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The architecture of children's use of language and tools when problem solving collaboratively with robotics

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Abstract

This paper demonstrates, following Vygotsky, that language and tool use has a critical role in the collaborative problem-solving behaviour of school-age children. It reports original ethnographic classroom research examining the convergence of speech and practical activity in children's collaborative problem solving with robotics programming tasks. The researchers analysed children's interactions during a series of problem solving experiments in which Lego Mindstorms toolsets were used by teachers to create robotics design challenges among 24 students in a Year 4 Australian classroom (students aged 8.5–9.5 years). The design challenges were incrementally difficult, beginning with basic programming of straight line movement, and progressing to more complex challenges involving programming of the robots to raise Lego figures from conduit pipes using robots as pulleys with string and recycled materials. Data collection involved micro-genetic analysis of students' speech interactions with tools, peers, and other experts, teacher interviews, and student focus group data. Coding the repeated patterns in the transcripts, the authors outline the structure of the children's social speech in joint problem solving, demonstrating the patterns of speech and interaction that play an important role in the socialisation of the school-age child's practical intellect.

Language constitutes the central subject matter for analysis of the human forms of behaviour (Vygotsky 1978). Yet there have been longstanding debates about the relationship between language and cognition, and many questions about the precise nature of this relationship remain unresolved (Baldo et al. 2005). The focus of this paper is the convergence of speech and practical activity in children's collaborative problem solving and interactions with robotics. Problem solving is regarded here as series of steps, including the analysis of a problem, generating possible solutions, testing solutions, and modifying behavior or switching to other strategies when a solution is unsuccessful (Baldo et al. 2005).

Vygotsky theorised that, "the most significant moment in the course of intellectual development, which gives birth to the purely human forms of practical and abstract intelligence, occurs when speech and practical activity… converge" (Vygotsky 1978, p. 24). Speech is one of multiple modes of language that humans use to communicate, which is often complemented by gestures, and particular spatial positions among speakers and listeners. It often includes references to external objects within the visual field of the speaker.

In a society in which technological tools are increasingly necessary to solve everyday problems, learning experiences that allow children to use language and tools to jointly engineer solutions are vital to human thought and scientific progress. Students require problem-solving skills – the successful use of language and tools to overcome constraints in a task environment to achieve a goal. Problem solving is essential for individuals to respond to the multiple pathways and collaborative decision-making necessary to negotiate personal, corporate, and civic life that is essentially social.

We argue here that language is integral to the generation of knowledge and human discovery, such as in the STEM fields – Science, Technology, Engineering, and Mathematics. The children in our study not only acted when attempting to achieve an individual or collaborative practical goal or solve a problem – they spoke, gestured, wrote, read Lego instructions, created podcasts, composed digital images, and so on. The children's speech, gestures, and use of tools arose spontaneously, frequently guided by interactions with others, and continued almost without interruption in problem solving interactions. This aligns with Vygotsky's (1978) observations of very young children, who observed that speech increases and becomes more persistent as the demands of the task become more complex, and the goal more difficult to attain. Recent, clinical studies have demonstrated that when language ability is disrupted or impaired, either by neurologic insult (e.g. stroke patients) or verbal interference, such as conditions of articulatory suppression, humans are left with a less sophisticated, less flexible capacity for analysing and solving complex problems (Baldo et al. 2005). Conversely, the ability to internalise language in the form of inner speech, which Vygotsky (1962, p.252) defines as: "a distinct plane of verbal thought, mediated internally by word meanings." It allows us to manipulate concepts and solve problems covertly and differs to external speech for others.

Existing literature and research indicates that language is foundational to problem solving, and is essential for connecting and positioning knowledge claims within canonical disciplines (Gee 2005;

Norris and Phillips 2003; Yore 2000). For example, Gee (2005) argues that science makes demands on students to use language, including digitally mediated forms of communication, such as using Internet search engines or disseminating knowledge via electronic media. Similarly, Norris and Phillips (2003) and Yore (2000) identify cross- curriculum reforms in English-speaking countries that emphasise a language and literacy component that is foundational to cognition, critical thinking, habits of mind, and information and communication technologies. Language is increasingly necessary to understand complex problems in society, and to inform and persuade others about these ideas.

Researching the Collaborative Dimension of Problem solving

Many complex problems in research and in everyday life are not solved independently, but in collaboration with others. It is surprising then, that many psychologists have typically researched problem-solving activity by observing individuals working on well-defined problems in a laboratory (Forman & McPhail, 1993). A lesser number of psychologists, educational researchers, and anthropologists have paid some attention to the thinking of participants engaged in naturalistic group problem solving tasks, and then this research is often with adults, rather than children (Lave, 1991; Scribner, 1984). This research with adults has demonstrated that collaborative problem solving environments can both support and constrain individual thinking. In collaborative contexts, the objective can shift from finding a solution to the problem, to a struggle to come to a shared definition of the problem and shared forms of communication (Schoenfeld, 1989). Such research with adults raises questions about the constraints and supports for the child's thinking in naturalistic problem solving contexts in classrooms, where children are often grouped with their age-level peers. Research of collaborative problem solving among children has drawn attention to the importance of children learning to negotiate shared problem definitions and mutually understood ways of negotiating and interacting productively in group problem solving environments (e.g. Forman, 1989; Newman, Griffin and Cole, 1984).

Socio-cultural paradigm and problem solving

This study is based on socially constructed views of language and problem solving, in particular, situated learning (Brown et al. 1989). Theorists from this perspective attempt to capture increasingly sophisticated thought and language processes as they develop through both maturation and guided practice (Sinatra and Broughton 2011). Learners are guided to participate in activities and knowledge that is distributed among the individuals, tools, and artifacts of the learning community (Mason 2007). Language use is seen as socially situated and ideological, because human interactions are always located within broader structures of cultural, economic, and political power (Luke et al. 2003). Consistent with this paradigm, we employ anthropological research methods to analyse the language in problem solving interactions to observe the social learning patterns in the classroom – learning that is influenced in some way by the social environment (Bandura 1986).

Robotics research in middle primary classrooms has tended to focus on exploring and understanding mathematics, science, and technology concepts, without foregrounding the role of language and literacy in problem solving processes (Chambers et al. 2007; Norton et al. 2007; Portz 2002). Case studies have demonstrated the potentials of inquiry methods of learning with robotics to facilitate teamwork, problem solving, critical thinking, and students' metacognitive ability to reflect on their problem solving (Chandra et.al 2013; Barak and Zadok 2009). Similarly, key features of the enacted curriculum that support students' creative solutions in robotics problem solving have been identified in classroom research, such as opportunities for both seriousness and play (Sullivan 2011). Previous educational research of robotics with children has not addressed the use of language and tools in children's collaborative problem solving from socio-cultural perspectives of learning.

Background and aims

This research analyses primary students' uses of language and tools when mutually solving problems. Problem solving was predominantly collaborative, because the peers jointly constructed something new that neither had understood prior to their social interactions (Tomasello et al. 1993). The observed interactions also partially involved transmission from mature to immature learners. The research involved the students' use of Lego robots and programming software, regarded here as cultural tools. A tool serves "as the conductor of human influence" on a goal-centered activity (Vygotsky 1978, p.55). The mediating power of tools is tied to the accumulation of knowledge of prior generations that are embedded in the design of the artifact (Cole and Engestrom 1993). Examples of tool use in Vygotskian experiments include everyday objects, such as string or sticks, to extend one's reach for a candy (Vygotsky 1978). A tool can be a simple as a stick, or as complex as a robot.

Based on this premise, we aimed to investigate the architecture or structure of problem solving language in children's interactions with others, and with new cultural and technological tools. Central to our research is the principle that "all mental functions are internalised social relationships…their composition, genetic structure and means of action [forms of mediation] - in a word, their whole nature is social. Even when we turn to mental [internal] processes, their nature remains quasi-social" (Vygotsky 1981, p. 164). An outcome of our analysis is a model of the architecture of collaborative problem solving language. Four discrete, recurring functions of language use were identified. Salient features of the children's social interactions and a model of the structure of children's problem solving language will be presented.

Research design

The data presented here were generated in the context of a classroom ethnography with a Year 4 class. Ethnographic classroom research draws on qualitative or descriptive methods to study human interaction in a naturalistic setting. Consistent with a socio-cultural approach, the quality of dialogue taking place between learners is an important way to assess learning and the merits of different problem solving environments (FitzGerald 2012). Micro-genetic or fine-grained analysis of speech or discourse captured *in situ* contains a richness of information, and permits replaying of events to identify subtle yet significant incidents relating to human interactions.

Described here is classroom ethnography focused on a robotics unit within the second years of a multiple strategy, digital media research project conducted over four years. This was preceded by 18 months of building rapport with school staff and teachers in the school by providing regular media workshops, professional development, curricular planning, and in-class learning support for students in digital technology use (e.g. web page design, blogging, online comics, video and music production, podcasting, and robotics).

We analysed a series of problem solving experiments in which Lego Mindstorms™ toolsets were used to create robotics design challenges among 24 students in a Year 4 class (students 8.5-9.5 years). The units were implemented in an intensive seven-week block during the third quarter of the second project year. Researchers worked with a Year 4 teacher to design and implement a series of problem solving design challenges of increasing complexity.

The Year 4 teacher came to the study with many years of teaching experience, but with little previous experience of Lego robotics and the programming software introduced in the research. With a disposition toward learning new skills, the teacher attended after-school robotics workshops offered by the university, and subsequently invited two university researchers to assist her to design a unit and teach robotics to provide problem-solving experiences for her students. The researchers, both former schoolteachers, had combined expertise in language studies and new teaching and learning technologies, including Lego robotics. The ethnographic findings were enabled by a partnership between researchers and practitioners to combine research rigor with teachers' knowledge of the local context.

Student participants

The classroom was selected for cultural and linguistic diversity and low socio-economic background, which is becoming typical of public schools in Queensland because of the increased privatization of schooling. The Year 4 class had 24 students, both boys and girls, primarily from suburbs in an economically and socially disadvantaged region of Southeast Queensland, Australia, including the school's adjacent State Housing Authority area. The majority of the students were from low SES, Anglo-Australian backgrounds, with several Indigenous Australian, Pacific Island, and migrant students who spoke English as a Second Language. Several students were ascertained as having significant learning disabilities, and qualified for specialist learning support. Five students did not return their signed ethnical consent forms, and these students were grouped together to be involved in the learning experiences, but data was not collected from these groups. The students' average scores in the most recent tested year (Year 3) on the National Assessment Program for Literacy and Numeracy (NAPLAN) for reading, writing, spelling, and grammar were classified as "substantially below" both the national average and the average for "statistically similar" schools (ACARA 2012).

Data collection and analysis

Anthropological and sociological studies have been perceived as partners with observation and experiment to explain human thought and language (Vygotsky 1978). Therefore, we used ethnographic classroom observation to analyse the students' use of language and tools in collaborative problem solving with robotics (See: Tedlock, 2000). These were collected during one intensive, seven-week unit implemented in partnership between the researchers and the teacher, preceded by a year-long researcher-teacher collaboration, introducing professional development workshops on robotics and other teaching practices. The data included the following:

i. Observational classroom data: audio recording of participant interactions;
ii. Post-lesson data: discussions with participants to obtain their perspectives;
iii. Artifact data: texts produced by students, such as screen shots of programming.

Observational data included simultaneous and continuous audio recording of the six consented student groups as they interacted with the robots in the classroom (n=19) using six recording devices, and a seventh device recording whole class talk during the robotics lessons (See: FitzGerald 2012). We took screen shots of the robot programming on the children's laptop screens, and the children used video cameras to create movies about their robotics.

Post-lesson data included audio-recorded semi-structured interviews with the teacher to gain her reflections on the problem solving process immediately after each lesson, and at the culmination of the unit (See: Spradley 1979). We also audio-recorded a student focus group at the end of the unit to obtain students' reflections on the problem solving learning experiences with a sample of six student participants (See: Morgan 1988). The students in the post-unit focus group were selected to include both genders, and varied cultural backgrounds.

Artifact data included the construction and archiving of the unit plans, multimedia teaching resources, and print and digital writing tasks completed by the students. For example, students created web pages using iWeb software outlining the robotics steps used to solve the problems. All artifacts created by the students were collected to build up a complete primary record of the problem solving events (See: Emmison 2003).

The complete record of transcribed data was manually coded to identify key themes in the lesson and interview transcripts, and in the students' written artifacts. We systematically coded the transcribed speech of the teacher, researchers, and children for socialising patterns of problem solving language when interacting with robots as tools. Open coding was applied to identify the recurring patterns in the participants' use of speech across the sequence of lessons (See: Silverman 2001). The transcript excerpts reproduced in this paper were selected from the full record because they provided the most condensed illustration of the repeated patterns observed in the students' collaborative problem solving language across all six groups. Therefore, the frequency of occurrence of different children in the excerpts is incidental to the content of the conversation, while including responses from children from diverse cultural backgrounds. The findings were discussed with the teacher participant to strengthen the validity of the account (Altheide 1994).

Problem solving curriculum and learning experiences

In the world of robotics engineering, much progress has been made in ground robot navigation in order to overcome the challenges of negotiating harsh and diverse terrains, such as a desert biome or planet Mars (Lalonde et al. 2006). Simulating some of the design challenges encountered by scientists, the students in this study were given problems that involved programming Logo robots on wheels to move to a target destination, overcoming increasingly challenging obstacles and within increasingly complex rules (e.g. Lego people blocking the desired route, uneven surfaces, table-top precipice). The teacher and researchers developed a robotics unit that addressed cross-disciplinary learning outcomes in literacy and content knowledge in mathematics and science. The learning objectives were also matched to the Technology Essential Learnings expressed in the context of the relevant state syllabus (QSA 2007). Each unit was comprised of eight lessons of 1.5 hours. The context of learning was aligned with the school priorities. In each lesson, a robotics kit and a laptop were assigned to each group. Lego NXT kits (9797) were used, and the programming software interface was uploaded to Macintosh laptop computers.

The problems required prerequisite understandings, such as knowing that robots need to be programmed in order to act, and that programming and testing discrete movements is more strategic than testing a series of contingent moves. A final, complex challenge involved using everyday objects to rescue Lego figures from the base of a conduit pipe, while working within given limitations (e.g. no manual interference with the robot).

In the latest robotics engineering advancements, robots are increasingly playing a role in mine rescue and recovery operations because robots can survive conditions that are adverse to human life (Murphy et al. 2009). Following the Chilean mine disaster, which captured media attention around the world, a focus of the design challenges was a simulation of the Chilean mine rescue. The most difficult challenge involved a task environment in which a PVC downpipe (15 cm diameter) was taped to the side of a desk (See Figure 1.0). The students had to identify the materials they needed to rescue the LEGO miner who was trapped at the base of the PVC pipe (mine shaft). The students brainstormed a list of necessary resources that they would need to solve the problem, using string, cardboard, small pieces of material, and adhesives, such as sticky tape. In addition to building and programming a robot, students designed and produced a rescue carriage from basic materials.

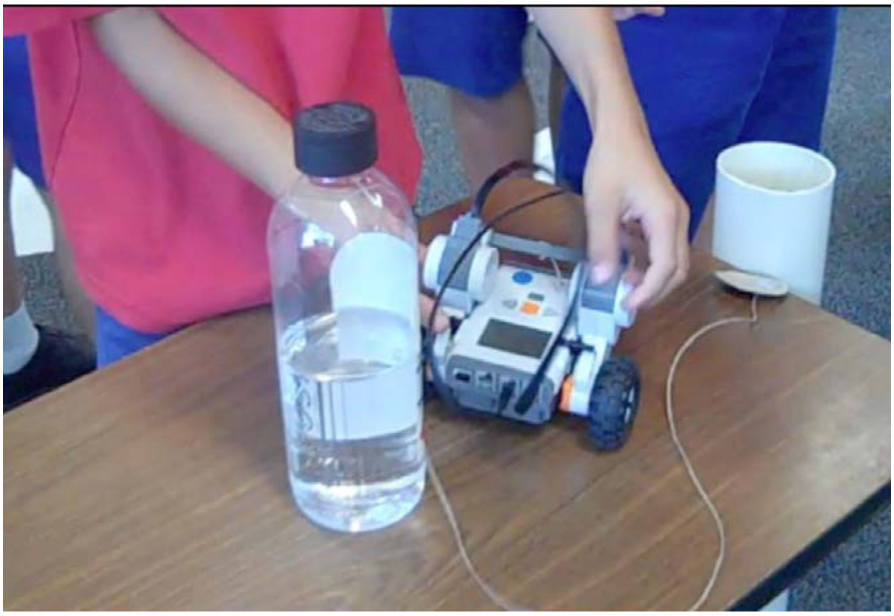

Figure 1.0 Chilean Mine Rescue

An adjoining room provided large amounts of indoor floor space to program and test their robots without noise interference from other groups. Students were allocated to groups of mixed gender, race, and ability by the teacher. The technology practice sequence – investigate, design, share and evaluate – was embedded in the lessons (Chandra 2010). The lesson sequence is indicated in Table 1.0 below.

New technical, mathematical, and science vocabulary and key concepts were introduced to students, including terms such as “rotations”, “power”, “speed”, “duration”, “direction”, “programming”, “icon” and “port”. Prior to each lesson, students were given a vocabulary list with examples of word usage, focusing on the key concepts to be introduced in the lesson. Understanding these concepts was important in terms of the students’ development of increasingly complex problem solving skills and language use. Reflection allowed learners to consider plans made prior to tasks, assess, and adjust as they work, and revise and relate the problems to authentic contexts (Ertmer and Newby 1996).

The presentation of each new problem-solving task included a designated time for groups to formulate a plan to solve the challenge. This planning of intended action was an activity, sometimes involving the use of digital technologies to document the planning. For example, students could choose to record their problem solution using a pencil and paper, or by word processing within Apple

Stages	Actions
Investigate	* Teacher screens a multimedia presentation on a real world relevant context or issue to the robotics design challenge (e.g. NASA podcast of the Mars Rover, Chilean Mine Rescue, Google's Driverless Car). * Inductive questioning for students to establish a shared understanding of the need for robots in society. * Present the aim and available resources to solve the design challenge. * A list of new technical vocabulary is provided and discussed with examples Of use
Create	* Groups brainstorm ideas to design a plan to tackle the challenge. * Groups enact the plan using the robots and other resources, adopting the plan as new information is gained in practice. * The teacher and researchers provide expert support to either the whole class or groups.
Share	* Groups share their intentions to solve the problem and demonstrate what their robots can do * Other groups share knowledge of solutions to groups who are encountering similar sub-problems to achieving the goal.
Reflect	* Students apply their new knowledge acquired from other groups to revision their solutions. * The reprogrammed robots are re-tested and re-evaluated. * All students reflect by writing in their handwritten or digital journals: What information was needed to solve the challenge? What intuitive thoughts did you have about the challenge? What ideas did not work and why? What bright ideas did you have? What alternative solutions might have worked? How did you manage your thinking? * Groups presented their final solution to the design challenge to the whole class. Final feedback sought from other groups and the teacher.

Table 1.0 Robotics Teaching and Learning Sequence

iWeb templates. In other lessons, they shared their intended solutions with other groups via a multimedia interview edited using Apple iMovie software. They took on roles as reporters, interviewees, and photographers to share their planned solution. The problem solving simulations and movies were presented to the school community at a school celebration of learning. The students were also required to spontaneously solve robotics challenges at the showcase event with their parents, teaching their parents how to program robots, and serving as the expert to induct family members into the learning community.

Findings

We observed that the use of language was central to both the children's ability to create new relations to the learning environment, and the mental organisation of their problem solving behaviour. The following transcript is one of many instances in which we observed how the children's speech shaped their problem solving activity into a structure. Two children are presenting a mock interview about their problem-solving task as a third student digitally records the interaction using a computer webcam (See Figure 2.0 and Transcript 1.0).

Figure 2.0 Children talking as they make an elevator to lift a Lego character.

Toby:	What is your plan to get the Chilean miner out of the shaft? [pretends to hold microphone]
Jao:	Ok. We are going to make an elevator out of cardboard and then we are going to get a robot with heavy string to tie it to the elevator and to the robot, and make the robot spin on one wheel to get the string to wrap around it [rotates hand]. Then it will get the miner out of the shaft.
Toby:	But how are you going to get the miner into the shaft?
Jao:	I will … (pause to think)
Toby:	How are you going to do that?
Jao:	[Cannot think of a solution. Photographer stops filming]

Transcript 1.0 – Verbally rehearsing a possible solution to the problem.

In this example, the children's speech was complemented by gestures, the spatial position of the speakers, and digitally mediated visual composition (e.g. photographer) to communicate their ideas to the class. The students used language in ways that allowed them to go beyond their prior experiences, since this was an original robotics problem. These children used language as the starting point of problem solving, creating new relations between language, tool, and intended action.

This problem solving structure later became elaborated and reshaped as the students began to action their plans – making cardboard elevators from cardboard or netting, attaching string of the correct length, and programming the robots within the precise limits of the operation (e.g. size of the desk, length of the pipe and string). Therefore, some of the complexities of the problem were unforseen at the stage of formulating a solution. This is evident, for example, in Jao's failure to generate a response to Toby's question about how he would get the Lego man into the elevator. This lapse indicates a breakdown in foresight, and a simultaneous interruption of the child's speech. Yet the children have a sufficiently developed capacity for language that enables them to overcome impulsive action, planning a solution prior to its execution, while accounting for the use of technical tools and auxiliary objects.

This is important, because the origin and development of speech, as well as other sign-using activity, such as gestures, is not independent of the organisation of the child's practical activity (Vygotsky 1978). Vygotsky argued that the internalisation of culturally produced sign systems brings about behavioural transformations and builds the bridge between early and later forms of individual development (Vygotsky 1978). We similarly observed that the externalisation of culturally produced signs – the use of communicative speech and action – was tied to the students' ability to engage with increasingly complex problem solving interactions.

When children were required to jointly solve problems, speech played a central role in structuring the task environment, and in interacting with others toward mutual goals. We could observe the use of public language, particularly the linguistic formulations themselves, and their adaptive role in collaborative problem solving (Clark 1998). In the following example, the two children cited above continued to discuss the problem of getting the Lego miner into the elevator carriage. In so doing, they recorded their interview again (See Transcript 2.0).

Toby:	This is the news. Well, Malachi Fitzgerald, what are you doing to do to get the Chilean miner out of the shaft?
Jao:	I am going to…We are going to make an elevator and some heavy string, and get a robot to turn around on one wheel to get the string wrapped around him, and we are going to… and that will bring him up. But we've got to figure out a way to get him into the elevator.
Toby	So Josh, how would you try to get the Lego miner into the elevator?
Jao:	I am going to wriggle him into the elevator and then we will shut the doors by an electric, by an electrical, no, we will get him into the elevator [manually] and then we will pull him up.

Transcript 2.0 – Reformulated rehearsal of possible solution to the problem.

The children's discussion of a plan indicates the independence of problem solving thinking from the structure of the material situation. The teacher structured the activity so that students had to commit to specific problem solving plans prior to enacting them or interacting with the tools. Through the use of speech, the students conceptualised possibilities for action, anticipating a sequence of preliminary acts to attain a shared objective. They included in their problem solving formulations tools that did not lie "within the immediate visual field" (Vygotsky 1978, p. 26). The formulation of the problem plan sometimes included a re-evaluation and reformulation of the planned pathway with further cognitive effort (e.g. "By an electrical, no, we will get him into the elevator"). Jao's reformulation occurred in response to recalling his discussion with Toby's after they stopped the camera at the end of the speech recounted in Transcript 1.0. Whether in direct response to others or simply to voice his thoughts aloud, speech was central to the organisation of the problem solving process.

During the subsequent whole-class discussion time for knowledge sharing, some of the groups verbalised multi-step pathways in anticipation of likely complications, such as the need to use a "guess-and-check" strategy (See Transcript 3.0).

Ethan	Um, we would um, program the robot to spin around a bottle and turn it, so it pulls up, and if it doesn't come up far enough [holds hand to show level], we're gonna program it to so far [indicates higher level with hands].
Teacher	I like how Ethan's group said that if it doesn't work, then they have another idea to try – well done!
Tristan	One idea was to make the robot go around [360º turns]. Hopefully, it comes up. If It doesn't come up, we'll make it go around the tower again.
Teacher	Ok. That's a good idea too. Tristan said that if he brings the robot up and goes around the tower once, and he still hasn't brought the miner high enough, his proposal – his hypothesis [slower and louder for emphasis] – is to go around the tower again. Why?
Rachel	It will make it come up …
Teacher	… higher.

Transcript 3.0 – Whole class sharing of possible problem solutions.

An important point of analysis is that the students used language to hypothesise about the cause and effect relationship between the rotations of the robot and the raising of the Lego figure in the elevator. Ethan predicted that it would be difficult to guess the precise number of turns of the robot required to raise the elevator to the desk height on the first attempt (Stanza 1). Ethan could anticipate, through the use of speech and gestures, the need to program and reprogram the number of turns of the robot through a process of trial-and-error. Here, the use of public speech functioned to externalise and organise a series of problem solving steps.

A second point is that the students' language was recapitulated and incrementally transformed though the teacher's speech. This was evident when the teacher elaborated Ethan's problem solving plan, demonstrating the use of scientific language, such as "hypothesis", to scaffold the students' thinking about the causal relationship between the rotations of the robot and height (Paragraph 4). The teacher inducted the children into the language of the scientific community, working within their "zone of proximal development", and introducing the term "hypothesis" with an everyday synonym – "proposal" (Paragraph 4) (Vygotsky 1978; Gauvain and Rogoff 1989). The teacher similarly drew on terms of measurement – "high enough", and the comparative term "higher" – to help the students understand the functioning of the robots as a pulley. In particular, she checked their understanding of the relationship between the robotic action of pivoting, and the subsequent raising of the elevator.

We observed that through this socialising process, students began to internalise and draw on these and other new vocabulary items in subsequent speech with one another. This was accompanied by short periods of direct instruction to introduce key terms and their meanings, such as "rotations", "power", and "duration".

We saw repeated evidence that the children applied new programming language in their verbal interactions with one another. As the children implemented their plan, the function of speech and the application of new vocabulary became connected to the immediate use of the tools (See Figure 3.0 and Transcript 4.0).

Figure 3.0 Programming Lego Mindstorms Robot

Jade	I pressed "delete". How many rotations?
Morris	Let's go 10 rotations.
Jade	Argh… so 10 rotations. Did we say 10 duration?
Morris	Change the power to about 10.
Jade	Ok, plug that in.
Morris	You've got to plug it into the USB port. Press download.
Jade	What?
Morris	Press download.
Jade	Where's download?
Morris	Right there. Here. [Point to icon on computer screen]. You didn't turn the robot on first.

Transcript 4.0 – Applying technical language to solve problems.

Here, we see that the students drew on new technical vocabulary and concepts in their problem solving speech, such as "delete", "rotations", "duration", "power" and "download". The students' problem solving functions include both internalised and externalised social relationships. As Vygotsky argues, "Their composition, genetic structure, and means of action is social" (Wertsch 1985, p.65). The children internalised the rules in accordance with the way in which external signs were used in the process of their problem solving dialogue. They frequently expressed their individual problem solving intentions to achieve their shared goal – the goal that binds the actions of the agents together.

An important point here is that the linguistic elements of their communication was not merely a medium of information transfer between the agents, but became a tool for structuring and controlling the problem solving action. For example, self-directed utterances of linguistic expressions such as "10 rotations" – internalisations –were drawn upon like tools or structures to guide subsequent problem solving behaviour, altering the computational problem space in a way that would be difficult to achieve in the absence of speech (Clark 1998). The use of speech had effects on the students' own behaviour, and the behaviour of others (Dennett 1991). In other words, the thinking was in the speaking – forming a "linguistically-mediated process of cultural storage" and refinement of thought and action (Clark 1998).

We also observed that the nature of collaborative learning is constituted in a situation in which neither participant is an authority or expert – the inter-subjectivity is generally symmetrical. The two peers work together to co-construct possible solutions to the series of problems, rather than requiring expert to novice transmission. A variety of studies have shown that the young children who learn most from peer interaction are not those who act in parallel or divide responsibilities, but those who share with their partners in the task and discuss the effects of their mutual activity (Behrend and Resnick 1989; Phelps and Damon 1989; Azmitia 1988). We see this here as the students engage in shared planning, responding to each other's ideas, and asking for clarification where necessary (e.g. "Did we say 10 duration?"). Collaboration involved more than orchestration of activity, but involved actively prompting the other to focus attention on aspects that might otherwise remain unnoticed. We see evidence of this when Morris corrects: "You didn't turn the robot on first".

Now we turn to examine the architecture of these co-constructed speech interactions that structured the enactment of the cooperative problem solving process. We observe the specific language formulations that enabled the students to focus, monitor, and control their problem solving behaviour (See Figure 4.0 and Transcript 5.0).

Figure 4.0 Testing the robot

Barbara	Is it running? [the program]
Ethan	I put it on 5 [Duration - The robot is hardly moving].
Barbara	Hang on, we need to plug this in. We've got to try something
Ethan	Hang on to the other end of the cord.
Barbara	Is it in? [Is the USB attached to robot to download the new program]
Ethan	Yeah.
Barbara	Ok. It's downloading.
Ethan	[Runs program] Barbara, it still doesn't work! [Robot is moving extremely slowly]

Barbara	Argh! [Reaches for robot] I'm going to stop this. Oh here, now try.
Ethan	Oh, we didn't have the wheels in!
Barbara	Yes we do.
Ethan	Are they plugged in properly?
Barbara	Wait, I just want to put… [voice trails off]
Ethan	Here you go. Got it?
Barbara	C'mon robot—hurry up! [The robot is still too slow]. Can you go get the teacher? [A third, observing student goes to get the teacher]
Teacher	Ghost Man's [name of robot] not running. Do you want to try putting it in one more time—just to make sure?
Barbara	We have done it already—4 times. I don't think we need to plug those in again.
Teacher	Have you tried undoing it?
Barbara	Must be because I broke a wheel.
Ethan	Yeah. Are you sure you've got the wheels in properly?

Transcript 5.0 – Patterns within problem solving language.

Here, and throughout the primary record of transcripts, we analysed the students' problem solving speech and identified four repeated functional categories of utterances. At the beginning of each newfound problem or obstacle, we observed that there was typically an utterance that provided a broad statement of the problem. The students frequently articulated the immediate problem at the start of their interaction with the tools. This is evident above when Barbara observes the almost stationary robot and questions, "Is it running?" (Line 1). This category of speech served to focus the group on a perceived starting point for the series of steps necessary to achieve a sub-goal or final goal. For example, they systematically eliminated possible causes of the program failure – checking whether the wheels were attached properly and the cord plugged in correctly, and reprogramming the robot. Restating the problem also occurred whenever an additional obstruction was identified in attempting to achieve the goal – "Barbara, it still doesn't work" (Line 9).

Second, we observed the frequent use of predictive questions. The students verbalised possible solutions as predictions, confirming these spontaneous hypotheses while interacting with the tools to eliminate unproductive paths. This occurs in the dialogue above when Ethan asks: "Are they plugged in properly?" (Line 13). It recurs when the teacher solicits: "Have you tried undoing it?" (Line 22), and is evident again when Ethan enquires: "Are you sure you've got the wheels in properly?" (Line 24). Predictive questions functioned to clarify the procedures and structure the verbal contributions and actions from the other agents. When the pursuit of several paths failed to yield a solution, students made appeals for help to the teacher as an expert (Line 16). The teacher then guided their problem solving (See Figure 5.0 and Transcript 6.0).

Teacher	Try programming it again.
Ethan	Ok, let's try [Changes power of robot in the program. Downloads new program].

Teacher	[Beep from robot]. Ok. Completed.
Ethan	Ok—we'll just test it here.
Barbara	It almost worked. Look at it! It's going slow. Oh! That's why!
Teacher	Oh—you made it too slow have you?
Barbara	Yeah—look at the power! Look—it's only at 5 %!
Ethan	Yeah. Conner [Third student] put it on 5 %
Barbara	Yeah—it's not fast enough—that's why it's not working!

Transcript 6.0 – Patterns in problem solving language.

Figure 5.0 Programming and Testing Robot

Demonstrated in this interaction is a third form of utterance used by students – directives, or statements that serve to directly influence the action of other agents. The use of directives structured the organisation of problem solving action in an effort to attain a shared goal. We see this in Ethan's statement "Ok. Let's try." (Line 2), and "Ok – we'll just test it here" (Line 4). These were often expressed using high modality evident in other recorded statements of students: "No, no, no – don't download!" and "Can someone get the [Lego] man out please!" The frequent use of directives and the associated influence on other's behaviour was a necessary part of the children's social learning and problem solving.

This language-mediated form of inter-agent action was central to the co-operative endeavour, at times transcending what the students could achieve through independent cognition. The use of directives created a series of juxtaposed actions between peers within the larger turn-taking sequence, creating an external mechanism or feedback loop to augment subsequent problem solving actions.

A fourth recurring utterance would typically coincide with the students' identification of a highly likely solution in the series of problems. Students would make a declaration that was clearly marked by increased emotion and emphasis. For example, this occurs in Barbara's dialogue above: "Yeah – look at the power! Look – it's only at 5%!" The exclamatory mood conveys an emotional response to the perceived discovery of a solution. This phase signals a climax in the problem solving process, which was typically followed by subsequent actions to confirm the prediction. In this way, a repeated pattern or architecture of speech was observed, which enabled the students to structure the organisation of negotiated problem solving. It is evident that the students' speech was central to the successful enactment of the solution to the immediate problem. Language not only accompanied the problem solving activity, but also played an important role in enacting it. The more complex the action demanded by the situation, and the less direct the solution, the greater the importance of language between the participants in the operation as a whole. We observed that more complex problems involved more extensive use of language, such as the scenario above in which the power setting of the robot had been modified without the students' knowledge. Multiple trial-and-error pathways were used to deduce the cause of the problem.

While the focus of this study addresses the patterns in the problem solving language of students engaged in collaborative robotics challenges, we triangulated our analysis of their recorded interactions with the teacher's observations. In the final post-lesson interview with the teacher reflected on the students' ability to use trial-and-error problem solving processes (See Transcript 7.0).

Researcher	What did you notice about the students' problem solving during the teaching of robotics?
Teacher	The children worked at different levels. There were some who relied on long sequences of trial and error. But there were others who could tell, ''Well, I programmed this sequence, so the robot did this. So now I need to go and change this.'' Towards the end, I think a lot more of the students were thinking that way. There were still the ones who were relying on a lot of trial and error, and who couldn't really work out why things went wrong. But there were…the students who embraced a different way of thinking about the problems.
Researcher	Given the nature of programming and testing the robots, I think trial and error is a key way of solving the problem, but you noticed that they were becoming more systematic about their trial and error.
Teacher	Yes—and there were some real world connections—the problems were connected to other real world events. Even the parents were quite observant of this element, ''Oh—the Chilean Miners!'' It's related to problems in the real world

Transcript 7.0 – Teacher reflections on the children's problem solving.

The teacher observed that the students worked at varying levels of proficiency when solving problems by repeatedly reprogramming and testing their robots. Over time, she observed that a greater proportion of the class were solving the robotics challenges more quickly and efficiently, demonstrated by making more accurate predictions about how the robot would move in response to the programming sequences (Lines 3-9). The students were able to "embrace a different way of thinking about the problems" (Line 9), and these problems were connected to issues of relevance in the world beyond the classroom. The variability in children's thinking has been demonstrated in research to exist at multiple levels, not just between children at different ages or the same age, but within an individual solving a set of related problems, the same problem twice, and even a single problem. This is referred to as "changing distributions of ways of thinking", to be distinguished from sudden shift or discontinuous movement from one way of thinking about problems to another (Siegler, 1994).

Student focus groups conducted at the end of the full lesson sequence confirmed the teachers' observations of variability in the students' thinking, and providing specific insights into the students' self-reflections on their collaborative problem-solving processes (See Transcript 8.0).

Researcher	Did you get quicker at solving problems?
Morris	Ella and me, when we first started we didn't know how to program the robot. And then when we had problems, we knew how to do it real fast.
Jade	At first, we didn't even know how to build robots, but when we came to the third problem we were quicker compared to when we first started.
Barbara	When we were testing to see if the miner could be rescued and we had the problem, my group with Ethan and Connor, we couldn't do it at first: but when we kept on trying, we got together and we thought of the idea of how we were going to save it, and then we tried it—and it…worked

Transcript 8.0 – Student focus group reflections on collaborative aspects of problem solving.

Here, the students report that they had no prior knowledge of how to program or build a robot (Lines 2-4). Once they became familiar with the type of robotics problems presented, they continued to improve their speed or rate of problem solving: "We knew how to do it real fast!" and "…when we came to the third problem, we were quicker compared to when we first started". The children explicitly acknowledged the collaborative nature of problem solving by naming their peers, further indicated by the consistent use of the personal and plural pronoun "we" (16 occurrences). Barbara's statement particularly emphasises these social processes: "…we got together and we thought of the idea of how we were going to save it" (Line 8). Through a process of enculturation in collaborative problem solving activity over several weeks, the students began to develop the means to discuss, reflect on, and validate collaborative procedures within a community of learners (Brown, Collins, and Duguid, 1989).

Discussion: Vygotsky's Inner Speech Extended to Understanding External Speech

These findings elaborate the specific ways in which young children describe and analyse a problem situation, which gradually leads to a more detailed plan articulating possible paths to the solution of the problem. An important feature of this linguistic pattern is that children not only verbalised what they were doing, but their speech and action formed part of a "complex psychological function, directed toward the solution of the problem at hand" (Vygotsky 1978, p.25).

These examples confirm and elaborate on the process that was observed in Vygotsky's experiments when four and five-year old children were obtaining pieces of candy from a cupboard. The candy was placed out of reach so the children could not obtain it directly. As the children got more involved in trying to reach the sweets, egocentric speech began to manifest itself as part of the active striving. The speech initially began as description and analysis of the situation, but gradually took on a "planful" character, reflecting possible paths to the solution of the problem (Vygotsky 1978, p. 25). Here we have elaborated the specific architecture of language-mediated problem solving in collaborative and formal contexts of learning. This begins with phases of interaction for each goal or sub-goal that typically begins with a statement or restatement of the problem, followed by the use of predictive questions and directive statements, and culminates in an emotive utterance of greater intensity upon realisation of a likely solution.

A key difference between these experiments and Vygotsky's work with young children is that his subjects were not working with age-level peers, but individually, and with the experimenter. Hence, Vygotksy (1978, 1981) gave attention to egocentric speech, which he regarded as the transitional form between external and inner speech. In the external form, he considered speech embedded in communicative speech. In contrast, our participants were observed in the context of regular classroom activity, where the social context called for communicative speech between members of the collaborative groups. In our work with cooperative robotics tasks and challenges, we observed that the relative amount of external speech among the learners increased when confronted with more complex robotics problems. The transcripts above were extracted from a much longer dialogue between the two students, whose bodies, speech, and hands were directed at solving the problem for a highly concentrated period of time.

Vygotsky (1978, p. 27) argued that the "history of the process of the internationalisation of social speech" is the "history of the socialisation" of children's "practical intellect". Similarly, there is evidence in our study that the externalisation of social speech situated in classroom settings also plays an important role in the socialisation of the school-age child's practical intellect. The children would turn to one another to solve the problem until they had exhausted multiple perceived paths to a solution, before approaching adult experts. The observed problem solving language took on an interpersonal function in the social context of the classroom, complementing the intrapersonal function of speech observed by Vygotsky.

Conclusion

There is a growing consensus in educational research that social and cultural dimensions of learning cannot be ignored (Tomasello et al. 1993). However, less is known about the language structures that mediate collaborative learning in problem solving contexts. We have demonstrated, in the context of collaborative robotics problem solving in a school, that language and the use of tools play a dynamic and interactive role in the learning process. We have demonstrated key patterns and principles of public language, extending Vygotskian principles to pedagogical situations in which children work together to plan and implement goal-directed solutions to practical engineering and applied mathematical problems.

When the children were confronted with new and challenging problems, they exhibited a range of responses to attain the goal, drawing on sophisticated technology tools and speech directed toward other persons to mediate their practical activity. In particular, we have identified the functional patterns in the children's language, which typically began with an initial statement of the problem or sub-problem. Children use clarifying questions and directive statements to focus their peers' attention on certain solutions. Newfound solutions to a problem or sub-problem were clearly signified by an emotive exclamatory utterance – an "aha" moment –when the problem-solvers gained new insights potentially leading to a solution.

The role of language is critical to the collaborative problem solving behaviour of young children. In particular, the use of speech, gestures, and tools produces new relations with the problem-solving environment, providing a window into the students' mental organisation of behaviour. As Vygotsky (1962) argues, speech "does not merely accompany the child's activity; it serves a mental orientation, conscious understanding…intimately and usefully connected to the child's thinking" (p.228). These observations of children's language patterns in collaborative problem solving have implications for guiding social and cultural learning processes in the STEM disciplines – science, technology, mathematics, and engineering. The transformation of culture and the capacity for its acquisition is a major theme of research within the paradigm of social cognition (Bruner 1990; Cole and Gallego 2000; Wertsch 1981). Apprehending the role and architecture of language in collaborative learning, as well as understanding the child's capacity for its application, is central to social cognition and cultural learning.

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