fisher & Loring, 2004).

Visuospatial constructional ability is complex, comprising multiple, distinct, but interrelated subcomponents (Cronin-Galomb & Braun, 1997). These include the ability to combine elements into meaningful wholes, to discriminate between objects, to distinguish between left and right, to understand relationships among objects in space, to adopt various perspectives in order to represent and rotate objects mentally, to comprehend and interpret symbolic representations of external space, and to work out solutions for non-verbal problems (Fernando, et al, 2003). It is essential to assess and treat clients with visuospatial deficits because constructional deficits have been shown to be related to poor activity in daily functioning (Katz et al, 1997).

The overall goal of the present research is to develop and evaluate a paradigm in which TUIs are used for the study, assessment and intervention of dynamic constructional processes among typically developed children and those with DCD. The objective of this paper is to describe the ActiveCube system and the special interface designed for assessing and treating children with DCD. The specific objectives of this present pilot study were: (1) to examine the feasibility and the usability of the Active Cube TUI in children with DCD as well as in typically developed children in terms of their ability to manipulate ActiveCube, their level of enjoyment and their extent efforts in the task, (2) to examine whether this novel interface distinguishes between children with DCD with constructional deficits and typically developed children, and (3) to establish the protocol for future research with the system.

2. METHODS

2.1 Participants

The experimental group consisted of: three male children with DCD, aged 6 to 7 years, who were recruited from a local Child Development Clinic. A preliminary screening of these children as having DCD was based on parental responses to the Children's Activity Questionnaire for early identification of children who suspected as having DCD (Rosenblum, in press). These children were also reported by the Clinic's occupational therapists as having difficulties in copying and constructing models. The children received a score of 5% or below on the Movement Assessment Battery for Children (M-ABC) (Henderson & Sugen, 1992). This score indicated the presence of significant motor coordination difficulties. Finally, a clinical diagnosis of DCD was made by a neurologist based on standard criteria for DCD, as outlined by the Diagnostic and Statistics Manual, DSM IV (American Psychiatric Association, 1994).

The control group consisted of three typically developed male children, aged 6 to 7 years, who were recruited via a convenience sample. They had no motor deficiencies, as evaluated by the M-ABC and had no difficulties in copying geometric figures, as evaluated by the Developmental Test of Visual-Motor Integration (VMI) (Beery, 1997). In addition, for visuospatial organization , as evaluated by the subtest Block Design from the Wechsler Intelligence Scale for Children (WISC-R95) (Cahan, 1998), they received scores in the range of the average norm. The parents of all six children gave their consent to participation in the study.

2.2 Instruments

2.2.1 Hardware. The Active Cube system, shown in Figure 1, is an automated system for constructional cognitive assessment as described above.

2.2.2 Software. A playground metaphor, shown in Figure 2, is used to present the assessment and intervention tasks. The playground includes six 3D playground structures: seesaw, dog, airplane, slide, carrousel and pyramid. Each apparatus may be constructed from up to seven cubes. The maximum number of cubes was reduced to seven from an initial ten cubes following a preliminary study that demonstrated that the combined mass of cubes makes larger structures unstable and cumbersome. Once an apparatus is selected, it is enlarged and presented on the screen by itself. The child's task was to successively use the ActiveCube system to construct this apparatus in a "matching" strategy that we have termed "Perspective Matching" (see Figure 3). In this strategy, the designated apparatus is displayed in its entirety; the child views only a perspective image of the structure or the screen. The child's task is to construct the displayed structure using the cubes.

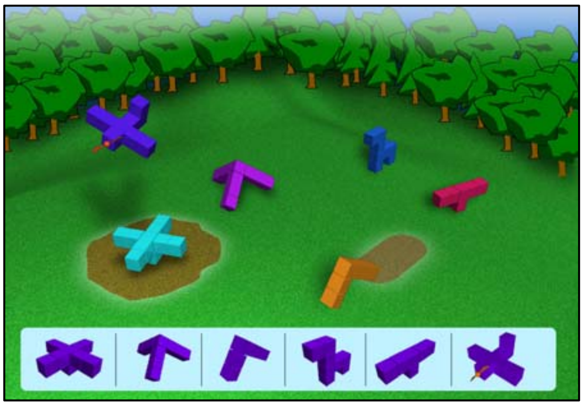

Figure 2. *The playground metaphor that is used to present the assessment and intervention tasks. Each of the six playground apparatus may be constructed from up to seven cubes.*

Figure 3. *One of the children who participated in the pilot study constructing an apparatus from the ActiveCube.*

A second construction strategy, "Following" was provided for children who were unable to correctly complete the structure with "Perspective Matching". In this case, the child constructs the designated apparatus, cube by cube, following a set of successive steps displayed on the screen. First, the base cube appears onscreen. Next, a second cube, which needs to be connected to the base cube, appears and flashes on and off on the screen. As soon as the child attaches this cube correctly, a third cube appears. The process continues until the structure is completed correctly.

2.2.3 Clinical assessment tools. The Movement Assessment Battery for Children (M-ABC) and DCD questionnaire were used to identify whether the participants met the diagnostic criteria for DCD. The Developmental Test of Visual-Motor Integration (VMI), Block Design test were performed to all participants to detect constructional deficits. The M-ABC was developed by Henderson & Sugen (1992) for children, aged 4-12 years with the aim of measuring the level of motor functioning; it has been demonstrated to have good test-retest and inter-rater reliability, and concurrent validity. The VMI was developed by Beery (1997) to test children aged 3-17 years with the aim of evaluating visual-motor integration; it has predictive validity for learning difficulties in various areas, particularly in writing and reading. The Children Activity Scale for Parents (ChAS-P) was developed by Rosenblum (in press) to identify children with Developmental Coordination Disorders aged 4-8 years. Internal consistency and content, construct and face validity have been established as well as a cut-off scores. The Wechsler Intelligence Scale for Children (WISC), is an intelligence test for children. We used the third edition of the Hebrew version of the WISC called WISC-R95, with Israeli norms for children ages 6-14 years. We used the WISC's subtest: Block Design, a construction test. In this WISC subtest children use red-and-white blocks to construct a pattern according to a displayed model.

2.2.4 Outcome measures. All sessions were recorded with a digital video recorder for subsequent viewing and analysis. A 3-point "Enjoyment Scale" was used to query each of the children following the Perspective Matching session. They were asked to rate their level of enjoyment while using the ActiveCube constructional activities. A 3-point "Effort Scale" was also used to query the amount of effort perceived by each child while performing each task.

All connections of the ActiveCube system were recorded online for subsequent offline analysis. The following outcomes were calculated:

Onset time − time from the start of the task (when the designated structure is displayed on the screen) until the first cube is connected to the base cube.

Connect time − time taken for each cube to be connected to or disconnected from the base unit.

Total time − time from the beginning of the task (when the designated structure is displayed on the screen) to its completion (when the last cube has been connected or disconnected).

Similarity − the similarity between the designated apparatus as displayed on the screen and the apparatus as constructed by the child is used as a measure of accuracy. When the structure is not identical to the original apparatus, a score is automatically computed by the system according to the number of cubes that have been connected correctly and the number that have not been connected correctly. Equation 1 for measuring similarity is the one described by Sharlin et al. (2002) where *i* is an intersection of *s* (the structure which the child built) and *p* (the prototype), and $|i|$, $|s|$, and $|p|$ are the number of cubes in *i*, *s* and *p* is maximized over all possible intersections *i* produced by rotating or translating *s*. Intuitively speaking, the algorithm computes similarity by the number of intersecting cubes minus the number of remaining "extra" cubes in the participant's structure, normalized by the number of cubes in the prototype.

$$Sim = 100\frac{|i|}{\max\left(|p|,|s|\right)} \quad (1)$$

The similarity function serves two main purposes: (1) to provide real-time feedback regarding the integrity of each ActiveCube connection and (2) to automatically compute the number of errors where error is defined as a connection or a disconnection which decreases the similarity and thus does not progress the task.

2.3 Procedure

The research conducted in a quiet environment (a special kindergarten room was used for the control group and a secluded room at the clinic was used for the experimental group). The children sat at a table suited to their anthropometric characteristics. The ActiveCube system and construction tasks were described to each participant at the start of the session and specific instructions in accordance with the experimental protocol were provided. At the beginning of the session there was a practice task. During this task the child learned how to connect the cubes via demonstration. The child was then asked to connect a few cubes independently, receiving help if necessary. The child then constructed each of the six playground apparatus using the "Perspective Matching" strategy. The order of the six apparatus was predetermined based on their complexity with the easiest apparatus first. The children were instructed to press the Escape key when they had completed construction of each apparatus. The session lasted for about 30 minutes. The children who were unable to complete an apparatus using the "Perspective Matching" strategy (i.e., they could not achieve a similarity score of 100%), were requested to complete it using the "Following" strategy.

2.4 Data analysis

The video recording observations of the ActiveCube construction process was used to verify that all ActiveCube connections and disconnections were correctly recorded as such by the software. Due to small sample size, data analysis consisted primarily of descriptive statistics as well as the graphical comparison of data from individual participants.

3. RESULTS

3.1 Feasibility and usability of the ActiveCubes

All the children rated their use of the ActiveCubes to construct the various structures with the highest score ('enjoyed very much') of Enjoyment Scale. In addition, based on observation of the children while performing these tasks, it was evident that they were motivated and maintained a high level of alertness while using the ActiveCubes. None of the children indicated that they wanted to stop prior to completion of the structures and they all performed the tasks in a systematic and steady manner. The majority of the participants recognized the natural playground setting in which the six structures were located. They also identified each of the structures.

Fifty percent of the children reported that the task was easy; 33%of the children reported that the task was moderate (neither too difficult nor too easy) and 17%of the children reported that the task was difficult.

All of the children succeeded in connecting and disconnecting the ActiveCubes by the male/female metal press-stub connectors. In some cases, for technical reasons, although a connection appeared to be intact mechanically, it was not recorded by the computer as being connected electronically. Unstable mechanical connections also occasionally led to a collapse of the ActiveCube structure when the child exerted too much force.

3.2 Similarity scores for a child with DCD compared to a typically developed child

These pilot results show that the ActiveCube paradigm appears to be able to distinguish between children with DCD who had constructional difficulties and those who are typically developed. For example, the similarity scores achieved by two children using the Perspective Matching strategy are compared in Figure 4. The typically developed child (shown in light grey) achieved a score of 100% for all six apparatus (i.e., he succeeded in correctly constructing each of the playground structures). In contrast, the child with DCD (shown in dark grey) achieved scores ranging from 42% to 83% for the same tasks. Note that the level of difficulty of the structures varied. The child with DCD achieved similarity scores of about 40% for the airplane and pyramid apparatus, about 60% for the dog apparatus and over 80% for the seesaw, slide and carousel apparatus.

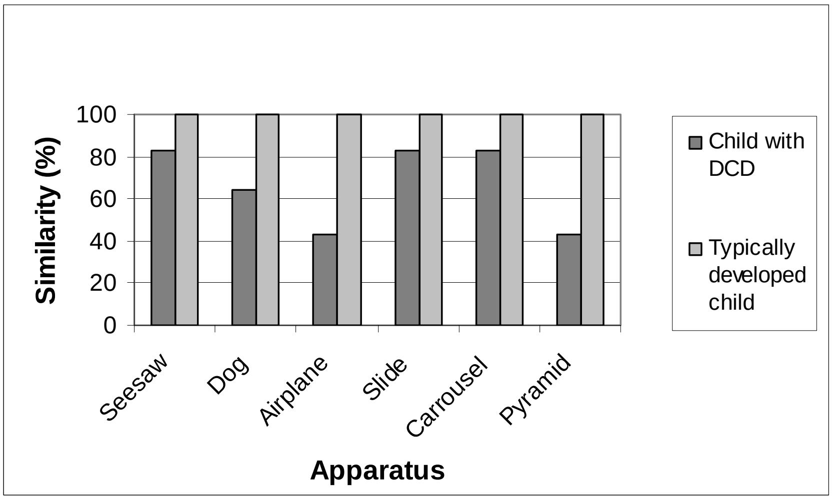

Figure 4. *Similarity scores for each of six apparatus for a typically developed child (light grey) and of a child with DCD (dark grey).*

In addition to providing a summary score for similarity, ActiveCube provides the ability to quantitatively track the similarity during the construction process. Figures 5 and 6 illustrate the process whereby various apparatus are constructed when using the Perspective Matching strategy. The similarity scores for a typically developed child who constructed the airplane (to be constructed from 7 cubes) are plotted as a function of time in Figure 5 (left panel). Figure 5 (right panel) shows a similar graph for the same structure for a child with DCD. Several differences in performance for the two children are apparent from a comparison of these two graphs. The typically developed child achieved a similarity score of 100% (perfect accuracy) in a 6-step task that took 130 s to complete. In contrast, the maximum similarity for the child with DCD was only 42%; he took 53 s to perform the task and completed only three steps.

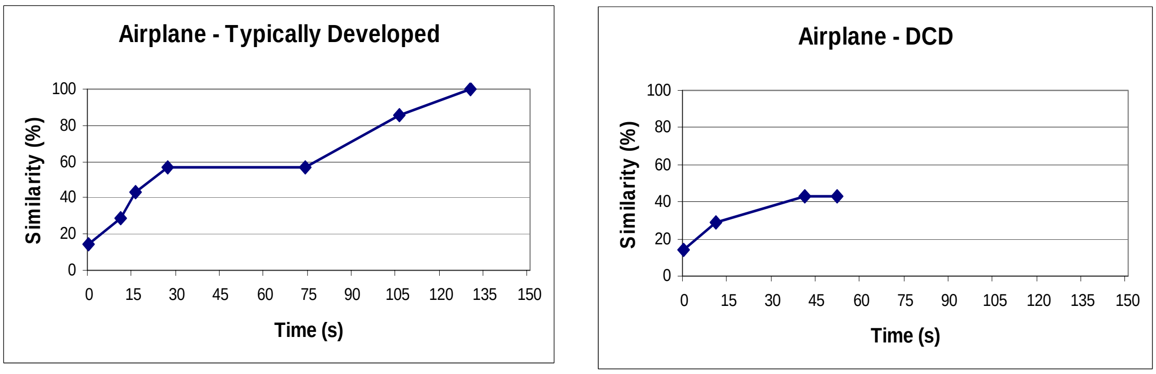

Figure 5. *Similarity versus time graph during the construction of the airplane apparatus by a typically developed child (left) and a child with DCD (right).*

The results for the pyramid apparatus (to be constructed from 7 cubes) are similar to those for the airplane apparatus. The similarity scores for a typically developed child who constructed the pyramid (to be constructed from 7 cubes) are plotted as a function of time in Figure 6 (left panel). Figure 6 (right panel) shows a similar graph for the same structure for a child with DCD. Again we note that the typically developed child achieved a similarity score of 100% (perfect accuracy) in a 6-step task that took 66s to complete. In contrast, the maximum similarity for the child with DCD was only 42%; he took 43 s to perform the task and completed only three steps.

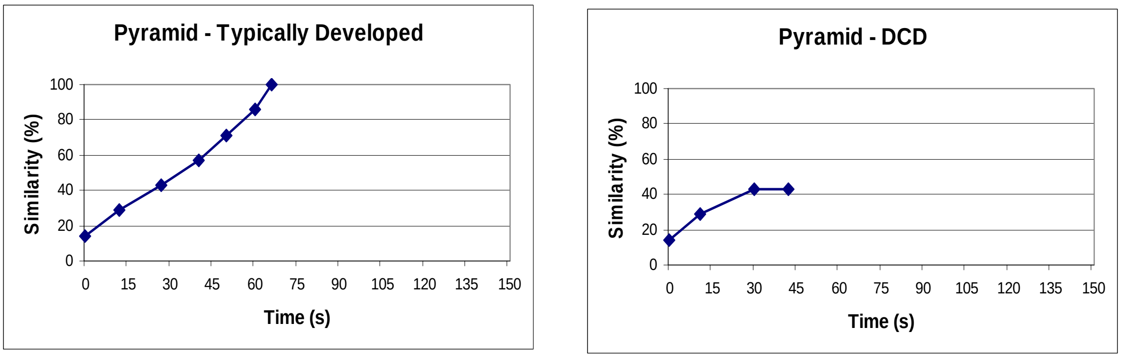

Figure 6. *Similarity versus time graph during the construction of the pyramid apparatus by a typically developed child (left) and a child with DCD (right).*

The child with DCD whose data are shown in Figures 5 and 6 was unable to complete the playground structures when using the Perspective Matching strategy. He was then given an opportunity to use the easier Following strategy wherein the child constructs the designated apparatus, cube by cube, following the successive steps as they are displayed on the screen. As shown in Figure 7, this child was able to correctly construct the airplane apparatus when using this strategy. He completed it in 151 s using six steps.

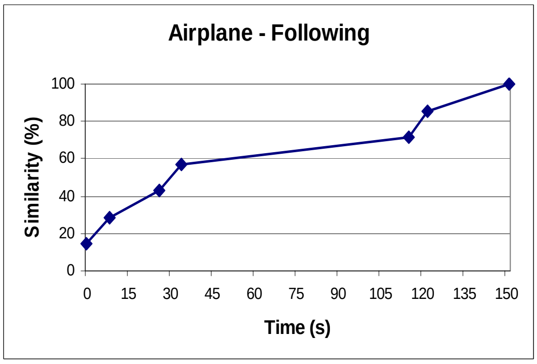

Figure 7. *Similarity versus time graph during the construction of the airplane apparatus by a child with DCD using the Following strategy.*

4. SUMMARY AND CONCLUSIONS

The results of this pilot study were highly positive in terms of verifying the participants' interest and enjoyment of the ActiveCube playground structure paradigm. They understood the tasks and were motivated to carry them out. A number of technical problems arose, most notably related to some difficulties in maintaining an intact connection between adjacent cubes. Another difficulty related to the total physical mass of the completed structure.

These results have confirmed several of the experimental protocol decisions. For example, based on our preliminary experience, we had chosen to limit the total number of cubes to no more than seven per apparatus during this pilot study. This number allowed the construction of structures of sufficient complexity and yet prevented the creation of masses that would lead to their collapse or become too wieldy for the children to manipulate during the post-construction play period. Despite the 7-cube limit, the structures appear to be sufficiently diverse in their levels of difficulty as demonstrated by the results shown in Figure 4.

On the other hand, the results have also provided important information concerning changes that will be needed prior to conducting the full study. The most important of these changes concerns the need to alter the mechanical method by which the cubes were attached to each other. Currently, adjacent cubes are attached by means of pressing their faces together; each cube contains two male and two female metal press-studs (one in each corner) which snap together. As indicated above, some connections appeared to the child to be intact, and yet were not recorded as such by the system. Moreover, the structures would sometimes collapse due to inadvertent disconnections between one or more cubes. The Human Interface Engineering Laboratory at the University of Osaka has now developed a newer version of the ActiveCube system which uses magnets (rather than press-stubs) for the inter-cube connections. Brief initial testing with a trial set of the magnet-based cubes has provided encouraging results regarding the integrity and stability of this alternate mechanism.

These initial results have provided important information concerning the feasibility and usability of the ActiveCube system for assessment and treatment of children with DCD. Despite the technical problems, the initial results show that the ActiveCube system and playground apparatus tasks appear to be sensitive to differences in the constructional abilities of the children.

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