Kindergarten Assistive Robotics (KAR) as a Tool for Spatial Cognition Development in Pre-school Education

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Abstract— **Kindergarten Assistive Robotics (KAR) is an innovative tool that promotes children's development through social interaction. This study describes how KAR assists kindergarten educational staff in the teaching geometrical thinking, one of the aspects of spatial cognition by engaging the children in play-like interaction. Children's reactions and performance were video-recorded for analysis. Most children exhibited positive interaction with the robot and demonstrated a high level of enjoyment when interacting with it. Our results show that the children's performances on a spatial task were improved while they "played" with robot. To measure children's learning we developed a novel measure of cognitive learning, which we call "velocity of learning". This study demonstrates the feasibility and expected benefit of incorporating KAR in pre-school education.**

Index Terms — **social assistive robotics, geometrical thinking, development of visual-motor skills**

I. INTRODUCTION

SOCIALLY ASSISTIVE ROBOTICS (SAR) [1] is the class of robotic technologies in which users are helped primarily through social, rather than physical, interaction with robots. The main populations in which SAR is currently applied are the elderly, patients with dementia or cognitive/motor disorders (e.g. [2]), and children with autism [3]). Socially assistive technologies have great potential for yielding efficient tools in education. SAR provides users with the opportunity not only to learn from a non-threatening, three-dimensional inanimate "toy", but also to learn through game-like interaction, thereby encouraging autonomous social behavior. In the field of child care, several studies have demonstrated the positive impact of SAR on typically developing children and on children with

social disorders (e.g. [4]). For example, iRobi, a humanoid teaching assistant robot, has been tested in elementary school [5]. This wheeled robot conducts educational activities (such as storytelling and English language learning) mainly through embedded computer-based games. Most students had a positive attitude to this robot, and had great interest in the robot's performance. Yamamoto et al. [6] found that a robotic pet (AIBO) caused 4- to 6-year-old children to derive increased enjoyment from activities introduced in the kindergarten class work.

A. The KAR Concept

We have developed Kindergarten Assistive Robotics (KAR) as a socially assistive technology for educational purposes. KAR is an assistive robotic technology that provides kindergarten education teams with a novel tool for educational purposes based on social interaction. The primary purpose of KAR is to help the staff by playing educational games with the children. Our technology contributes to the existing repertoire of tools for children's cognitive and social development.

Fig.1. Children enjoy playing with the robot

KAR can also monitor children's development over time and produce unique data on children's performance in specific tasks and different learning situations. Our initial study describes the "First Meeting Procedure", a one-to-one setup [7] designed to establish the optimal methods of introducing KAR to children and their parents, reduce parental concerns about the robot, and increase the effectiveness of the procedure. In practice, the "First Meeting Procedure" explores ways in which the robot can be introduced to the children in their first encounter, and how it proceeds to engage pre-school children in play-like interactions. To study the effect of group decomposition on children's acceptance of the robot, we performed an extended version of "First Meeting Procedure" in a one-to-many setup [8]. In that study we also demonstrated how ethical principles can be implemented in a kindergarten setting. Most of the children engaged in positive interaction

with the robot, exhibited increased attention and motivated performance, and demonstrated a high level of enjoyment when interacting with the robot. Our results suggested that a one-to-many setup is preferable to one-to-one.

One of the purposes of the KAR system is to promote children's motor development. KAR can also promote children's cognitive development in preschool education, for example by storytelling. In the present study we describe the use of KAR to promote children's geometrical thinking, one of the aspects of spatial cognition.

B. Child Development and Spatial Cognition

Spatial ability is recognized as an important human skill needed for effective learning, training, working, and even playing [9]. Many researchers have used spatial cognition as a benchmark of performance in mathematics, engineering, drawing and graphics, science education, physical education, and educational therapies. Its importance is further emphasized in highly visuospatial domains such as engineering, architecture, aviation, and technical education [9].

Rafi et.al. [9] reviewed various definitions used to describe spatial cognition. Spatial reasoning comprises cognitive processes by which mental representations of spatial objects, relationships, and transformation are constructed and manipulated. Spatial reasoning can also be defined as comprising skills in representing, transforming, generating, and recalling symbolic, nonlinguistic information. The National Council of Teachers of Mathematics defines spatial sense as "an intuitive feel for one's surroundings and the objects in them" and further maintains that students' development of spatial sense requires "experiences that focus on geometric relationships; the direction, orientation, and perspectives of objects in space, the relative shape and sizes of figures and objects; and how a change in shape relates to a change in size" [10].

To develop spatial cognition, a child must first develop visuospatial perception and spatial navigation. Visuospatial perception includes development of spatial awareness, spatial coordinate systems or spatial reference frames, and spatial feature integration. Spatial navigation [11] refers to spatial cognitive mapping, route finding, and path integration.

The dominant theory of the development of spatial cognition suggests that children have four sets of core knowledge: object representation, agents and their actions, numbers, and space [11]. Even very young children possess basic knowledge about the geometry of the environment, specifically the distance, angle, and relations among objects in a surrounding layout. This spatial information provides the basis for development of spatial skills and cognition. Newcombe and Huttenlocher [11] suggest that spatial cognition develops as different types of spatial information come into conflict. Such conflict allows children and adults to learn which spatial cues to attend to in different situations, and then to use that knowledge to solve spatial problems. They also suggest that these changes can be represented in a computational model as ''re-weighting'' [12]. It thus seems

that training in spatial skills might be helpful for children's spatial cognition development.

Various programs have been developed to promote children's spatial cognitive development. Over the last decade computers have become more popular in the teaching and learning of spatial cognition in general, particularly as expressed in geometry. Computer-supported educational tools are also examples of "stealth education" [13] situations in which children learn, often without realizing that they are being taught. Edwards [14] developed a computer micro-world that children use to explore introductory geometric transformational concepts. He found that students were able to use visual feedback from the micro-world and discuss them with partners to correct their own mistakes. Lehrer et.al. [15] conducted a longitudinal instructional experiment to examine the effects of LOGO on children's mathematics learning. This study shows positive evidence that the characteristics described in the stage of geometric thinking development are helpful for the design and implementation of learning environments. Other experiments with second-grade elementary school students indicated that GeoCAL [16], a multimedia learning software program based on van Hiele's theory of geometric thinking levels [16], produces significant learning effects in visual association, description/analysis and abstraction/relation, as well as in overall geometric thinking. The software includes several games, such as jigsaw puzzles, shape tracer, and stamping.

Spatial models designed to improve spatial ability using a Web-based Virtual Environment (e.g. [9]) that interacts in a 2D world (such as virtual reality or simulations) may completely break down in the 3D real world. Moreover, such models might simplify the environment to such an extent as to render the models fundamentally wrong. In contrast, an embodied platform not only forces the integration of different cognitive capacities (e.g., manipulation, memory, object tracking, visual search, and time prediction) but also highlights where and which spatial processing mechanisms are critical [17]. Trafton and Harrison [18] were the first to show how the embodiment system works by modeling two different developmental findings: gaze-following and Level 1 perspective taking.

We share the view of researchers who believe that spatial cognition models should be at least partially embodied. In the present study, we show how assistive robotics can serve educational staff in developing children's visual-spatial and motor perception.

C. Children's Perception and Cognition of Traditional Western Music

Music has always been associated with motor activity. Infants, young children, and adults move rhythmically to music and are able to synchronize their movements with music [19]. Sensitivity to rhythmic and tonal properties of traditional western music emerges within the first year of life. Changes in processing of these musical properties occur throughout childhood and without formal training, only listen the music [20].

Music has a great influence on child development. Two main considerations motivated us to incorporate traditional western music in the proposed developmental method. First, music is a powerful stimulant for arousing emotions [19]. Second, listening to such music can actually improve children's spatial abilities. Research has shown that infants exposed to classical music tend to have higher spatial IQs than babies without such exposure [19].

D. Methodology of Cognitive Task Measurement

Knowledge acquisition cannot be observed directly, but must be inferred by observing performance on a test. Measurement of knowledge acquisition is even more difficult. It has been suggested that an essential condition for knowledge acquisition is cognitive efficiency (CE), described as an increase in the rate, amount, or conceptual clarity of knowledge in relation to its cost, in terms, for example, of cognitive effort [21]. Researchers in diverse fields such as neuroscience, psychology, education, industry, and economics differ in their understanding of how individuals optimize their mental resources to achieve gains in learning, problem solving, or academic performance. Primarily two computational formulas are used to measure CE: (a) the deviation model, which measures differences between standardized performance scores and effort or time expenditures, and (b) the likelihood model, which compares the ratio between performance and a cost factor such as time or effort. However, some conceptual confusion prevails in the field of educational psychology, as researchers lack consensus on the meaning of CE, and frequently conflate CE with the efficiency of instructional design, pedagogical methods, or the contextual conditions associated with learning (for review, see [21]).

In another approach to CE measurement, knowledge is presented as a metaphor for energy. From the biological and psychological perspective our brain power is limited. Thus, any effort to understand an infinitely complex world using a finite mind seems to constitute a paradox, and this can be resolved by constructing thinking patterns or mental models. The metaphorical analysis of knowledge and intellectual capital is presented in the seminal work by Andriessen (for review, see [22]), who concluded that we need to find new metaphors for knowledge.

In the present study we introduce a novel approach to the measurement of knowledge acquisition by showing how the acquisition of spatial-motor knowledge can be measured using a metaphor of velocity.

II. METHODS

A. Experimental Platform

Nao, a Linux-based humanoid robot developed by the French company Aldebaran Robotics (see Fig. 1), met our requirements for the robot's appearance [23]. Nao is 60 cm (23 inches) tall, has 25 degrees of freedom, and is equipped with an inertial sensor, two cameras, and many other sensors including touch. These allow it to comprehend its environment with stability and precision. The experimental procedure presented below was originally designed by a developmental psychologist and a specialist in human-robot interaction. The design documents setting out the robot's movements, speech, emotional expressions and program flow were then coded by programmers using Python language and the Nao system's graphical user interface.

B. Setup and Participants

The study was carried out in a typical Israeli kindergarten, a natural environment for the children. The room used for the study is typically used to accommodate small groups of children. We used the same experimental platform as in previous studies with similar features [7, 8].

Nine children (Israeli born, seven boys and two girls), mean age 3.3 ± 0.3 years) were randomly selected from the kindergarten's 3–4-year age group for participation in the study. The robot was placed about 1 m in front of a group of 2 or 3 children, within their personal space. A member of the kindergarten staff was present in the room, seated approximately 0.5 m from the imaginary line connecting the robot and the children. A monitor was placed to the left of the robot, at a distance of approximately 0.8 m from it, and the study session was photographed by a camera positioned behind the robot. Also in the room was one technician, seated approximately 0.8 m from the robot.

Fig.2 An image of the robot appears on the screen, with images of the seasons shown on the robot's buttons.

C. Experimental Procedure

1) *Pre-process:* We prepared the documents describing the experimental procedure. These were distributed to the parents, who were asked to sign their consent to their children's participation. The kindergarten staff participated in the design and approved its final implementation.

2) *First Meeting:* The first meeting procedure was the same as that used in our previous studies [7, 8], and took place 1 week before the beginning of the teaching session.

3) *Four Seasons Procedure:* The kindergarten teacher, who functioned as the authority in all activities with the robot, invited a group of 2 or 3 children to participate in the day's activity with the robot. After obtaining their agreement, the teacher allowed the robot to initiate the "Four Seasons" game (with the unstated intention of introducing them to the music of Vivaldi's "Four Seasons"). The robot started the procedure from a sitting position. It woke up, greeted the children, told them that it was happy to see them again, and explained the current activity, which the robot calls a musical game.. The robot told the children to look at the monitor and focus on the pictures representing the robot's body (Fig. 2). An image of each season was then shown serially on the screen, and the robot danced and played the

corresponding piece of music (for 26–30 seconds each). An image of the robot then appeared on the monitor, with images representing each season shown, one on each of the robot's four buttons (Fig. 2).

Geometrical thinking levels	Procedure
Level 0 - Recognition: recognition of the geometrical shape of the robot; paid attention to the visual characteristics of geometric patterns.	The robot asks to look on the screen and recognize basic shape of its picture.
Level 1 - Visual Association: infer shapes based on their characteristics.	The robot asks recognize parts of it body and buttons on the body.
Level 2 - Description/ Analysis: identify attributes of geometric shapes such as spatial relationships between different parts.	The robot ask to distinguish between upper and lower parts of it's body (hands, head), front and back parts of it's head (back and front buttons on the head).
Level 3 - Abstraction\Relation: categorizations of geometric shapes.	Not included.
Level 4 - Formal Axiomatic: understand geometric attributes	Children are asked to find relevant buttons.
Visual motor skills: eye hand coordination	Robot asks to push relevant button.

Fig.3 Implementation of the learning process of geometric thinking

Van Hiele's level theory of geometric thinking (described in [16]) was then applied in order to develop the children's geometric thinking. The robot asked the children to look at the screen and pay attention to the basic shape of its body, e.g. the overall shape of the head and hands shown on the screen (level 0, Fig. 3a). It then asked them to find these parts and find buttons on them (level 1, Fig. 3a). The robot directed their attention to the location of the head at the upper part of it's and the hands at the lower part. It also directed attention to the three buttons on its head: front, middle and back (level 2, Fig. 3a). The middle head button was not in use in the presented game. Finally, the robot asked the children to find the relevant buttons on its body, depending on which music they wanted to hear (level 4, Fig. 3a). It explained that they should press the button (visual-motor skills, Fig . 3a) that represents a particular season if they wanted to hear the music again and dance with the robot. If a child pressed the correct button, the robot gave positive feedback by playing and dancing to the music of that season again. If the wrong button was pressed, the robot asked the child to try again. After four wrong attempts the teacher showed the child the right button. Finally, the robot thanked the children for participating, said goodbye, and sat down.

The "Four Seasons Procedure" was conducted twice, with an interval of 1 week between the sessions. In this way, the children became familiar with the music.

Considering the age of our target population, post-hoc analysis of video footage of interaction sessions is the only feasible method of data collection and analysis.

D. Interaction Level (IL)

To evaluate the quality of child-robot interaction, we extended *IL*, the KAR Interaction Index described by Fridin and Yakobi [23]. To measure *IL*, we measure eye contact (*EC*) and an emotional factor (*F*). *EC* is awarded a value of 3 when the child looks at the robot; a value of 2 if the child seeks support from the other children; a value of 1 if the child looks at the kindergarten teacher; and 0 if the child becomes distracted or is not involved in the interaction session at all. $Sign_S$ indicates a positive or negative emotion (1 or –1, respectively), measured by valence 2d emotional space (e.g., see [25]). The emotional factor (*F*) is awarded 1 if the child expresses emotions facially; 2 if the emotions are expressed through body gestures or movements; and 3 if emotion is expressed vocally. W_F, is a binary variable that indicates whether the child expresses emotion or not. The entire procedure is divided into logical segments (*S*). The *IL* is measured for each segment. Thus, a child's KAR *IL* index in segment *S* of the interaction is given by:

$$IL_s = EC_s * Sign_s * \sum_{F=1}^{3} W_F F \qquad (1)$$

where EC_S is a variable measuring the child's *EC* in segment *S* of the interaction. $W_F F$ represents the emotional factor. Cronbach's alpha for *IL* is 0.686.

E. Velocity of Cognitive Learning (V)

We developed a novel method for measuring cognitive skill acquisition. A metaphor of movement velocity is used as the basis of a formula for measuring velocity of learning. Velocity of learning can be defined as the first derivative of cognitive performance (*dP*) with respect to time (*dt*):

$$V = \frac{dP}{dt} \qquad (2).$$

The first derivative of cognitive performance is measured as *1 – Standardized Score of Mediation*. The latter score is measured as the percentage of knowledge that the child acquires from the kindergarten teacher's verbal explanation (*VE*), or the number of attempts (*A*) made by the child to press the robot's buttons. We take into account four levels of *VE*: none, minor, major, and fully mediated, represented by the values 0, 1/3, 2/3 and 1, respectively. *A* denotes the ratio of the number of times the child presses the robot's button to the number of times he/she is instructed to do. In our case, *A = Number of attempts / 4*. If the child presses the robot's buttons more times than instructed by the teacher to do so, *A* will be greater than 1.This could mean that the task is completely unclear to the child, or that the child is inattentive, or disobedient, or simply curious about the other buttons.

Thus:

$$dP = 1-(VE+A) \qquad (3)$$

where the scale of *dP* is [–1;1]; 1 is the case where the child has the full knowledge required to perform the task and –1 is the case where the child fails to acquire necessary knowledge.

The overall formula for velocity of learning is given by:

$$V = \frac{1 - (VE + A)}{RT} \qquad (4)$$

RT is the child's response time. Cronbach's alpha for the *IL* is 0.638.

F. Data Analysis

Repeated measures (stages of the procedure, Fig.3a) ANOVA was performed separately for the two main factors, *IL* and velocity of learning *V*. The two between-subject factors were session (*1, 2*) and gender (boy, girl).

To evaluate *IL* over time, we compared *IL*s in similar segments ("Introduction", "Motor Game" and "Parting") of the "First Meeting" and "Four Seasons" procedures by repeated measures ANOVA. In this test, repeated measures are sessions *1* and *2* of the "first interaction" and "Four Seasons" procedures, and two between-subject factors: gender (boy, girl) and procedure segments ("Introduction", "Motor Game" and "Parting").

III. RESULTS

IL remained positive throughout the entire procedure, and *IL* measurements revealed no significant differences between the procedure's segments. Mean *IL* results (± SE) are presented in Fig. 3a. Neither gender nor session had a significant effect on *IL*.

TABLE 1. CHILD-ROBOT INTERACTION LEVELS BY PROCEDURE SEGMENT FOR THE FIRST MEETING AND "FOUR SEASONS" PROCEDURES

Procedure Segments	Gender	"First Interaction"	"Four Season" Session 1	Session 2
Hello	Boys	12.0 (4.2)	13.7 (4.8)	12.4 (4.3)
	Girls	15.0 (4.2)	18.0 (.0)	12.0 (8.4)
Motor Game	Boys	13.2 (3.4)	15.4 (6.2)	19.7 (5.4)
	Girls	18.0 (.0)	18.0 (.0)	18.0 (.0)
Parting	Boys	20.1 (7.0)	15.7 (8.9)	12.4 (10.4)
	Girls	18.0 (.0)	24.0 (8.4)	18.0 (8.4)

Comparison of *IL* measures between corresponding segments of child-robot contact in the First Meeting Procedure and in both sessions of "Four Seasons" procedure yielded no significant differences. Neither gender nor procedure segment had a significant effect on *IL*. Child-robot *IL*s (means (± SE) are presented in Table 1.

Analysis of the velocity of learning (*V*) in the first and second sessions of the Four Seasons procedure showed significant differences between them (F (1, 14) = 11.61, p = 0.004). Neither gender nor procedure segment had a significant effect on *V*. Mean results (± SE) of velocity of learning are presented in Fig. 3b.
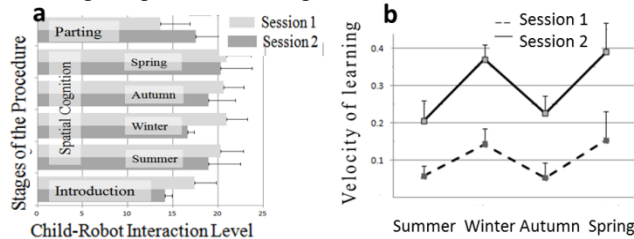

Fig.3. **a:** Interaction levels during different stages of the procedure; **b:** Velocity of visual-motor skill acquisition during both sessions of the Four Seasons procedure.

IV. DISCUSSION

This study demonstrates how humanoid assistive technology can be applied in a kindergarten to assist the educational staff in educational tasks. The procedure presented here promotes children's geometrical thinking. Following proposals such as those by Wilson [26] and others, this experiment illustrated that spatial cognition in general and geometric thinking and visual motor skills specifically can be promoted when embodiment is taken seriously. The proposed procedure also demonstrated how this can be achieved by "stealth education" [13]

The finding that interaction levels were positive throughout the study shows that the children enjoyed the robot's presence. They expressed positive emotions and cooperated with the robot at the "First Meeting Procedure" and at both sessions of the "Four Seasons Procedure."

Learning to use symbols is an important stage in the development of spatial cognition. Each of the four seasons in our procedure was represented by a symbol, and the children were able to identify each season correctly by pressing its symbol on the robot's buttons. Pressing of the buttons also trained the children's visual-motor skills. In addition, we showed, in line with van Hiele's theory of geometric thinking levels, that their geometric thinking could be developed, [16].

The experiment performed in the kindergarten exposed a few points in the procedure that could be improved on. The feedback given to the children by the robot could be enriched if the robot were to give the children more detailed instructions.. In this study, that function was performed by the teacher. It remains a challenge to define proper for this procedure team decomposition. We suggest that the team decomposition should be adapted to the children's personal profiles. It is also possible that application of the procedure should be adapted to the children's style of learning [28].

Over the past decade, an impressive body of research has shown that both positive emotions and emotional intelligence are associated with multiple successful outcomes in the domains of mental health, social relationships, work, and learning (for review see [27]), as well as emotional intelligence, and successful experiential learning. The positive IL values obtained here indicate that the robot-teacher successfully promoted children's emotional involvement in the educational process. These findings are consistent with previously demonstrated positive interactions with a robot, accompanied by expressions of positive emotions, in studies of children with autism [2, 3]. We also showed here how to incorporate music in a learning procedure.

In the novel formula developed here for measuring the velocity of learning, cognitive efficiency is conceptualized (in contrast to other known measures) as a quantitative measure of knowledge acquisition [21]. The differences observed between the velocity of learning in the first and

second sessions indicates that the children had learned the spatial task.

In our further research we intend to develop a similar procedure for learning children at geometric thinking, where the robot represented on the screen by a multi-view drawing instead of the image (Fig. 2). Moreover we intend to develop procedures that will support children's meta-cognitive development [31]. In those procedures, children who already study the geometrical thinking with this game with the robot will teach children without such experience how to think geometrically.

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