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Early insights into Piaget's cognitive development model through the lens of the Technologies curriculum

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Abstract

Piaget's theory of stage structure is synonymous with discussions involving cognitive development. As with any theoretical model, researchers inevitably and rightly seek to affirm and/or contest the elements of the model presented. In this comparative study, students' performance across three hands-on engineering tasks for two distinct student cohort groups were investigated including young primary school students (aged 8 to 10) in Piaget's concrete operations; and older secondary school students (aged 15 to 18) in Piaget's formal operations stage of cognitive development. The purpose was to gain an insight into Piaget's stage structure from the perspective of the compulsory national Technologies curriculum in Australia, of which engineering is a core subject. The senior students outperformed their younger peers on all three tasks (simple, complicated and complex), with differences in abstraction and spatial inferential reasoning abilities increasing, as the task complexity increased. Although there is very limited evidence linking practical technological subjects and Piaget's cognitive development model, the findings were consistent with respect to students' abstract thinking capabilities and their cognitive development.

Keywords Abstraction · Cognitive development · Piaget's cognitive development model · Technologies curriculum

Introduction

Abstraction, and the related term of spatial inferential reasoning, are arguably central to developing innovation capabilities that are considered critical to a country's future prosperity (Nadelson & Seifert, 2017; Stewart, 2017). Within this paper, abstraction refers to an individual's ability to form a general mental idea for a possible solution to a Technologies problem (Falkner et al., 2014; Seemann et al., 2019). Related to abstraction is spatial inferential reasoning, which refers to the individual's ability to draw upon their prior knowledge, and visualise how the component parts will interact, transforming the original mental

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idea into a three-dimensional form (Seemann et al., 2019). While testing regimes such as PISA (Programme for International Student Assessment) tend to focus on student performance in literacy, numeracy and science, spatial abilities are largely overlooked (Bleazby, 2015; Çakiroğlu & Çevik, 2022). Given government and business rhetoric around the urgency of developing innovation capabilities in Australia, the national Technologies curriculum learning area is considered pivotal to achieving this objective (National Research Council, 2007; Office of the Chief Scientist, 2014; Stewart, 2017). As such, increased attention on developing the skills of abstraction and spatial inferential reasoning is needed, in particular, providing teachers with evidence-based research that will allow them to better tailor classroom learning activities in the Technologies curriculum to align with students' cognitive development.

Both abstraction and spatial inferential reasoning are cognitive capabilities that develop over time. Piaget's cognitive development model, which has captured the development of human cognition from birth to adulthood, remains a critical area of educational research, with considerable effort already expended in analysing the work of Piaget and students' cognitive performances across subject/learning areas and developmental age. While children's ability to think improves with developmental age, at the concrete operations stage (7 to 11/12 years of age) the main limitation is their inability to think in abstractions (Inhelder & Piaget, 1958). This ability to think about abstract possibilities is a key characteristic of students in the formal operations stage (from ages 11/12 to adulthood) of cognitive development (Inhelder & Piaget, 1958).

There however remains a lack of research in abstraction and spatial inferential reasoning. The importance of abstraction and spatial abilities research is noted by Peterson et al. (2020), who argue students' spatial abilities are a reliable predictor of student achievement and success in the STEM domain. Students with high spatial ability are considered to be an "important human-capital resource for developing scientific technological advances" (Kell et al., 2013, p. 1835). Not surprisingly, spatial skills are seen as necessary in the STEM disciplines, however, they can have a much broader impact on other learning areas through developing knowledge and creative thought more generally (Kell et al., 2013).

Much of what is learnt through the Technologies curriculum area is through hands-on problem-solving, which aligns with Dewey's (1997) view of progressive education theory and his belief in the role of hands-on learning as a means of developing students as problem solvers. Dewey's advocacy of learning by doing was a belief shared by Papert (1993) and his constructionist approach to teaching and learning. The notion of learning by doing places a load on students' cognitive abilities, such as imagining potential ideas/solutions in their mind (abstraction), communicating these abstract ideas to peers, and being able to make inferences when working on novel problems (Seemann et al., 2019).

In this study, we aimed to understand the effect of developmental age on abstraction and spatial inferential reasoning through the lens of teaching Technologies, with the following two research questions:

RQ1. How does student performance vary with task complexity across the two distinct developmental age groups of students in the capabilities of abstraction and spatial inferential reasoning?
RQ2. How do students initially approach a complex hands-on task? That is, do the students plan first, or launch straight into building?

The purpose of this paper is not to provide an extensive investigation on abstraction and spatial inferential reasoning. Rather, the intention is to offer some early insight into the differences in students' abilities to approach and undertake hands-on problem-solving tasks of varying complexity, individually and collaboratively. Central to this purpose, is developing a comparison of students' abilities to abstract and infer, across the two latter stages of Piaget's cognitive development model: concrete operations, and formal operations.

Literature review

Cognition, which refers to knowledge and associated inferential processes, such as conceptualisation, interpretation, thinking, and reasoning (Moshman, 2013) has been a focal point of substantial research across curriculum learning areas. Both abstraction and inference making are cognitive capabilities which develop with age. As such, any discussion around cognitive development would at the very least include the work of Piaget, given his theoretical stage structure model has had an immeasurable influence on education (Bidell & Fischer, 1994; Erneling, 2014; Lourenço & Machado, 1996; Schneider & Näslund, 1992). Despite the substantial research undertaken, there remains gaps in the literature when discussing abstraction and spatial inferential reasoning in the Technologies curriculum learning area, of which engineering is a core subject.

Abstraction (abstract thinking) has been traditionally regarded as an "ability that emerges relatively late in children's thinking development" (Van Oers & Poland, 2012, p.123). Whether or not this is also the case in the Technologies curriculum learning area, and one that specifically could be observed in students engaged with practical hands-on problem-solving tasks, remains unclear. Reasoning can be described as "a process of thinking systematically and logically to obtain a conclusion or proof" (Jumiarsih et al., 2020, p. 2), and inference making involving the action of going beyond the raw data/facts (Moshman, 2013). When applied to the Australian Technologies curriculum, inference making would equate to students going beyond the individual pre-assembled components of an engineering model, to abstracting and inferring how those individual components work together as part of an engineered system. Having a clear understanding of where students are at in their cognitive development is therefore a necessity for teachers, to ensure they constantly challenge students in the classroom through implementing appropriate tasks that offer the right level of complexity.

At any year level in a school, the cognitive ability levels of students, from least advanced to most advanced, can span by as much as five to six years (Freedberg et al., 2019; Gonski et al., 2018). Developmental expectations of students are therefore a critical consideration for teachers if they are to deliver appropriate and effective learning outcomes. Setting a task with an expectation that is beyond the cognitive ability of students is likely to result in the teacher spending significant portion of class time labouring on knowledge and skills that should be attempted later in a student's development stage.

Accordant with Piaget's (1972) cognitive development model, a child's intellectual development moves through a recognisable set of four stages, which are characterised by different thinking processes. For instance, in the concrete operations stage (7 to 11/12 years of age) children can think logically about objects but struggle to think in abstractions. Hence, these children are dependent on what they see, hear, and feel, and if given a three-dimensional (3D) model to replicate (e.g. a windmill structure), they (concrete thinkers) would require a complete set of instructions to successfully build a replica model. As children continue their development, they are likely to display more sophisticated cognitive abilities, such as abstraction and spatial inferential reasoning (Burgoon et al., 2013). For instance, this could manifest in students being able to think about abstract possibilities, such as visualising the missing components in a partially completed 3D tactile engineering model (e.g. tower crane), or reasoning that a solar panel could act as an on/off switch, as part of a simple steering mechanism (e.g. steerable boat). Thinking about abstract possibilities, such as a solar panel acting as an on/off switch, are typical of children operating in Piaget's (1972) formal operations stage.

Considerable attention has been given to Piaget's theoretical model across a range of curriculum learning areas. For instance, Susac et al. (2014) in their investigation on student preparedness in learning algebra, found that younger students used concrete strategies such as trial and error substitution to solve algebraic equations compared to their older peers who used rules-based (abstract) strategies. Metz (1995, p. 120) in her critique, supported the view that primary school science classes should place a focus on hands-on activities as students are "concrete thinkers whose reasoning [abilities are] tied to concrete objects". Firoozalizadeh et al., (2020, p. 25) argued that Persian-speaking students demonstrated the ability to "comprehend abstract concepts at about 5 years of age", which was contrary to Piaget's cognitive development model and his belief that abstract thought occurred later in a child's life.

Some researchers, such as Firoozalizadeh et al. (2020), questioned the universality of Piaget's cognitive development model, an issue previously noted by Bidell and Fischer (1994) who argued that Piaget's stage structure did not account for some of the variability observed in children. Differences observed in students cognitive thinking, including concrete and abstract thinking, was dependent on the subject area, content and the nature of the tasks given to students (Bidell & Fischer, 1994; Jamison, 1977). For example, a 13-year-old student may struggle to think abstractly during an algebraic problem-solving task in Mathematics yet could excel in abstract thinking when working on the designing and building of an engineering structure as part of a Technologies class.

Furthermore, Chiappetta (1976) recognised the complexity of applying Piaget's cognitive development model, having found frequent instances where students who demonstrate formal operational thinking on Piagetian tasks function at the concrete operational level in science. Gopnik (2012) also observed that contrary to Piaget's view, pre-schoolers (as young as 2) demonstrated aspects of abstract reasoning during experimentation which included simple inductive processes. Furthermore, the US-based National Research Council (2007, p. 53) had previously noted that contrary to the prevailing view that considered young students as "being concrete and simplistic thinkers", young students were capable of thinking in both concrete and abstract modes. Other researchers, such as Papert (1993), a contemporary of Piaget's, accepted the distinction between the two stages of concrete operations and formal operations. However, Papert (1993) argued that technology such as computers, could move the boundary that separated the two stages and their modes of thinking. Similarly, Uttal et al. (2013) provide evidence that targeted skills training can help facilitate the development of abstract spatial abilities.

Notwithstanding the complexity of Piaget's cognitive development model, the mechanisms by which children's knowledge and understanding is formed and transformed within set contexts remains unacknowledged (Ackermann, 1996). Increasingly, research in developmental psychology indicates that cognitive development is "not a smooth, incremental progression from concrete to abstract" modes of thinking (Ackermann, 1996, p. 26).

This research does not intend on contributing to the understanding of the continuum of cognitive development as suggested by Piaget. However, it does strive to offer the perspective of the authors belief that students' abilities in abstraction and spatial inferential reasoning will align with Piaget's model for the concrete and formal operations stages, through a comparative case study of junior students aged 8 to 10 (concrete) and senior students aged 15 to 18 (formal). A comparison of the junior and senior student cohort groups is shown in Table 1.

Methodology

A comparative case study methodology was adopted, involving two metropolitan schools, one primary (Foundation to Year 6, ages 4/5 to 11/12) and the other secondary (Years 7 to 12, ages 12/13 to 17/18). Thirty-six students from two different stages, concrete operations and formal operations, of Piaget's cognitive development model (Inhelder & Piaget, 1958), participated in the study which focused on abstraction and spatial inferential reasoning in the context of students solving one of three hands-on engineering tasks.

The research instruments

The research instruments used in this study consisted of three hands-on engineering tasks of varying complexity. Each task required students to build a 3D tactile model: simple windmill; complicated tower crane; or complex steerable boat. Each student or student group was assigned to only one task. The resources used were presented to the student participants, as follows:

- *Simple kit* comprised of interconnecting plastic parts similar to LEGO®. The kit contained a precise number of parts to construct a windmill model, with a full set of pictorial instructions.
- *Complicated kit* comprised of interconnecting plastic parts similar to LEGO®. The kit contained more parts than necessary to construct a functioning tower crane model, with several steps removed from the set of pictorial instructions.
- *Complex kit* comprised of an assortment of parts, allowing students to make alternate design decisions, such as choice of motors (low speed vs high speed), energy sources (battery packs vs solar panels), and propeller systems (three-blade traditional boat vs two-blade airboat). However, one key part (i.e. the pontoon element) was not included in the kit but was visible to the students. No build instructions were provided to the students, however, the solution to be built was described in the form of a design brief. Figure 1 shows the complex kit of parts and the pontoon element that students could use as part of their boat's design.

Table 1 A comparison of junior and senior students within Piaget's cognitive development model

Junior Students (aged 8 to 10)	Senior Students (aged 15 to 18)
Concrete operations stage: • think logically, but lack the capability to think more abstractly • more reliant on trial and error when problem-solving	Formal operations stage: • think abstractly • solve problems systematically through reasoning, rather than trial and error

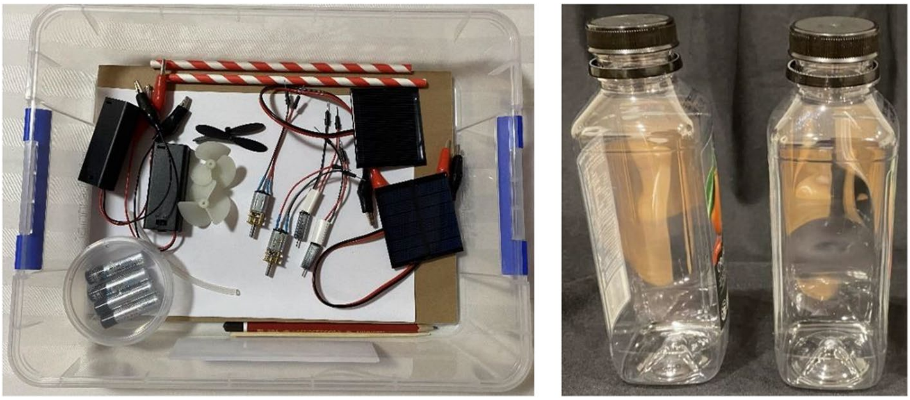


Fig. 1 The complex kit of parts (left) and plastic bottles which could be used as the pontoon element (right)

For the complex steerable boat task, at least one solution existed which would satisfy the three design criteria outlined in the design brief, of having a boat that would float, be powered by electricity, and was steerable. Making the boat steerable could be achieved by using the solar panels instead of the battery packs as an energy source; this was one of the design decisions that students would need to make to deliver a successful model for the complex task.

A summary of the three tasks given to the student participants is shown in Table 2.

Times assigned to each of the three tasks were based on data collected from a pilot study which allowed validation of the research instruments and task assessment rubrics.

Prior to the students commencing the construction of their model, a script was read. This ensured that each student and student group received a consistent message on the nature of the task, and the expectations. The script was written by the researchers and presented to students describing the nature of the task and the protocols for interacting with the resources provided as part of the model building process.

Participants

School A provided 24 junior students aged 8 to 10, and School B provided 12 senior students aged 15 to 18. Both schools were in a similar geographical area, designated by the Australian Bureau of Statistics (2023) as being in the top 20% of most advantaged suburbs in Australia, which assisted in mitigating the risk of introducing the confounding variable of socio-economic status of schools and students in this research. A summary of the participant schools is shown in Table 3.

As each of the three tasks (Table 2) were to be completed individually and in groups of three students, there was a requirement to recruit 12 students from each distinct cohort group. This study received approval by the university's Ethics Committee. Student participation was voluntary, and they could withdraw at any time without providing reasons.

Procedure

The 36 students formed the four cases upon which this research was based (Table 4). Each student was initially randomly assigned to work either individually, or in a group by the

Table 2 Students required to build one of three engineered models

Model	Simple windmill	Complicated tower crane	Complex steerable boat
Cognitive load	Low	Moderate	High
Build time	20 min	30 min	40 min
No. of parts	55 (excluding links for chain)	114 provided, but only 83 required	–-
Instructions / solution	Image of the final solution and all steps provided	Image of the final solution and most (but not all) steps provided	No image of solution provided, but solution described in design brief

Table 3 Participant schools and student background information

Description	School A	School B
School	State Government Primary School Foundation to Year 6 Student population ~ 800 students Co-educational	Catholic Secondary School Years 7 to 12 Student population ~ 1200 students Co-educational
Student participants	Junior: aged 8 to 10	Senior: aged 15 to 18
Piaget's stage of cognitive development	Concrete operations	Formal operations

researchers. Next, each student or group was randomly assigned to either a simple, complicated or complex hands-on engineering task to complete. Observations and audio-visual recordings were made of the students as they worked on their assigned hands-on problem-solving tasks: to determine the nature of any problems they were experiencing during their model construction (e.g. incorrect positioning of the plastic inter-connecting elements for the simple and complicated tasks); whether or not the kit of parts for the complex task was checked prior to building their model; whether or not any planning and/or designing occurred for the complex task; and if any inferences were made during the complex task construction (e.g. plastic bottles can provide the pontoon element for a boat to float; solar panels can be used to help steer the boat).

Table 4 Student assignment to a case and task

Case description	Unique student IDs and model assigned
Case 1: Junior students working individually	S01, S02, S03 assigned to simple task S04 assigned to complicated task S05, S06 assigned to complex task
Case 2: Junior students working collaboratively	S07, S08, S09 formed Junior Group 1 assigned to simple task S10, S11, S12 formed Junior Group 2 assigned to complicated task S13, S14, S15 formed Junior Group 3 assigned to complicated task S16, S17, S18 formed Junior Group 4 assigned to complicated task S19, S20, S21 formed Junior Group 5 assigned to complex task S22, S23, S24 formed Junior Group 6 assigned to complex task
Case 3: Senior students working individually	S25 assigned to simple task S26 assigned to complicated task S27 assigned to complex task
Case 4: Senior students working collaboratively	S28, S29, S30 formed Senior Group 1 assigned to simple task S31, S32, S33 formed Senior Group 2 assigned to complicated task S34, S35, S36 formed Senior Group 3 assigned to complex task

Each model built was assessed on its quality. The quality score indicated how accurate students were in delivering their solution, in the form of a working model, to the problem (simple, complicated, complex) assigned to them. The quality score was determined using a rubric developed by the authors to assess each model for its accuracy. The use of a rubric in this study is considered appropriate, as measuring cognitive abilities such as abstraction and spatial inferential reasoning, are considered difficult to achieve (Çakiroğlu & Çevik, 2022). The use of a rubric also aligned with the assessment approaches commonly used by teachers. The argument posited by the authors is that if a student had built a perfectly functioning windmill (simple task) or tower crane (complicated task), then logically that student must have been able to:

1. Accurately translate the 2D pictorial images (provided as part of the instructions) into the corresponding 3D tactile form for both the simple and complicated tasks; and/or
2. Visualise a mental image of the missing steps for the complicated task.

Hence, the students would have demonstrated their ability to operate in the abstract world. A carefully designed rubric should therefore have the potential to act as an indicator of student ability to abstract and infer. The rubrics used for the simple and complicated tasks are shown in Fig. 2. These rubrics could therefore provide a comparative measure of a student's ability to abstract and infer (Çakiroğlu & Çevik, 2022). For the complex task, a rubric was created, however, an additional measure that captured the number of inferences that students were required to construct a steerable boat that could float and was powered by electricity was needed.

For the simple and complicated tasks an additional performance measure, percent model completed, was calculated. The percent model completed was calculated as follows:

Simple Task: Windmill

Scoring split across six categories, as follows:

- Structural Frame – Vertical (maximum of 2.5 points)
  - 1 point for each one of the two completed vertical structural sections
  - 0.5 point for correct height (i.e. at least one of the two vertical sections must be the correct height, as machine might be partially built)
- Horizontal Connections (maximum of 2 points)
  - 0.5 point for each correctly located (i.e. vertical positioning) horizontal connections
    - two grey spacers at the top
    - one double black connector in the upper middle
    - one grey spacer lower middle
    - one mid-sized black connector/spacer at the bottom
- Blade Mechanism (maximum of 1 point)
  - 0.5 point for each set of three blades on rotating wheel
  - 0.5 point deduction if blade mechanism does not turn freely
- Gear Mechanism (maximum of 2.5 points)
  - 0.5 point if handle is in position and turns freely
  - 0.5 point for correct size of gear and orientation of upper gear relative to grey spacers
  - 0.5 point for correct size of gears and 0.5 point for their accurate orientation to each other
  - 0.5 point for correct size of gear and orientation gear to the handle
- Chain-Drive Pulley Mechanism (maximum of 1 point)
  - 0.5 point for each chain-drive pulley system that is present (i.e. total of two pulley systems) and with some 'slack' evident to allow gears to rotate easily
- Windmill End-Product (maximum of 1 point)
  - 0.5 point if the machine resembles a windmill
  - 0.5 point if windmill works (i.e. rotation caused by motion of handle); note: there could be construction issues, but machine works as intended (i.e. blades spin)

Total marks for the Windmill: 10 points

Complicated Task: Tower Crane

Scoring split across four categories, as follows:

- Structural Frame – Vertical (maximum of 3.5 points)
  - 1 point for each one of the two completed vertical structural sections
  - 0.5 point for correct height (i.e. at least one of the two vertical sections must be the correct height, as machine might be partially built)
  - 0.5 point for each pair of black struts on vertical frame angled correctly/symmetrically; note: two pairs are present on the machine
- Horizontal Connections (maximum of 2.5 points)
  - 0.5 point for each correctly located (i.e. vertical positioning) horizontal connections
    - one black barrel at the top
    - one dark grey connector
    - one (second) dark grey connector
    - two side-by-side black spacers
    - one white 2 × 8 long thin brick
- Gear Mechanism (maximum of 3 points)
  - 0.5 point for four inner gears inline (if partially complete, accept three inner gears aligned)
  - 0.5 point for two outer gears inline
  - 0.5 point for correct sized gears used in correct order (inner set)
  - 0.5 point for correct sized gears used in correct order (outer set)
  - 0.5 point for handle turns with minimal friction
  - 0.5 point if 'ratchet and pawl' functions correctly
- Tower Crane End-Product (max of 1 point)
  - 0.5 point for horizontal beam correct length and solid connection evident
  - 0.5 point for beam parallel to ground

Total marks for the Tower Crane: 10 points

Fig. 2 Rubrics used for the simple and complicated tasks

$$\frac{\text{total number of plastic inter-connecting elements used by the student(s) at the end of the build period}}{\text{total number of inter-connecting plastic elements required to construct a functioning model}} \times 100\%$$

The total number of plastic inter-connecting elements used by the student(s) was determined at the conclusion of the build, by disassembling each model and counting the number of individual plastic elements that had been used. This disassembling occurred after each model had been photographed from multiple angles and once the quality score was determined. This method of determining the percent of the model completed was only used with the simple and complicated models, as both these models consisted of a fixed number of elements (see Table 2) required to construct a fully functioning model. The percent of the model completed was intended on providing a measure of the students' fluency (i.e. speed) in completing a task.

Results

As the simple model had a low cognitive load, the difference in the ability of junior students compared to senior students to abstract was small, as indicated by the differences in model quality score. While all students (junior and senior) struggled to complete the simple task in the allotted 20-minutes, the senior students did slightly better on the quality of their model, as determined by the rubric used to assess each model. The models produced by the junior and senior students are shown in Fig. 3, with the quality score calculated and percent model completed also included for comparison.

Four complicated tower crane models were built by the junior students (one individual and three groups), and two by the senior students (one individual and one group). These are shown in Fig. 4 and Fig. 5 along with the quality score and percent model completed.

With several steps removed from the complicated task's pictorial instructions, a moderate cognitive load was placed on students to visualise in their minds, the missing steps and how the component parts in the missing steps were connected. These were

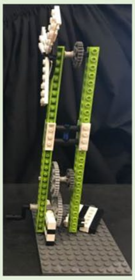
Junior Students				Senior Students	
S01	S02	S03	Junior Group 1	S25	Senior Group 1
					
Quality Score 2.5	Quality Score 6.5	Quality Score 6.0	Quality Score 7.5	Quality Score 7.0	Quality Score 8.5
40% complete	78% complete	87% complete	98% complete	86% complete	100% complete

Fig. 3 Junior and senior student models for the simple task

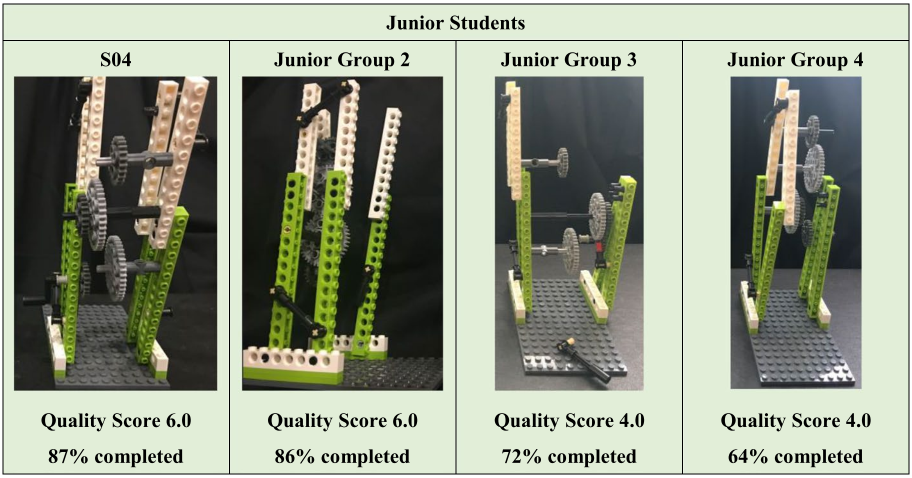


Fig. 4 Junior student models for the complicated task

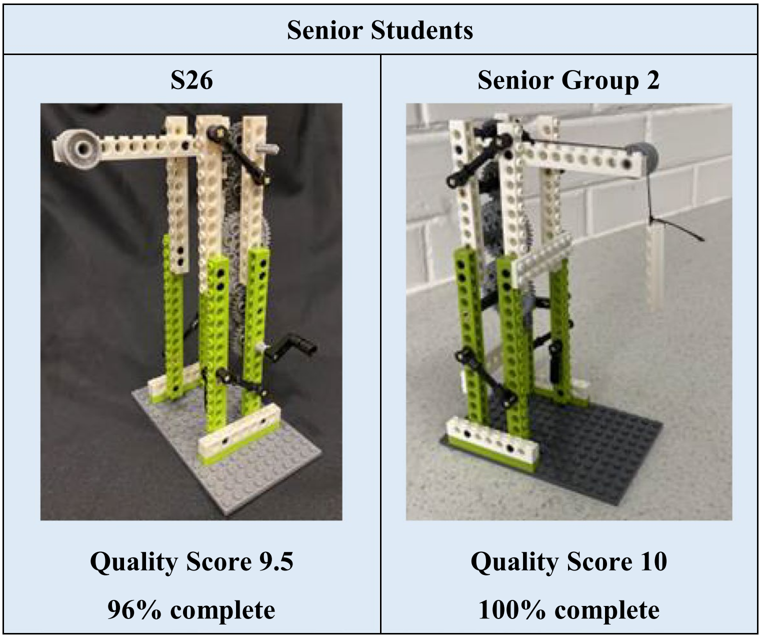


Fig. 5 Senior student models for the complicated task

reflected in lower quality scores and percent model completion by the junior students. All attempts by the junior students to build a working tower crane were unsuccessful. In contrast, the senior student group successfully completed construction of their model tower crane, including the key aspect of this study, which was the successful visualisation of the missing steps. The senior student, working individually, while unable to complete his model in the time allotted, was able to successfully visualise/imagine the missing steps.

The difficulty experienced by the junior students on the complicated task, due to the increase in cognitive load required of the students, can be noted in the following segment of conversation which captured the feelings of student S17 from Junior Group 4, nearing the end of their allotted 30-minute build period:

> *"I thought I am good at building LEGO. I build so many LEGOs in my home. I build the LEGO friends. I build two of them and I did great. But I can't do this. I'm not sure what to do right now. With my LEGO, every page is in a book."*

For the high cognitive load task, at the end of their allocated 40-minute build time, none of the junior students were able to make the necessary inferences to advance their complex steerable boat models to the state of addressing all three key design criteria (i.e. boat must float, be powered by electricity, and be steerable). The result for the junior students was an inference making score of 0 from 3 with their models (Fig. 6).

In contrast, the senior students were more successful in demonstrating their ability to abstract and infer on the high cognitive load task. The senior student models are shown in Fig. 7.

A summary of student performance across all three tasks of varying complexity is shown in Table 5, for both student individuals and student groups.

Discussion

The authors in this study sought to understand Piaget's cognitive development model from the perspective of spatial hands-on problem-solving tasks in the engineering subject area of the Technologies curriculum. This study's objective is embodied in the first research question: *How does student performance vary with task complexity across the two distinct developmental age groups of students in the capabilities of abstraction and spatial inferential reasoning?* While differences in ability to abstract and infer between the junior and

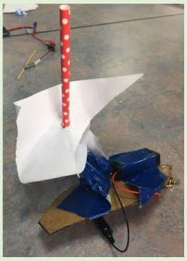
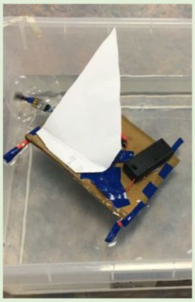
Junior Students			
S05	**S06**	**Junior Group 5**	**Junior Group 6**
			
Quality Score 4.0	**Quality Score 2.0**	**Quality Score 3.0**	**Quality Score 5.0**
0 inferences made	**0 inferences made**	**0 inferences made**	**0 inferences made**

Fig. 6 Junior student models for the complex task

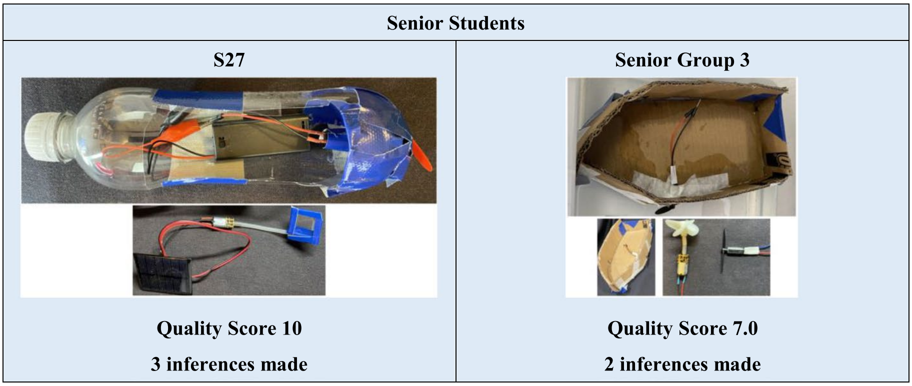


Fig. 7 Senior student models for the complex task, including novel design ideas/solutions

Table 5 Comparison of student performance across all three tasks, individually and collaboratively

Task and Measure	Junior Individual ($n=6$)	Senior Individual ($n=3$)	Junior Group ($n=6$)	Senior Group ($n=3$)
Simple model successful completion	0 / 3	0 / 1	0 / 1	0 / 1
Quality score (maximum score of 10)	2.5 – 6.5	7.0	7.5	8.5
Percent completed	40 – 87	86	98	100
Complicated model successful completion	0 / 1	0 / 1	0 / 3	1 / 1
Missing steps successfully visualised (Y/N)	No	Yes	No	Yes
Quality score (maximum score of 10)	6.0	9.5	4.0 – 6.0	10.0
Percent completed	87	96	64 – 86	100
Complex model successful completion	0 / 2	1 / 1	0 / 2	0 / 1
Kit of parts checked prior to building (Y/N)	No	Yes	No	Yes
Planning and/or designing undertaken	No	Yes (both)	No	Yes (both)
Quality score (maximum score of 10)	2.0 – 4.0	10.0	3.0 – 5.0	7.0
Number of inferences made	0	3	0	2

senior students were not initially evident with the low cognitive load simple task, the rubric developed provided a discernible relative measure of abstraction and inference making (Fig. 8). Despite the simple nature of the windmill task and a full set of instructions provided, there remained a cognitive requirement, albeit low, for students to translate the 2D images to a 3D tactile form. The small difference in abstraction and spatial inferential reasoning for the simple task, with older students performing better than the younger students, was observed for the individual and group cases. The need to constantly move between the 2D pictorial and 3D tactile worlds had placed a cognitive load, especially on the students' working memory which not unexpectedly resulted in older students being more fluent (or quicker) in correctly manipulating the component parts of their engineering model, than their younger peers. Moving back-and-forth between the 2D pictorial instructions and 3D tactile model also led to the occasional mistakes being introduced in the students' models, with senior students being quicker to identify and fix their mistake/s. These observations, with the quality score calculated for each student and student group, suggests that the older students (aged 15 to 18) outperformed their younger peers (aged 8 to 10) in abstraction and spatial inferential reasoning.

Differences in student performance (ability to abstract and infer) increased with the complicated task, which had a moderate cognitive load compared to the simple model (Fig. 8). These observed differences in abstraction and spatial inferential reasoning were evident across all cases, students working individually and in groups of three, with senior students demonstrating higher levels of abstraction and inference making, than their younger peers. The use of the two measures, quality score (which measured the accuracy of the models produced) and percent completed (which provided a measure of students' fluency in understanding the problem and being able to manipulate the resources to create a completed artefact), provided evidence of differences in students' cognitive abilities in undertaking hands-on problem-solving tasks in the Australian national Technologies curriculum. The senior students' greater fluency in processing the information presented in the form of 2D pictorial instructions compared to the junior students, was evident when fixing mistakes introduced during the 2D (pictorial images) to 3D (tactile model) translation process.

The greater fluency observed with the senior students in the simple and complicated hands-on engineering tasks mirrored the research observations in text comprehension and language fluency observed by Kolić-Vehovec et al. (2010). When given a hands-on task, the senior students were able to complete construction more quickly than the junior students. This was particularly evident when observing students undertake the complicated tower crane task and the younger students were unable to visualise/imagine the missing elements required to bridge the gap in the provided instructions for the complicated model.

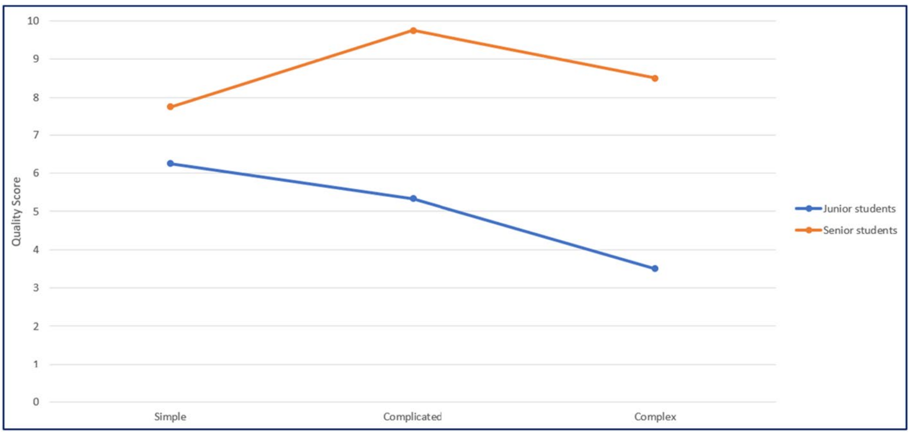


Fig. 8 Divergence in the quality score (abstraction capability) of students' model building efforts

The observations of student performance in the simple and complicated problem-solving tasks were consistent with those of Demetriou et al. (2002) and their findings that information processing was more efficient in older adolescent students (aged 16) compared to those in early childhood (aged 8). The perfect score for senior group 2 (students S31, S32, S33) and the near-perfect score for senior student S26 reflected their ability to successfully imagine and correctly infer the missing steps for the complicated tower crane model. While the senior group completed the model's construction, the senior student working on his own ran out of time (96% of model completed), however, he was still successful in visualising and re-constructing those parts of the model for which the steps had been removed.

The senior students' success in visualising in their minds the missing steps, and then translating those missing steps from an abstraction to a 3D tactile form, indicated a more sophisticated ability to process information in working memory. Arguably, the ability to take the imagined solution in their mind and successfully transpose that mental visualisation into the 3D tactile world is only present in Piaget's (1972) final stage of cognitive development, which he termed, *formal operations*. This therefore suggests that the senior students in this research were operating within Piaget's formal operations stage.

If junior students (aged 8–10) were operating in the *concrete stage* of Piaget's cognitive development model as suggested by the researchers, then the ability to re-create the missing steps in their minds for the complicated task, from the perspective of Piaget's (1972) theory of cognitive development, would be beyond them. This appeared to be the case based on these junior student participants, and one that was summed up by S17's comment, "every page is in a book", when referring to the missing steps. S17's remark attempted to explain the difficulty that her group was experiencing in trying to visualise in their mind, the missing elements needed to bridge the gap created by the missing steps in the pictorial instructions provided for the complicated task. This observation therefore appeared to affirm Piaget's cognitive development model, with this junior group (aged 8 to 10) unable to create the abstractions in their minds and make the inferences necessary, that would allow them to successfully complete their tower crane model. Similar struggles with imagining the missing steps were experienced by all the junior students, individually and as a group of three. The junior students therefore appeared to be operating in the concrete stage of cognitive development, as per Piaget's theoretical model.

The difference in students' ability to abstract and infer was most pronounced with the complex task. With no solution provided, other than being described in a design brief, a higher cognitive load was placed on students to abstract and infer, so as to produce a model boat that would float, be powered by electricity, and was steerable. To successfully advance from the resources given to the students, to the point of having a final working model as per the design brief, the students were required to make at least three key inferences. With the complex task the junior students were unable to meet any of the three design criteria, with no consideration given to how the pontoon element (i.e. plastic bottles), located nearby, could be used to keep their boat afloat. There was no attention given to developing a strategy, planning, or coming up with potential designs. All junior students, working individually and collaboratively, launched straight into building their model, with no initial examination of what component parts they had been given to address the three design criteria.

A methodical approach is generally considered key to successful problem-solving (Gilad & Loeb, 1983; Russo, 2016), as is the use of design sketches when commencing the problem-solving process (Genyea, 1983). Unlike the junior students, the senior students were systematic in examining what parts were included in the complex build kit provided, and in sketching preliminary designs for their model boat. In the cases of working individually and collaboratively, the senior students looked beyond their worktable to help solve the criterion of buoyancy. Both the senior student working individually, and the senior student group noticed the plastic bottles (pontoon element) positioned to the side of their workspace. They made clear inferences that the plastic bottles could be used to provide buoyancy. While senior group 3 (students S34, S35, S36) made a total of two inferences (buoyancy and novel connection from energy source to propulsion system), the senior student S27 made the minimum three key inferences in addressing the design criteria and producing a perfect score for the quality of their steerable boat model.

Of the three design criteria, the requirement of building a boat which was steerable, presented the students with the hardest challenge. However, this criterion could be addressed by using the method taken by senior student S27, who drew upon her prior knowledge of Physics and how solar panels function. By changing the light intensity shining on a solar panel, S27 had successfully inferred that the solar panel could act as an on/off switch to control a motorised rudder. The light shining on the solar panel could be adjusted from some maximum value (i.e. switch ‘on’) and the motorised rudder moving, to a minimum value (i.e. switch ‘off’) ceasing the rudder’s motion. The final artefacts presented by the senior students, including the novel working solutions for the complex task, are shown in Fig. 7.

We are now well-placed to provide meaningful insight to addressing the two research questions posed. Firstly, as task complexity increased, differences in abstraction and spatial inferential reasoning abilities of the two student groups became more pronounced, with the senior students aged 15 to 18 performing better than their younger peers aged 8 to 10. These results aligned with Piaget’s cognitive development model from the perspective of hands-on engineering problems in the Technologies curriculum, with the younger students operating within the concrete operations stage and the senior students within the formal operations stage of cognitive development. Based on our study and the research instruments used, the case studies appeared to demonstrate that the junior students aged 8 to 10 appeared to be lacking in abstraction and spatial inferential reasoning abilities, compared to their older peers (aged 15 to 18).

Secondly, the lack of a systematic approach to problem-solving further undermined the junior students problem-solving capabilities. This was evident in each instance of the junior students undertaking the complex task, as they immediately launched into building their model boat, without any thought given to planning and designing. Unlike the junior students, the senior students initially looked at each component provided in their kit of parts as part of an initial ‘stocktake’, to determine possible approaches to problem-solving. Furthermore, both the senior student individual and senior student group spent the initial part of their build time to create a potential design of their model, using the pencil and paper included in the kit of parts. Planning and designing were features of a systematic problem-solving approach used by the senior students, which were missing from the junior students’ repertoire of strategies. Given that Piaget’s formal operations stage is noted for students demonstrating a more systematic approach to problem-solving (Emick & Welsh, 2005), the senior students’ (formal operations stage) higher level of performance compared to the junior students (concrete operations stage) was not unexpected. Having a methodical, systematic problem-solving approach, in contrast to an approach that is based on trial and error, is a characteristic of the formal operations stage of Piaget’s cognitive development model.

Notwithstanding the limited number of students in this case study, the aim of this research was to provide a preliminary insight into student divergence (based on age) in abstraction and spatial inferential reasoning performance with engineering task complexity.

Figure 8 shows this divergence as a comparison between those students in a developmental age group that places them in Piaget's concrete operations stage (aged 8–10) versus those students in a developmental age group that places them in Piaget's formal operations stage (aged 15–18).

Limitations and future research

To minimise the impact of this research on schools, the tasks developed for the purpose of eliciting students' abstraction and spatial inferential reasoning abilities presented a challenge. One full set of observations required a minimum of 12 student participants (3 × individual tasks and 3 × group tasks), with the tasks developed and the times allocated to the completion of each engineering problem-solving task allowing a full set of observations to be completed within one school day.

Developing the tasks to meet the constraint of completing one full cycle within one school day was further complicated by the young age of the junior students, which eliminated many tools for safety reasons. For instance, to overcome the safety issues for the complex task and meet the 40-minute build time allocated, several components were pre-assembled, such as the motors, solar panels, and battery packs.

Future studies would look at a larger group of participants to collect and synthesise conclusions that are statistically significant. A larger number of participants would explore abstraction and spatial inferential reasoning abilities of students across both low and high socio-economic regions. Given that determining the socio-economic status is a complex concept, the Australian Bureau of Statistics (2023) and its decile rating system, can be used to identify those regions that are of low socio-economic status and of high socio-economic status.

Additionally, students' working memory appeared to be noticeably different between the junior and senior student participants. This difference raises an intriguing question around the role played by working memory on hands-on engineering problem-solving tasks, especially on those tasks requiring students to alternate between working within the 2D (visual/pictorial) world and 3D (tactile) world.

Conclusion

The two capabilities of abstraction and spatial inferential reasoning within the context of the Technologies curriculum were hypothesised to align with Piaget's cognitive development model. That is, an observable difference in abstraction and inferential reasoning should exist between those students in Piaget's concrete operations stage, compared to those in Piaget's formal operations stage of development. Credence to this hypothesis was given in a review of the research literature and the assertion that abstraction and spatial inferential reasoning are recognised cognitive functions that improve with developmental age. The findings of this study support the perspective that the cognitive capabilities (i.e. abstraction and spatial inferential reasoning) within the context of practical hands-on engineering problem-solving tasks, could be understood through Piaget's cognitive development model. From this study two key conclusions can be argued, and which address the central research questions. Firstly, the younger students (aged 8 to 10) experienced a deterioration in their ability to problem solve hands-on engineering tasks as the level of task complexity increased. These younger students lacked the level of accuracy of their model construction, were slower (i.e. less fluent) and struggled to make inferences across both the complicated and complex hands-on tasks, compared to their senior peers. The difference in abstract thinking was noted even on the low cognitive load simple windmill task. Despite their familiarity with building LEGO® models, the younger students were slower in their ability to reconstruct the 3D tactile components/model structure from the 2D visual images provided. The rubrics designed to assess the quality of the windmill (simple) and tower crane (complicated) models provided a useful method of measuring students' relative cognitive performance of abstraction and spatial inferential reasoning. The audio-visual recordings complemented the rubric for the complex task by identifying explicit inferences made by students on the complex task, which could not otherwise be captured in the final assessed model.

The lower performance of the younger students relative to their older peers was further compromised by the lack of any observable systematic strategy of planning and designing. While senior students placed a value on thinking before building, which included analysing each part within the complex kit provided, and how the parts might be used, against the design criteria provided, the junior students jumped straight into building. There was no obvious systematic approach adopted by the younger students. These observations suggest that within the practical technological subjects, such as engineering, the appearance of students' abstract thinking capabilities aligns with the predictions made by Piaget's cognitive development model. That is, the younger students aged 8 to 10 (in the concrete operations stage of development) were outperformed in the ability of thinking in abstractions by their older peers aged 15 to 18 (in the formal operations stage of Piaget's model) when given a hands-on engineering task to problem solve. Whereas the senior students appeared to value the importance of apportioning time to planning and designing as part of a systematic approach to problem-solving, planning and designing were absent from the approach used by the junior students. As a systematic approach to problem-solving is argued to be a characteristic of individuals operating in Piaget's formal operations stage of cognitive development, this study suggests that a student's developmental age does influence their ability to abstract and infer in accordance with Piaget's cognitive development model.

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Declarations

The authors have no competing interests to declare that are relevant to the content of this article.
All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.
The authors have no financial or proprietary interests in any material discussed in this article.

Ethical approval We hereby state that the work presented in this paper is original, was not submitted to another journal, and was not published in any form of language, partially or in full.

Informed consent This study was performed in line with the principles of the Declaration of Helsinki. Informed consent was obtained from all individual participants included in the study to participate in the study and to publish the anonymized data.

Consent to participate All authors agreed with the content, and all gave explicit consent to submit. All authors obtained consent from the responsible authorities at the institute/organization where the work has been carried out before the work was submitted.

Consent to publish The participants have consented to the publishing of the outcomes from the research.

Research involving human participants and/or animals Ethical approval was granted by the Swinburne University Ethics Review Committee.

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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