Canadian Journal of Science, Mathematics and Technology Education

ISSN: 1492-6156 (Print) 1942-4051 (Online) Journal homepage: https://www.tandfonline.com/loi/ucjs20

Multidisciplinary Perspectives on a Video Case of Children Designing and Coding for Robotics

Krista Francis, Cathy Bruce, Brent Davis, Michelle Drefs, David Hallowell, Zachary Hawes, Lynn McGarvey, Joan Moss, Joanne Mulligan, Yukari Okamoto, Nathalie Sinclair, Walter Whiteley & Geoff Woolcott

To cite this article: Krista Francis, Cathy Bruce, Brent Davis, Michelle Drefs, David Hallowell, Zachary Hawes, Lynn McGarvey, Joan Moss, Joanne Mulligan, Yukari Okamoto, Nathalie Sinclair, Walter Whiteley & Geoff Woolcott (2017) Multidisciplinary Perspectives on a Video Case of Children Designing and Coding for Robotics, Canadian Journal of Science, Mathematics and Technology Education, 17:3, 165-178, DOI: 10.1080/14926156.2017.1297510

To link to this article: https://doi.org/10.1080/14926156.2017.1297510

CANADIAN JOURNAL OF SCIENCE, MATHEMATICS AND TECHNOLOGY EDUCATION
2017, VOL. 17, NO. 3, 165–178
http://dx.doi.org/10.1080/14926156.2017.1297510

Routledge
Taylor & Francis Group

OPEN ACCESS

Multidisciplinary Perspectives on a Video Case of Children Designing and Coding for Robotics

Krista Francis[a], Cathy Bruce[b], Brent Davis[a], Michelle Drefs[a], David Hallowell[c], Zachary Hawes[d], Lynn McGarvey[e], Joan Moss[d], Joanne Mulligan[f], Yukari Okamoto[c], Nathalie Sinclair[g], Walter Whiteley[h], and Geoff Woolcott[i]

[a]Werklund School of Education, University of Calgary, Calgary, Alberta, Canada; [b]School of Education and Professional Learning, Trent University, Peterborough, Ontario, Canada; [c]Gevirtz Graduate School of Education, University of California, Santa Barbara, California; [d]Ontario Institute for Studies in Education, University of Toronto, Toronto, Ontario, Canada; [e]Faculty of Education, University of Alberta, Edmonton, Alberta, Canada; [f]School of Education, Macquarie University, Sydney, Australia; [g]Faculty of Education, Simon Fraser University, Vancouver, British Columbia, Canada; [h]Mathematics & Statistics, York University, Toronto, Ontario, Canada; [i]School of Education, Southern Cross University, Lismore, Australia

ABSTRACT

Spatial reasoning plays a vital role in choice of and success in science, technology, engineering, and mathematics (STEM) careers, yet the topic is scarce in grade school curricula. We conjecture that this absence may be due to limited knowledge of how spatial reasoning is discussed and engaged across STEM professions. This study aimed to address that gap by asking 19 professionals to comment on a video that documented children's progression through 5 days of building and programming robots. Their written opinions on the skills relevant to their careers demonstrated by the children revealed that spatial thinking and design thinking are central to what they see.

RÉSUMÉ

Le raisonnement spatial joue un rôle essentiel dans la décision d'entreprendre une carrière STEM et de réussir dans les domaines concernés. Pourtant, ces matières sont peu représentées dans les curriculums à l'école primaire. Nous supposons que cette absence puisse être due à un manque de connaissances quant à la façon dont le raisonnement spatial est traité dans l'ensemble des professions STEM. Cette étude vise à combler ce manque en demandant à 19 professionnels de commenter une vidéo qui documente la progression d'enfants qui construisent et programment des robots pendant 5 jours. Les commentaires écrits des répondants sur les habiletés pertinentes illustrées par les élèves montrent que la pensée spatiale et la pensée conceptuelle sont fondamentales dans leur profession.

Spatial reasoning is of vital importance in today's world, especially in careers associated with sciences, technology, engineering, and mathematics (i.e., the STEM disciplines). This realization has particular relevance to educators, with mounting evidence that spatial reasoning competencies are correlated with achievement (Casey, Dearing, Vasilyeva, Ganley, & Tine, 2011; Wai, Lubinski, & Benbow, 2009) and are malleable (Sorby, 2009; Uttal et al., 2013) and that learning experiences in the early years are of extreme importance (Bruce & Hawes, 2015; Hawes, Tepylo, & Moss, 2015).

CONTACT Krista Francis kfrancis@ucalgary.ca Werklund School of Education, University of Calgary, 2500 University Drive NW, Calgary, AB T2N 1N4, Canada.

There is a growing recognition of the roles of spatial reasoning in early years and in STEM professions, alongside acknowledgment of its central place in learning and cognition (e.g., see the Spatial Intelligence and Learning Center [SILC] program at http://spatiallearning.org/index.php/research-and-other-links-of-interest and the Research in Spatial Cognition [RISC] lab at http://sites.temple.edu/risc/). However, the topic has a scarcely discernible presence in grade-school curricula (Davis, Okamoto, & Whiteley, 2015), and our suspicion is that the lack may be in part due to limited knowledge of how spatial reasoning is discussed and engaged across STEM professions. The purpose of the research reported here was thus to expand educators' understandings of the role of spatial reasoning across a range of STEM careers. Following the example of Hoyles and Noss (2002), our strategy was to survey working professionals using one focus point: a video of children coding and building robots.

The research was further motivated by the coinvestigators' previous research that conducted searches of academic literatures for terms associated with spatial reasoning (e.g., *visualization, spatial awareness*) in order to identify related interests, diverse foci, spread, and directional influences (Bruce et al., 2016). We analyzed the current research databases to conduct a complex network analysis (e.g., Newman, Barabási, & Watts, 2006) of research across domains (education, psychology, mathematics, neuroscience, medicine, and engineering). In particular, methods of citation analysis (Fu, Song, & Chiu, 2014) were used to represent a social network around the concept of spatial reasoning. Our network analysis work revealed a relative lack of connectivity between research in education and research in other disciplines that make extensive use of spatial reasoning. In each of the domains examined, the vast majority of citations on the topic were to writings in the same domain. The resulting silo effect, we suspect, further inhibits the cross-pollination of ideas.

We wondered whether the same siloing and lack of connectivity arise among careers. How do professionals talk about spatial reasoning? Do professionals recognize spatial reasoning? We also wondered whether our own research-based interpretations and relative emphases were consistent with professionals' understandings, uses, and emphases. A more thorough understanding of the interpretations and applications of spatial reasoning across professions is essential to an integrated and more powerful approach to school curricula and teaching methods. In an age of increasing integration and transdisciplinarity, we sought input from professionals and researchers in domains outside of education to gain insights into perceptions of spatial reasoning that (a) transcend disciplinary silos and (b) offer insights into how spatial reasoning supports 21st-century learning practices and curricula.

Method

We had previously studied children's (aged 9–10 years) engagement in spatial reasoning as they built and programmed robots (see Francis, Khan, & Davis, 2016; Khan, Francis, & Davis, 2015). Robotics is an integrated spatially demanding STEM task that has been shown to foster deeper static and dynamic understandings of geometric shapes (Bussi & Baccaglini-Frank, 2015) and contributes to children's learning about constructing, debugging, and explaining "a robot's behavior in terms of abstract rules … and using rules to construct the robot's behavior" (Mioduser & Levy, 2010, p. 100). From the previous study (Francis et al., 2016), we compiled a video[1] that documented children's progression through 5 days of building robots. We selected an excerpt that could be easily clipped and viewed by participants and that showed students collaborating to design a robot to remove infected trees while leaving healthy trees and vegetation from a represented forest. For the first 2 days the children worked individually to gain skills and experiences building and programming the robots. On the third day, children were placed in teams of three for the grand challenge. Each team was given a uniquely colored T-shirt. Table 1 is a brief description of the video.

Informed by Wai, Lubinski, and Benbow's (2009) longitudinal study of the relationship between the spatial reasoning abilities and career outcomes, we identified career categories that are associated with a range of spatial abilities. We then looked across our respective social networks to populate these categories and sent out personal invitations to watch the video and reply to three questions: (a) What skills are the students using? (b) What kinds of reasoning are the students doing? (c) How might this

Table 1. Brief description of the video.

Days 1 and 2: Children individually built the basic robot from the Lego manual in the Lego Mindstorms EV3 education kits. Then they learned how to program the robot to move and interact with the environment using the touch and light sensors.	
Scene 1	Logan building Lego from a plan (26 s)
Scene 2	Jeffrey building Lego from a plan (24 s)
Days 3 and 4: Children worked in teams of three to complete a challenge to remove the red trees without disturbing the green trees, vegetation, and people.	
Scene 3:	Jeffrey building a Lego robot from a .pdf file on the computer screen (12 s)
Scene 4:	Gray team building a Lego robot from a .pdf file on the computer screen (34 s)
Scene 5:	Orange team debugging their program (29 s)
Scene 6:	Dark Gray team debugging their program (18 s)
Day 5: Challenge competition.	
Scene 7:	Gray team removes a red tree (20 s)
Scene 8:	Orange team removes a red tree (17 s)

contribute to the skill set of your profession or discipline? Importantly, we were careful to avoid "priming" research participants by using vocabulary related to spatial reasoning.

From those invitations, 19 individuals responded. The researchers and professionals were from the following fields: computer science (2), business (3), medicine (3), artist (2), dentistry (2), geography (1), biology (1), chemistry (1), engineering (1), mathematics (1), and architecture (2). Their e-mails formed the corpus of data.

The text-based e-mail data were loaded into nVivo (QSR International, 2016) for analysis. Following established protocols in grounded theory (Charmaz, 2014; Strauss & Corbin, 1998), analysis consisted of open and axial coding, using the unit of an utterance—a full thought (Rowe, 2004). First, in an iterative process of reading and chunking text, 76 nodes (open codes) were developed. When a new code was established, previously coded text was revisited to ensure inclusion of all instances of each code; that is, the data were coded to saturation.

Frequently, utterances were intertwined with other codes. As such, utterances could have more than one code. Author 1 frequently conferred with Author 2 whenever questions about utterances or nodes arose. We next searched for patterns and clusters, narrowing from the 76 nodes to 67 that centered on STEM experiences. The 67 STEM specific nodes were confirmed using nVivo's queries and through a sequence of distillations identified four driving themes (upper level nodes): spatial thinking, design thinking, logical thinking, and applications.

Findings

Table 2 displays the number of utterances by theme.

Spatial thinking

All 19 participants mentioned aspects of spatial reasoning, with a total of 158 utterances on the topics. From the participants' responses to the video segment of children working on a robotics task, we identified seven key aspects of spatial thinking that were invoked: 2D–3D oscillations, [de]constructing, visualization, making comparisons, 3D reasoning, spatial reasoning, and other. Less articulated aspects (other) included identifying, mapping, relationships among objects, fine motor skills, locating, sensing, shape and pattern recognitions, translation, copying, rotation, and scaling.

2D–3D oscillations

Participants

There were 38 utterances by 12 participants that focused on 2D–3D reasoning where there is a back-and-forth type of thinking between two dimensions and three dimensions. For example, the financial analyst responded to question 2, "What kinds of reasoning are the students doing?" by saying:

Table 2. The number of utterances by theme.

	Number of utterances
Spatial thinking	
2D to 3D	38
[De]Constructing	23
Visualization	18
Comparing	14
3D reasoning	9
Spatial reasoning	9
Other (6 or less each): identifying (6), mapping (6), relationships among objects (6), fine motor skills (4), locating (4), sensing (4), shape and pattern recognition (4), translation (4), copying (3), rotation (3), scaling (3)	47
Total	158
Design thinking	
Engaging in the design process	57
Problem solving	35
Collaborating	28
Computer programming and coding	19
Communicating	11
Creating	4
Total	154
Symbol-based thinking	
Reading	14
Logical thinking	10
Following instructions	8
Other (6 or less): observation (6), time (4), making sense of data (3), measurement (3), drawing (2), computer use (1), numeracy (1), scientific method (1)	21
Total	53
Application	
simulations (5), 3D printing (1), business trends (1), cartography (1), chemistry (1), computational biology (1), financial engineering (1), geographic information systems (1), logic (1), mathematics (1), sculpting (1), surgery (1)	
Total	17
Other (not included in tertiary analysis)	
Attitudes	8
Affect	7
Not applicable	18
Total	33

> The main reasoning I saw was projecting a target representation of 2D data into 3D and evaluating the object in terms of its inherent functionality and how closely congruent it is to the 2D representation (via shape and color). … The data in the instructions is encoded in "2D" (the page) so there is a mapping of the data onto the 3D referent (the Lego piece).

When we asked participants to describe how the activity of the students might "contribute to the skill set of your profession or discipline," a medical doctor responded:

> Of note, one of my current areas of interest falls under the rubric of "computational biology." This is a discipline that looks at serial sections of a body part or part of an embryo as 2D images, reconstructs them in 3D, and then develops software language that, in simulation, recreates the embryologic development of that organ. Additionally, on a daily basis, being able to imagine forms in 3D without being able to fully see the form is an essential skill all good surgeons must possess.

Interestingly, a visual artist made a similar connection to his work:

> The ability to observe, or visualize 2D images and transform into 3D is how I work. Sketches in a sketch book become 3D objects. The visualization of the finished work and the construction process are all part of the deal, and then the reconsideration of it, from a functional perspective, is all part of making a 2D drawing actually stand up!

Similarly, an architect noted the importance of mentally manipulating plans so that they could be imagined as 3D structures in their work:

> The model building exercise—moving from either 3D printed images or 2D plans would also mirror our need to constantly translate between 2D and 3D.

Interpretation

The video shows children seeking/finding/assembling each Lego piece with its corresponding illustration in the instruction booklet. Understanding the two-dimensional representations of three-dimensional objects requires recognition and interpretations of conventions used for depiction (e.g., shape, light and shadows, lines for edges, scale, size and orientation; see Francis & Whiteley, 2015). Essentially, participants interpreted that the children in the video were engaged in 2D-to-3D-to-2D thinking and that this skill has use in their own fields.

[De]Construction

Participants

There were 23 utterances of constructing/deconstructing by 10 participants. Participants readily identified constructing and deconstructing activities in the robotics video segment. As a general statement, a computer scientist stated that "spatial reasoning is about how 3D shapes fit together (or not)." A dentist elaborated on this generalization by stating that the students were engaged in the "reconstruction of a whole system from individual components and 'real world' evaluation from a functional (and esthetic) set of criteria." And with even greater detail, a geographer described the skills the children were using as, "break[ing] objects into constitutive parts, perspective taking, creating, comparing."

Participants made reference to comparing as something the children were doing both directly, such as comparing 2D designs to 3D figures, and indirectly such as comparing function, form, and instructions. Such utterances received multiple codes. A financial analyst referred to specific children in the video segment:

> Jonathan seems to approach the build referring mainly to the actual object itself, making sure the functionality and fit is appropriate. He then confirms the shape on the laptop screen. The gray team is using a sort of combination of what we saw with Liam and Jonathan, referencing the actual piece itself (function of the object) and the instructions on screen. Since there is vocalization, we also observe that they are using the data about the color to map between the instructions and the object.

He also simply explained that the children were using "comparative reasoning as they compare the 3D construct with the 2D instructions." (Note: This utterance could have been represented in another category.)

Interpretation

Constructing and composing as well as deconstructing and decomposing are essential spatial reasoning skills used by children and by adults throughout life (Clements, 2004). When we compose a 2D figure, for example, we can combine a range of irregular or regular shapes to make the larger figure, such as two congruent right-angled triangles combined to make a rectangle. Construction plays an important role in robotics design tasks when children build 3D models and test their function. Not only are they constructing in physical space but they are also stringing ideas (written as code) together to program movement.

Visualization

Participants

In this study, there were 18 utterances by 11 participants coded as "visualization," where they used the exact term or not. For example, one engineer stated, "Not sure what it's called but the ability to take a figure and move it around in your mind."

Providing more detail, a computer scientist responded by saying that we need to analyze and understand image data of various kinds. Much of this analysis involves understanding spatial relationships among various components at multiple levels of scale and abstraction; for example, image pixels, regions, shapes, objects, motion, volumes, etc. Even beyond 2D and 3D elements, there is a need to visualize information in very high-dimensional spaces and reason about distances, subspaces, and other aspects of these spaces.

The geographer observed that the task requires children to "align objects with diagrams, which includes the ability to visualize objects in space." A medical doctor participant explained that this type of visualization is important "on a daily basis, being able to imagine forms in 3D without being able to fully see the form is an essential skill all good surgeons must possess."

Interpretation

Visualization has had a long history of interest by researchers in psychology, mathematics, engineering, and other disciplines (e.g., Bishop, 1988; Piaget & Inhelder, 1971). It involves "constructing and transforming both visual mental imagery and all of the inscriptions of a spatial nature that may be implicated in doing mathematics" (Presmeg, 2006, p. 206). More generally, visualization is the use of any technique to create images (still or moving) or designs (either mentally or physically) that convey information (to self or other).

Comparing

Participants

There were 14 utterances by four participants about comparing. Participants interpreted that the children used comparisons for finding and evaluating whether they had the right piece (or not) for building. When asked, "What kinds of reasoning are the students doing?" the geographer stated, "Reasoning includes comparative and criteria reasoning (comparing model to diagram); deductive reasoning (i.e., separating model into parts) and spatial reasoning, of course." The financial analyst stated:

> There is also a simple evaluation of the length and shape of the first piece he grabs from his tool kit (I assume the representation of that particular piece is to scale) requiring him to understand appropriate real world measurements. … Jonathan seems to approach the build referring mainly to the actual object itself, making sure the functionality and fit is appropriate. He then confirms the shape on the laptop screen. Gray team is using a sort of combination of what we saw with Liam and Jonathan, referencing the actual piece itself (function of the object) and the instructions on screen. Since there is vocalization, we also observe that they are using the data about the color to map between the instructions and the object.

Interpretation

The comparative reasoning that the participants articulated was closely tied with 2D–3D reasoning. Participants noticed that the children were comparing between the images in the instruction manual and the actual physical Lego piece. Aspects of spatial thinking are closely related and intertwined in the robotics tasks.

3D reasoning

Participants

There were 9 utterances by four participants about 3D reasoning. The utterance were mostly about building 3D objects and navigating in 3D space. A dentist stated, "Completion of complex, functional, 3D objects from simple, standardized components." Likewise a computer scientist stated, "Spatial reasoning about how 3D shapes may fit together (or not). … Similarly, virtual reality almost entirely relies on a user's intuitive understanding of spatial concepts, especially in navigating through a 3D virtual space."

Interpretation

These utterances allude to how we live in a 3D world. Children learn spatial reasoning from their 3D experiences. Building and navigating are aspects of how we experience and learn 3D spatial reasoning.

Spatial reasoning

Participants

The specific naming of spatial reasoning as such occurred on nine occasions by six participants. For example, the mathematician said, “For building, some spatial reasoning is needed … the spatial reasoning and connecting that to numeracy is very meaningful.” The engineer described, “Spatial reasoning/awareness: interpreting a plan and manipulating pieces to match the plan.”

Interpretation

With only nine utterances, the term spatial reasoning is likely not a term at the forefront of many professionals’ vocabulary. There were, however, 149 references to spatial reasoning without using the term spatial reasoning. We found this interesting because although many participants did not name spatial reasoning, the commonalities across disciplines wer striking.

Other spatial thinking

Forty-seven utterances of other aspects of spatial reasoning were noted by participants of the study, but each of these additional skills were noted far less frequently. They included identifying (6), mapping (6), relationships among objects (6), fine motor skills (4), locating (4), sensing (4), shape and pattern recognition (4), translation (4), copying (3), rotation (3), and scaling (3).

Summary

Spatial reasoning involves making sense of space, objects, the body, and movement in the mind and in the physical world. As Cohen and Hegarty (2012) explain, spatial reasoning is the ability to create and manipulate mental representations of actual and imagined shapes, objects, and structures. There are many aspects to spatial reasoning identified by the Spatial Reasoning Study Group, including visualizing, diagramming, locating, navigating and way-finding, manipulating and imagining objects moving in space, perspective taking, composing and decomposing, and constructing and deconstructing (see Davis et al., 2015; Spatial Reasoning Study Group, n.d.). The participants’ noticing and interpretation was surprisingly consistent with the above definitions.

Design thinking

The 154 utterances by participants about design thinking included references to engaging in the design process (57), problem solving (35), collaborating (28), computer programming and coding (19), communicating (11), and creating (4). Like spatial thinking, all 19 participants mentioned aspects of design thinking.

Design process

Participants

There were 57 utterances by 15 participants about the design process. In response to “How might this contribute to the skill set of your profession or discipline?” an entrepreneurial software developer noticed several similarities to what the children were doing and to his field of work. The commonalities included experimentation, trial and error, trying again to achieve a common goal or to improve performance, teamwork, and negotiation:

> As a small-business owner, our team is constantly looking to identify trends and buying patterns to align our company with market demands. This means trial and error is a constant. We’re constantly experimenting with products and price, recording results and then trying again, always working toward a common goal. In this short video, the students have identified the objective and follow instructions to build a robot that will complete the objective. However, the robot’s ability to perform is based on the students’ time and effort during the testing of their robot.

> In business development, whether building a product, negotiating a deal, or working as a team to improve performance, the skills and reasoning used during this video are extremely important.

Though most participants found the children's design thinking relevant to their fields, two did not find the children's processes in the video relevant at all. The orthodontist stated that "trial and error is not advised as a strategy" for his profession.

Problem solving

Participants

There were 35 utterances by 14 participants about problem solving. Problem solving is often mentioned within utterances of the design processes. Likewise, Daniel, a financial analyst, interpreted elements of design thinking (test, assess, debugging, troubleshooting, revising, and retesting) as relevant to his profession. He perceived that the skills he observed the children using could transfer easily to financial engineering:

> Within quantitative finance, a substantial amount of debugging and troubleshooting is needed and often times elegant solutions that take a long time to find are not as useful as running through whatever study or program we are writing to see if there are any issues and fixing it "on the fly." The constant "test–assess/evaluate–correct–retest" loop is essential for any application of engineering, including financial engineering. Even though the exercise was in robotics, the skill sets transfer readily. Also, simply articulating a problem statement well is essential before solving any problem and often, if done well, this alone will help find a solution.

Interpretation

There are multiple definitions of the design processes, but most include cycles of iterative planning, prototyping, testing, and revising (e.g., see National Aeronautics and Space Administration, 2014). Razzouk and Shute (2012) defined design thinking as "an analytic and creative process that engages a person in opportunities to experiment, create and prototype models, gather feedback, and redesign" (p. 330). Engaging in design processes is not about adherence to a rigid and sequential, step-by-step predetermined plan.

Collaborating

Participants

There were 28 utterances by 13 participants about collaborating and teamwork. Like the software developer's observations above about children learning to work on a team, one of the architects noted that teamwork and cooperation "is fundamental. Learning to work together to both lead and be led, is extremely important." The biologist noted that "the groups are also building their teamwork skills. … Teamwork skills are always essential … for the majority of professions."

Interpretation

Collaboration and teamwork is a key component of 21st-century learning and design thinking. Engineering educators refer to collaborative skills as *soft skills*. Such skills are viewed as necessary for success in industry, yet are not often not taught in undergraduate engineering education (e.g., see Berglund & Heintz, 2014). The participants noted the importance of these skills with terms like *fundamental* and *extremely important*.

Computer programming

There were 19 utterances by nine participants about computer programing. For example, the businessperson noticed "the orange team is systematically approaching debugging" in reference to computer programming. A mathematician noted:

> One also needs to be able to think about how the robot will move about the board picking up trees and will need to know how to properly input the commands to make the robot move appropriately. … They need to have an end product (the actions of the robot) in mind as they are working.

The engineer noted the intensity of computer programming: “The programming aspect is a very strong skill (not sure exactly what was involved for this exercise but it looked quite intense).”

Interpretation

Many of the utterances included computer programming as part of the design task. Their inclusion guided our analysis to include computer programming in the broader theme of design thinking because it was an integral component of the task.

Summary

When developing themes from the analysis, we initially considered the theme of “21st-century learning skills.” This phrase rose to prominence near the end of the last century, used to reflect the transition from an industry-based society to an information- and technology-rich knowledge-based society. Broadly, 21st-century skills include critical thinking, problem solving, digital literacy, communication, collaboration, and creativity (see Abbot, 2014).

However, a noticeable absence in such lists, along with most definitions and descriptions of 21st-century learning, is *design thinking*, which moves beyond acquisition of yet another skill set into fostering the development of a process-focused mindset. Design thinking requires a flexible, emergent, and creative approach to solving a problem. As such, design thinking is more about a process of being open to possibilities than strictly focusing on a predetermined outcome. Through iterative cycles of conceptualization and rigorous testing, “the product” becomes more and more viable, feasible, and functional.

Symbol-based thinking

There were 53 utterances about symbol-based thinking, including key aspects of reading (14), logical thinking (10), and following instructions (8). Other less mentioned aspects included observation (6), time (4), making sense of data (3), measurement (3), drawing (2), computer use (1), numeracy (1), and scientific method (1).

Reading

Participants

There were 14 utterances by seven participants about reading. Being able to reading symbols and syntax was interpreted as skill for application. A mathematician noted that “one needs to understand the syntax and be able to use it properly.” Similarly, reading was closely associated with following instructions. For instance, a financial analyst stated, “This simple ‘reading of instructions’ is similar to mapping between two categories in mathematics so that the interrelationships on the page between distinct objects can be translated to the Legos.”

Interpretation

Reading has long been first among schooling’s entrenched basics of readin’, ‘ritin’, and ‘rithmetic. Design thinking is not about diminishing that status, nor about replacing basic skills, but about encompassing and applying such skills into broader learning processes such as modelling, designing, innovating, and inquiring.

Logical thinking

Participants

There were 10 utterances by nine participants about logical thinking. Logic and conditional reasoning were perceived by the medical doctor as skills that helped a person "rationally work through data, make sense of things, and come to a defensible/testable conclusion or with computer programming." More frequently, logic was perceived as useful for computer programming. As a mathematician noted,

> For programming, they need to have a good sense of logical flow of information. They need to understand logical forms like "if–then" and "while." … Understanding logic and sequential flow of commands is really important.

Likewise, a businessperson stated, "The programming aspects almost definitely requires some conditional reasoning, in order to get the robot to behave in the correct manner (i.e., the orange team debugging the robot)."

Interpretation

The participants noticed the integration of logical thinking and computer programming. As Steve Jobs (*Steve Jobs Says Everyone Should Learn to Program*, 2012) claimed, "I think everybody in this country should learn how to program a computer because it teaches you how to think." Programming technologies like the Lego Mindstorms^{TM} that the children used provide unique opportunities for learning logical thinking (and more).

Career and function applications

The final theme arose from our third question posed to participants that asked how the children's skills and actions in the video might contribute to the skill set of their profession or discipline. Participants yielded 17 utterances of professional applications. A geographer found that "the skills the students are using are highly germane for cartography, as well as for geographical information systems in general." The visual artist exclaimed that the applications were "HUGE—it's what I do all the time." A chemist described how her spatial skills in organic chemistry improved with help from her brother:

> When I was enrolling in one of the organic chemistry courses for the first time, one of the tasks I was asked to do was to complete a reaction and outline the involved synthesis steps (a non-mathematical problem); that was difficult for me. I then thought I was not clever enough to be in such a field. Fortunately, my genius brother helped me out by torturing me with numerous repetitive tasks such as drawing chemical figures, predicting products from reactants physically (drawing on paper) and mentally. We also viewed multiple chemical representations simultaneously using the computer-based visualization tool to enhance my spatial ability. These exercises allowed me to better relate to chemical symbolic and process quickly. Thus, I was able to complete my chemistry school assignments in a much more accurate and quicker manner.

Less positively, Ben from business found the children's tasks meaningless:

> This kind of activity is often wrapped up in the notion of problem-based enquiry … but seriously—the template for the children to succeed is at their fingertips! It requires no deeper engagement or investigation, comparison, or global connection. Hence, this kind of simulation, and the skills exercised through the process is meaningless for my profession and discipline—which requires a very deep engagement with problems in order to come up with solutions.

Interpretation

The businessperson's interpretation of spatial skills in the children's activities in the video was minimal. Wai et al. (2009) noted that business is one discipline that high school students with lower spatial reasoning tend to choose. Individuals with poorly developed spatial reasoning skills might be less able to recognize others using these skills. Perhaps the businessperson's limited interpretation could be attributed to less developed spatial reasoning skills.

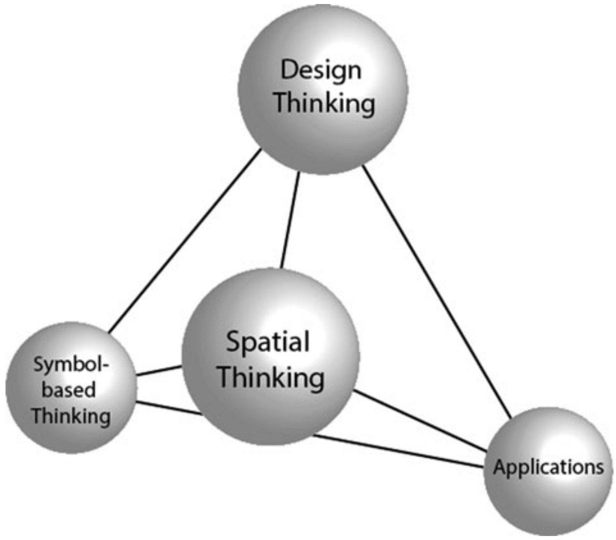

Figure 1. Explanatory diagram of coding results.

Discussion

Figure 1 is an illustration of the four themes generated from the analysis. We chose a three-dimensional tetrahedron shape with a spheroid on each vertex as one of the four themes. The three-dimensional edges of the figure illustrate the spheroids connections to the other spheroids, which is representative of the intertwining utterances of the participants. The size and proximity of the spheroids is representative of the corresponding number of utterances. Professionals viewing the video interpreted that spatial thinking was central of what they saw. As such, the spatial reasoning spheroid in the diagram is the largest and closest. Aspects of design thinking had the second most utterances—almost as many as spatial reasoning. Utterances of applications and symbolic-based reasoning were the fewest. Their relating spheroids are the smallest and most distant in the diagram. Next, we will discuss the meanings and the participants' perspectives of the themes.

In this study, we shared a 3-min video segment of students engaged in design thinking in a robotics task with 19 participants from a range of professions and backgrounds. Our goal was to learn more about *how* people in different disciplines interpret the same piece of data (the video segment), in order to identify what the students were doing, what skills they were using, and how these skills apply to various disciplines and professions. We also wanted to learn more about whether the interpretations were common in nature or quite distinct from one another. To attain these goals, we gathered all responses and coded them by utterance using an open coding approach (the themes emerged from the data rather than setting a priori codes).

Through this analysis we have learned that, in fact, many respondents across a range of STEM disciplines, as well as architects and artists, did indeed identify similar thinking skills in the video segment and readily connected these to their respective professions. Of particular interest was a dominant observation that both spatial thinking and design thinking were central to the student work. Because the authors are educational researchers of spatial reasoning, we were surprised at the extent to which participants described the activity of students as forms of spatial reasoning. The participants clearly interpreted that the children were manipulating objects in space, visualizing, comparing, moving between 2D instructions and 3D configurations, and constructing. What was more surprising was the emphasis participants placed on their observations of design thinking. The children in the video were persistently described by participants as using the design process, problem solving, collaborating, coding, and communicating. Trouble shooting, trial and error, and experimenting were elements of almost every participants' described experiences, including the visual artist, who noted how deeply connected the children's work was to his own work stating the connecting is "HUGE—it's what I do all the time."

Limitations to this study are fourfold. First, the video segment selected was focused on a particular form of skill development in the area of robotics and programming. Any number of videos from a range of STEM-related tasks could have been selected and would have led to quite different results. For example, if the video segment featured two children working to explore the dynamic properties of triangles in the Geometer's Sketchpad (McGraw-Hill, 2014), the participants would perhaps identify thinking strategies, such as understanding foundational mathematics principles from those identified with the robotics task. Second, there is no attempt at all to claim representativeness across professions. Thus, there may have been a wider range of responses if other professions had been included. Given the range of interpretations encountered across the limited professions surveyed, it is reasonable to expect that a more diverse group would have seen many others things. Third, the video was too brief to afford access to the more flexible, open aspects of the activity. A businessperson stated that he saw "occasional 'imagining'—but very little free/unguided thought." The businessman's observations could be considered accurate. The video displayed the children's progression of skill development from beginning to end—rather than a focus on the less structured final challenge that enabled children to incorporate and apply the newly gained skills in novel ways. Likewise, the low number (four) of utterances about creativity are not surprising, given that the selected video did not focus on the children's creativity for building an arm to remove the red trees. Had we the space for a longer video, the more open, flexible portions of the task would have been obvious. Fourth, the data were written responses, affording no opportunity for seeking clarification or delving deeper.

Conclusion

For us, the most notable result of this research is that every one of the professionals who participated commented—without priming or prompting—on multiple aspects of spatial reasoning as they related to their career responsibilities.

On the one hand, that result is not surprising. After all, as exemplified in the work of Wai et al. (2009), the link between spatial reasoning and STEM-related careers has been well established. On the other hand, however, there would seem no reason to expect that professionals would be inclined to highlight such elements, given the unlikeliness that spatial reasoning skills would have been a significant or explicit part of their formal education. This research, then, might be interpreted as an exclamation point on a statement already made by researchers: Not only are spatial reasoning competencies vital across so many careers but professionals tend to be very aware of those skills and how they play into their work lives. Their relative absence from grade-school curricula and postsecondary education is thus even more shocking.

This point is amplified by the fact that there appeared to be little difference in the amount of detail or the range of spatial topics between study participations who were in STEM professions and participants who were included because these were not in STEM professions. In particular, we fully expected that, for example, architects and visual artists would point to different elements of spatial reasoning. After all, their work is highly spatial, and their preparations would have reflected that. However, we did not expect that physicians, chemists, and mathematicians (among other STEM professionals) would offer analyses that were as varied and nuanced.

Of course, the research reported here is preliminary only. More extensive surveys involving many more participants are needed to confirm its preliminary results. That said, however, we believe it sufficient to add important fodder to current discussions of the place of spatial reasoning in modern curricula. It is evident that core skills across a vast range of professions are unaddressed in contemporary schools.

Note

1. Watch video at https://vimeo.com/170068141.

Funding

The authors are grateful for support from the Imperial Oil Science Technology Engineering and Mathematics Initiative at Werklund School of Education.

References

Abbot, L. (Ed.). (2014, August 26). 21st Century skills definition. *The Glossary of Education Reform*. Retrieved from http://edglossary.org/21st-century-skills/

Berglund, A., & Heintz, F. (2014). Integrating soft skills into engineering education for increased student throughput and more professional engineers. In *Proceedings of the LTHs 8:e Pedagogiska Inspirationskonferens*. Lunds Tekniska Högskola. Retrieved from http://www.lth.se/fileadmin/lth/genombrottet/konferens2014/11_Berglund_Heintz.pdf

Bishop, A. J. (1988). Mathematics education in its cultural context. *Educational Studies in Mathematics*, *19*(2), 179–191.

Bruce, C. D., Davis, B., Sinclair, N., McGarvey, L., Hallowell, D., Drefs, M., … Woolcott, G. (2016). Understanding gaps in research networks: Using "spatial reasoning" as a window into the importance of networked educational research. *Educational Studies in Mathematics*, online, 1–19. doi:10.1007/s10649-016-9743-2

Bruce, C. D., & Hawes, Z. (2015). The Role of 2D and 3D mental rotation in mathematics for young children: What is it? Why does it matter? And what can we do about it? *ZDM: The International Journal on Mathematics Education*, *47*, 331–343.

Bussi, M. G. B., & Baccaglini-Frank, A. (2015). Geometry in early sources: Sowing seeds for a mathematical definition of squares and rectangles. *ZDM: The International Journal on Mathematics Education*, *47*, 391–405.

Casey, B. M., Dearing, E., Vasilyeva, M., Ganley, C. M., & Tine, M. (2011). Spatial and numerical predictors of measurement performance: The moderating effects of community income and gender. *Journal of Educational Psychology*, *103*, 296–311.

Charmaz, K. (2014). *Constructing grounded theory* (2nd ed.). Thousand Oaks, CA: SAGE Publications.

Clements, D. H. (2004). Geometric and spatial thinking in early childhood education. In D. H. Clements, J. Sarama, & A.-M. DiBiase (Eds.), *Engaging young children in mathematics: Standards for early childhood mathematics education* (pp. 267–298). Mahwah, NJ: Lawrence Erlbaum.

Cohen, C. A., & Hegarty, M. (2012). Inferring cross sections of 3D objects: A new spatial thinking test. *Learning and Individual Differences*, *22*, 868–874.

Davis, B., Okamoto, Y., & Whiteley, W. (2015). Spatializing school mathematics. In B. Davis (Ed.), *Spatial reasoning in the early sources: Principles, assertions, and speculations* (pp. 139–150). New York, NY: Routledge.

Francis, K., Khan, S., & Davis, B. (2016). Enactivism, spatial reasoning and coding. *Digital Experiences in Mathematics Education*, *2*, 1–20.

Francis, K., & Whitely, W. (2015). Interactions between three dimensions and two dimensions. In B. Davis (Ed.), *Spatial reasoning in the early years: Principles, assertions, and speculations* (pp. 121–136). New York, NY: Routledge.

Fu, T. Z. J., Song, Q., & Chiu, D. M. (2014). The academic social network. *Scientometrics*, *101*, 203–239.

Hawes, Z., Tepylo, D., & Moss, J. (2015). Developing spatial thinking: Implications for early mathematics education. In B. Davis & Spatial Reasoning Study Group (Eds.), *Spatial reasoning in the early sources: Principles, assertions and speculations* (pp. 29–44). New York, NY: Routledge.

Hoyles, C., & Noss, R. (2002, July). *Problematising statistical meanings: A sociocultural perspective*. Paper presented at the International Conference on Teaching Statistics, Cape Town, South Africa. Retrieved from https://iase-web.org/documents/papers/icots6/2e3_hoyl.pdf

Khan, S., Francis, K., & Davis, B. (2015). Accumulation of experience in a vast number of cases: Enactivism as a fit framework for the study of spatial reasoning in mathematics education. *ZDM: The International Journal on Mathematics Education*, *47*, 1–11.

McGraw-Hill. (2014). Home—The Geometer's Sketchpad Resource Center. Retrieved from http://dynamicgeometry.com/

Mioduser, D., & Levy, S. T. (2010). Making sense by building sense: Kindergarten children's construction and understanding of adaptive robot behaviors. *International Journal of Computers for Mathematical Learning*, *15*(2), 99–127.

National Aeronautics and Space Administration. (2014, January 8). Engineering design process. Retrieved from http://www.nasa.gov/audience/foreducators/best/edp.html

Newman, M., Barabási, A.-L., & Watts, D. J. (2006). *The structure and dynamics of networks*. Princeton, NJ: Princeton University Press.

Piaget, J., & Inhelder, B. (1971). Mental imagery in the child: A study of the development of imaginal representation. *British Journal of Educational Studies*, *19*(3), 343–344.

Presmeg, N. (2006). Research on visualization in learning and teaching mathematics. In A. Gutiérrez & P. Boero (Eds.), *Handbook of research on the psychology of mathematics education* (pp. 205–235). Rotterdam, the Netherlands: Sense Publishers.

QSR International. (2016). NVivo qualitative data analysis software. Retrieved from http://www.qsrinternational.com/

Razzouk, R., & Shute, V. (2012). What is design thinking and why is it important? *Review of Educational Research*, *82*, 330–348.

Rowe, S. (2004). Discourse in activity and activity as discourse. In R. Rogers (Ed.), *An introduction to critical discourse analysis in education* (pp. 79–96). Mahwah, NJ: Lawrence Erlbaum. Retrieved from http://ezproxy.lib.ucalgary.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=nlebk&AN=104206&site=ehost-live

Sorby, S. A. (2009). Educational research in developing 3-D spatial skills for engineering students. *International Journal of Science Education*, *31*, 459–480.

Spatial Reasoning Study Group (SRSG). (n.d.). The Spatial Reasoning Study Group. Retrieved from http://www.spatialresearch.org/

Steve Jobs says everyone should learn to program. (2012). Retrieved from https://www.youtube.com/watch?v=mCDkxUbalCw

Strauss, A., & Corbin, J. (1998). *Basics of qualitative research techniques and procedures for developing grounded theory* (Vol. 2). Thousand Oaks, CA: Sage Publications.

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin*, *139*, 352–402.

Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 sources of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology*, *101*, 817–835.