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Towards a Child-Robot Symbiotic Co-Development: a Theoretical Approach

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Abstract. One of the main characteristics for an effective learning is the possibility for learners to choose their own ways and pace of learning, according to their personal previous experiences and needs. Social interaction during the learning process has a crucial role to the skills that learners may develop. In this paper, we present a theoretical approach, which considers relevant theories of child's development in order to proceed from a child-child collaborative learning approach to a child-robot symbiotic co-development. In this symbiotic interaction, the robot is able to interact with the learner and adapt its behaviours according to the child's behaviour and development. This sets some theoretical foundations for an on-going research project that develops technologies for a social robot that facilitates learning through symbiotic interaction.

1 INTRODUCTION

This paper discusses the conceptualization and some initial investigation of children's collaborative learning through symbiotic child-robot interaction in a specific educational setting. According to Douglas [1], biologist Heinrich Anton de Bary used the term "symbiosis" in 1879 to describe any association between *different* species. In this context, symbiotic learning describes the process, during which members of a team mutually influence each other resulting in an alteration of their behaviour. However, relationships among members may sustain imbalances. In order to support symbiotic interactions in learning, special considerations should be given to the orchestration of the relationships and the process between members of the team, from which they all benefit. The core motivating principle of symbiosis and the collaboration within it is reciprocity. Thus, learning emerges through a harmonized openness, responsiveness and adaptation. Elements of this kind of interaction may appear also in collaborative learning settings, which may not be especially designed for symbiotic interactions. Identifying elements of symbiotic interaction in children's collaborative learning may provide us with features for a more effective interaction design and for the design of robot behaviours as the child's co-learner.

In the following sections, we describe some constructivist aspects of child learning focusing on the need for learners to take responsibility for the regulation of the form and pace of learning. We then describe how symbiotic interaction can provide a theoretical and practical framework for understanding child-robot inter-dependence.

2 ASPECTS OF CHILDREN'S LEARNING PROCESSES

According to Foston and Perry [2], learning is a constructive activity that occurs through the interaction of individuals with their surroundings. Stages of development are understood as constructions of the active re-organization of learner's knowledge. This view builds on the constructivist framework of Piagetian developmental theory [3] according to which learning is a dynamic process comprising successive stages of adaption to reality, and during which learners actively construct knowledge by creating and testing their own theories and beliefs.

Two aspects of Piaget's theory underpin the pedagogical approach adopted here: First, an account of the four main stages of cognitive development through which children pass [4]. Since their birth, children go through (i) the sensori-motor stage (0-2 years), (ii) the pre-operational (2-7 years), (iii) the concrete operational (7-12 years) and (iv) the formal operational stage (12 years and onwards). For this project, we consider children in the age group between 7 and 12 years. During this stage, children are able to imagine "what if" scenarios, which involve the transformation of mental representation of things they have experienced in the world. These operations are "concrete" because they are based on situations that children have observed in the environment.

Second, an account of the mechanisms by which cognitive development takes place [5], which we consider in relation to environmental, social and emotional elements of child's development. These mechanisms describe how children actively construct knowledge by applying their current understanding.

2.1 Learning as a dynamic process

According to Piaget's classic constructivist view, learning occurs in a sequence of stages from one uniform way of thinking

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to another. Cognitive conflict, arising from discrepancies between internal representations and perceived events, functions as the motivating force for changing from concrete modes of thinking to more abstract forms. Although these stages relate to the child's genetic predispositions and biological development, environmental factors affect the transition from one stage to the next in complex ways. However, since Piaget first defined his framework it has been recognized that developmental transitions are not necessarily age specific events, but it occurs within an age range that can differ from child to child [6]. Additionally, the relationship between child development and the context in which this occurs, is bi-directional which results in a dynamical, iterative process; children affect and, simultaneously, they are affected by factors of their environment [7]. This can happen either in informal settings [8] which support tinkering and learning by doing or by following more formal and standardized processes, such as the inquiry cycle process [9], which will be described in 2.1.2 of this paper.

2.1.1 Child and the natural need for learning through exploration

In order for a child to be strongly engaged with a task it has to be meaningful for them. Since children have an inherent motivation to explore and understand their surroundings, the relevance of the task will stimulate their curiosity and willingness for exploration. Science education provides a formal learning setting that should share some of the characteristics of informal settings in order to help children acquire new concepts and develop transferable skills. Building on constructivist principles, children's natural enthusiasm for play can be a key factor in learning. During play, children can explore the real world, logically organize their thoughts, and perform logical operations [10]. However, this occurs mainly in relation to concrete objects rather than abstract ideas [8]. Children are also able to reflect on their intentional actions which may result in a self-regulated process of change [11].

2.1.2 Inquiry cycle: a systematic process of learning

'Inquiry is an approach to learning that involves a process of exploring the natural or material world, and leads to asking questions, making discoveries, and rigorously testing those discoveries in the search for new understanding. Inquiry should mirror as closely as possible the enterprise of doing real science' [12] (p.2). The main claim of inquiry learning, in relation to science learning, is that it should engage learners in scientific processes to help them build a personal scientific knowledge base. They can then use this knowledge to predict and explain what they observe in the world around them [13]. Thus, having as a starting point child's tendency for informal exploration, with developmental appropriate scaffolding, children develop their scientific thinking. This transferable skill can then facilitate child learning in different contexts.

There are many models that represent the processes of inquiry, but all include the processes of (1) *hypothesis generation* in which learners formulate their ideas about the phenomena they are investigating, (2) *experimentation* in which children perform experiments to find evidence for rejection or confirmation of their hypotheses and (3) *evidence evaluation* in which learners try to find logical patterns in their collected data and to interpret this data to form a conclusion [14, 15].

Banchi and Bell [9] describe a four-level continuum to classify the levels of inquiry in an activity, focusing on the amount of information and guidance that is presented to the learner [9, 16]:

Confirmation inquiry: In this form of inquiry learners are provided with the research question, method of experimentation and the results that they should find. This is useful if, for example, the goal is to introduce learners to the experience of conducting investigations or to have learners practice a specific inquiry skill such as collecting data.

Structured inquiry: Here, the question and procedure are still provided but the results are not. Learners have to generate an explanation supported by the evidence they have collected. In this case learners do know which relationship they are investigating.

Guided inquiry: In this form learners are provided only with the research question. Learners need to design the procedure to test their question and to find resulting explanations.

Open inquiry: This is the highest level of inquiry. Here, learners have the opportunities to act like scientists, deriving questions, designing and performing experiments, and communicating their results. This level requires the most scientific reasoning and is the most cognitive demanding. This low- to higher-level continuum of inquiry is important to help learners gradually develop their inquiry abilities [9]. The obtained inquiry skills are transferable to other contexts.

2.2 The zone of proximal development (ZPD)

The level of potential development is the level at which learning takes place. It comprises cognitive structures that are still in the process of maturing, but which can only mature under the guidance of or in collaboration with others. Vygotsky [17] distinguished between two developmental levels: the level of actual development and that of potential development. The actual development is the level, which the learner has already reached and she can solve problems independently. The level of potential development, which is also known as the *Zone of Proximal Development (ZPD),* describes the place where child's spontaneous concepts meet the systematic reasoning under the guidance or in collaboration with others [18]. In that way, Vygotsky argues that the interpersonal comes before the intrapersonal. This is considered to be as one of the fundamental differences between Vygotsky's conceptualization of child development and that of Piaget.

Learning takes place within the ZPD and here a transition occurs in cognitive structures that are still in the process of maturing towards the understanding of scientific concepts. The level of potential development varies from child to child and is considered a fragile period for child's social and environmental support through the educational praxis. In this context, Vygotsky introduced the notion of 'scaffolding', to describe the expansion of the child's zone of proximal development that leads to the construction of higher mental processes [19]. However, only if we define what causes the expansion of ZPD, we will be able to provide appropriate scaffolding for learners. Siegler [20], for example, has highlighted the question of what causes change in learning mechanism and he concluded that seemingly unrelated acquisition are products of the same mechanisms or mental process. Scaffolding is considered a core element for the support of child's mental changes in the context of collaborative learning.

2.3 Collaborative learning

Rogoff's [21] definition of collaboration includes mutual involvements and engagement and participation in shared endeavours, which may or may not serve to promote cognitive development. This broad definition allows for flexibility regarding its interpretation and it is adjustable into different contexts. For the present research, we use this definition as a basis for our theoretical approach for collaboration in the context of learning.

Vygotsky [17] emphasized the importance of social interaction with more knowledgeable others in the zone of proximal development and the role of culturally developed sign systems that shape the psychological tools for thinking.

In addition to the development of their cognitive skills, children's social interactions with others during the learning process may trigger their meta-cognitive skills, as well. Providing explanations during collaboration in which children reflect on the process of their learning (meta-cognitive skills) leads to deeper understanding when learning new things [22, 23]. There are two forms of explanation: (1) self- explanation, which refers to explanation of the subject of interest to oneself, and (2) interactive explanation, which refers to explanation to another person [24]. In both cases, the presence of a social partner facilitates children's verbalization of their thinking. However depending on the type of the social partner, children may exhibit different behaviours, which relate to different kind and quality of learning.

The following sections describe two different types of social partners as mediators for children's learning to occur.

2.3.1 Child – tutor

With regard to adult-child interactions, Wood et *al.* [25] defined tutoring as 'the means whereby an adult or 'expert' helps somebody who is less adult or less expert' (p.89). Receiving instructions from a tutor is a key experience in childhood learning (ibid.). This definition of tutoring implies a certain mismatch in the knowledge level between the parties involved, in such a way that the tutor has superior knowledge or skill about a subject which is then passed on to a child via tutoring mechanisms.

2.3.2 Child – child

In combination with tutoring, peer learning has been defined by Topping [26] as 'the acquisition of knowledge and skill through active helping and supporting among status equals or matched companions' (p.1). Topping continues to describe that peer learning 'involves people from similar social groupings who are not professional teachers helping each other to learn and learning themselves by so doing' [26]. This learning method has proven to be very effective amongst children and adults and has been widely researched over the past decades. Peer learning assumes a matched level of initial knowledge of both parties. In ideal peer learning situations, both parties will increase their knowledge levels at a similar pace through collaborative learning mechanisms.

2.4 Emotional engagement and social interaction (in learning)

The importance of positive feelings during the learning process has been reported as crucial [27]. They promote the individual's openness to new experiences and resilience against possible negative situations [28]. It has been reported that dynamic behaviours involve reciprocal influences between emotion and cognition [29]. For instance, emotions affect the ways in which individuals perceive the reality, pay attention and remember previous experiences as well as the skills that are required for an individual to make decisions.

3 SYMBIOTIC INTERACTION

The educational and developmental theories outlined in the previous sections describe various forms of collaborative learning. Social interaction between learners is emphasised as an important factor in successful collaborative learning, where both students co-develop at a complementary pace through shared experiences.

Within the context of this co-development we define *symbiotic interaction* as the dynamic process of working towards a common goal by responding and adapting to a partner's actions, while affording your partner to do the same.

The fundamental requirements for team collaboration have been discussed in detail by Klein and Feltovich [30]. They argue that in order to perform well on *joint activities*, or collaborative tasks, there must be some level of *common ground* between teammates. These concepts have been introduced by Clark [31] to describe the intricate coordination and synchronization processes involved in everyday conversations between humans.

Common ground between team participants is the shared mutual knowledge, beliefs and assumptions, which are established during the first meeting and continuously evolve during subsequent interactions. A strong common ground can result in more efficient communication and collaboration during joint activity, since a participant can assume with relative safety that other participants understand what she is talking about without much additional explanation [30].

Klein and Feltovich [30] argue that in order for a task to qualify for effective joint activity, there must firstly be an *intention* to cooperate towards a common goal and secondly the work must be interdependent on multiple participants. As long as these preconditions are satisfied, a joint activity requires *observable, interpretable* and *predictable* actions by all participants. Finally, participants must be open to *adapt* their behavior and actions to one another. The different processes of the joint activity are choreographed and guided by clear *signaling of intentions* between participants and by using several coordination devices such as agreement, convention, precedent and salience.

3.1 Intention to act towards a common goal

An important precondition for symbiotic interaction is the *awareness* of a certain common goal, and a clear *intention* to work towards this goal. During the process of establishing and maintaining common ground, both parties will (implicitly or explicitly) become aware of the goals of the other. Maintaining common ground relies on being able to effectively signal your intent to a partner, while at the same time interpreting and reacting to the intent of his or her actions [30].

3.2 Observability of actions and intentions

Equally important to being able to effectively *signal* intent is the ability of the partner to *observe* and *interpret* this intent. A sense of *interpredictability* can be achieved when such signals can be naturally and reliably generated, observed and interpreted by both partners. A healthy level of interpredictability between partners can contribute to an increased common ground and mutual trust between partners [30].

3.3 Interpredictability, adaptability and trust

Within the context of an interaction, predictability means that one's actions should be predictable enough for others to reasonably rely on them when considering their own actions. Over the course of an interaction, certain situations arise which allow a person to estimate the predictability of a partner's actions, or in other words, the amount of *trust* you place in the predictability of your partner. Simpson [32] argues that in human-human interaction, trust levels are often established and calibrated during trust-diagnostic situations "in which partners make decisions that go against their own personal self-interest and support the best interests of the individual or the relationship" [32]. This *willingness* to act predictably and *adapt* one's behavior to support a partner's best interests is a key component of building mutual trust and supporting a symbiotic relationship [33].

In summary, an effective joint activity relies on signaling, observing and interpreting the intent of actions towards a common goal. By establishing a strong common ground, both partners achieve a level of interpredictability. An important factor in building trust is to expose a willingness to act predictively and adapt one's behavior to match the common goals shared with a partner.

4 CHILD-ROBOT INTERACTION

The work reported in this paper is part of a project on social robots in learning scenarios. Social interaction with a robot affects the child's independence during the learning process. Robots can take either end of the spectrum depending on its role, in other words, it can be either tutor-like or peer-like for child learning [34]. Depending on the amount of support needed for the child's learning, the robot might adapt its role to fit this need, shifting either more towards the tutor or the peer role. This adaptive behavior fits the theories on symbiotic interactions outlined above. Together with clear signaling of intents, which contribute to an increased level of predictability, it is this adaptability that proves to be an important factor in building a long-term symbiotic relationship.

Belpaeme et al. [35], for example, have reported the importance of adaptive behavior of the robot when it interacts with children with diabetes. In this study, researchers adapted robot behaviour according to children personality (extroverted / introverted) and to the difficulty level of the task. They concluded that adaptation to user characteristics is an effective aid to engagement.

In the context of the learning process, a robot may adapt its behavior to the child's cognitive, social and emotional characteristics with a purpose to facilitate the expansion of children's zone of proximal development. Thus, the robot can scaffold the process of change by adapting its behaviour according to the user. It shows its awareness and willingness to be influenced by others. The robot then will adapt to the child's next level in order to contribute to the iterative process of development. In this way, we create a learning context based on symbiosis of the child and the robot.

5 FUTURE AGENDA

Inspired by the insights derived from the previously introduced theoretical framework for co-development in learning, we outline our future goals, which focus on the elaboration of aspects of this framework and explore its utility for designing robot-child interactions for inquiry learning. To conclude this paper we briefly describe a contextual analysis we are performing to validate the framework in the specific pedagogic setting of inquiry learning. Thereafter we briefly present some of our ideas for future experiments.

5.1 Some first insights from a contextual analysis

An initial contextual analysis is being performed based on observations of twenty-four children who are working in pairs on a balance beam task. The balance beam task is a specific implementation of a type of structured inquiry learning. Using the balance beam children investigate the weight of several provided objects, exploring both the influence of weight rations and the distance of the object to the pivot.

The setting for this contextual analysis was as follows: a total of 11 pairs of two children (aged 6-9 years) received a structured assignment, which they could complete by using the balance beam that was presented. This assignment was designed according to the processes of structured inquiry (e.g. hypothesis generation, experimentation, evidence evaluation). The children could place pots that differed in weight on different places on the balance, make predictions about what would happen to the balance (tip left, tip right, or stay in equilibrium), perform experiments by removing wooden blocks that held the balance in equilibrium, observe what happened with the balance and draw conclusions about the variables that influence the balance (weight, distance). These procedures were videotaped and than annotated. These annotations are not yet fully analysed, but a few first indications will be described here.

1. It appeared that children who followed the steps of the assignment correctly were engaging in the different processes that are typical for inquiry learning, and were interacting with each other about the process and the outcome of the task.
2. Most children were able to identify the influence of the two variables (weight and distance) on the balance eventually.
3. Several children asked for additional guidance from the experimenter during the task.

These first insights from the contextual analysis have been taken into account for our next steps for the design of child-robot interaction in the same context. We observed that children in this age may follow the inquiry process during the activity. However, in order for them to reflect on this process, verbalize their thoughts and explain the scientific phenomenon under investigation, they needed the support from a social partner. The teacher facilitated child's process by different types of interaction, such as supporting children's inquiry process by probing questions or asking for explanations and summarizations. In addition to the verbal interaction, we considered non-verbal cues of social interactions that appeared during this contextual analysis. The emerging types of social interactions have informed our design for future experiment on child-robot interaction.

5.2 Planned experiments

Our next steps include two experiments on child-robot interaction. In the first experiment we will focus on the influence of a social robot on explanatory behavior. Explanatory behavior includes the verbalization of scientific reasoning of the child.

The experiment is comprised of two conditions. In the experimental condition the child will be working on an inquiry assignment with the robot. The background story of the robot is that he comes from another planet. He has an assignment from his teacher to study the effects of balance on earth. The robot wants to explore this phenomenon with like-minded people: children. The robot is presented as a peer learner but he does have well-developed inquiry skills. Therefore, the robot will provide instructions and ask questions to help learners explore the phenomenon of balance with the balance beam. The children will provide their answers by talking to the robot. The input of the state of the learning material for the robot will be controlled by a 'Wizard of Oz' technique.

In the control condition learners will be working on the same assignment but without the robot. In this case the tablet provides instruction and will pose exactly the same questions to help learners explore the phenomenon of balance. In the control condition there is no background story, but children are asked to do the assignment as part of their educational program. The children will provide their answers verbally, and it will seem as if the tablet records the answers. In both conditions video recordings will be made of the children working on the task. It is hypothesized that when working on the task in an appropriate social context, in this case being accompanied by the robot, giving answers to the questions will result in more verbal explanatory behavior. Verbally explaining to another person can facilitate greater understanding of one's own ideas and knowledge [23] and might therefore lead to better learning and transfer [36].

The second experiment will focus on the expected cognitive competence children believe the robot has. There will be three conditions. In all conditions the robot will make some incorrect suggestions. The difference between the conditions is that the children are primed to believe that the robot is (1) an expert, (2) a novice or (3) no priming. The goal is to find out how competent and trustworthy children believe the robot is before and after the experiment.

In this paper, we have described some aspects of an initial theoretical framework that we use to design our experiments and user studies to investigate child-robot symbiotic interaction. We are going to give an emphasis to the process of learning in different contexts, focusing on collaborative learning and exploiting the robot as an adaptive co-learner. Thus the robot can scaffold the child to go through an effective learning process. For the future work we aim to investigate how a social robot can scaffold child's inquiry process by facilitating the expansion of ZPD in an effective and enjoyable way focusing on the development of children's meta-cognitive skills.

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