

ARTICLE

Domain-specific knowledge and domain-general abilities in children's science problem-solving

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Abstract

Background: Problem-solving in early and middle childhood is of high relevance for cognitive developmental research and educational support. Previous research on science problem-solving has focussed on the process and strategies of children handling challenging tasks, but less on providing insights into the cognitive network that enables science problem-solving.

Aims: In this study, we aimed to investigate whether performance in science problem-solving is mainly determined by domain-specific rule knowledge, by domain-general cognitive abilities or both.

Methods: In our study, 215 6- to 8-year-old children completed a set of three domain-specific rule knowledge tasks and three corresponding problem-solving tasks that were content-coherent, as well as a vocabulary task, and a reasoning task.

Results: Correlational and regression analyses revealed a negligible impact of domain-specific rule knowledge on corresponding problem-solving tasks. In contrast, the associations between problem-solving performance in different domains and the associations between problem-solving performance and domain-general abilities (vocabulary and reasoning) were comparably strong.

Conclusions: The findings suggest that science problem-solving in primary school children primarily relies on domain-general cognitive abilities. Implications of these findings are discussed with regard to cognitive theories and early science education.

KEYWORDS

domain-general cognition, domain-specific knowledge, primary school education, problem-solving, rule knowledge

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INTRODUCTION

Problem-solving abilities in children are assumed to foster subsequent personal and professional success (Diamond, 2018). Thus, problem-solving is a relevant research topic regarding childhood development and educational support (Keen, 2011). Problem-solving describes the process of reaching a desired state (i.e., a goal) that is different from an initial state (Funke et al., 2018). This process requires cognitive effort on the part of the problem solver because the gap between the initial state and the desired state arises from a lack of ability or routine knowledge (Funke et al., 2018; Mehadi Rahman, 2019). The problem-solving process includes interdependent steps, such as understanding the problem, testing partial solutions and continuously matching the current state with the goal state (Adams & Atman, 1999; Funke et al., 2018; Lee & Johnson-Laird, 2013; Strimel et al., 2018).

A core aspect of problem-solving is rule knowledge that highlights logical problem aspects (Luo & Niki, 2003), which can be related to domain-specific content. Some researchers consider domain-specific content knowledge as the main factor contributing to successful problem-solving (cf. the seminal work by Chi et al., 1982; Perkins & Salomon, 1989), while others consider domain-general aspects, such as fluid and crystallized intelligence, crucial for problem-solving (Greiff et al., 2014; Mehadi Rahman, 2019).

Our study aims to analyse the role of domain-specific rule knowledge and the role of domain-general cognitive abilities in 6- to 8-year-old children's problem-solving. For this purpose, we tested domain-specific rule knowledge in two content domains: gear-turning mechanisms and stability of building block constructions. In addition, we measured vocabulary and reasoning as indicators of intelligence and investigated the effects of age and gender on problem-solving performance.

The role of rule knowledge in problem-solving

Rule knowledge represents the understanding of relationships underlying logical problems, whereas rule application represents the use of this knowledge to solve a problem (Bühner et al., 2008; Fischer et al., 2011; Greiff et al., 2015; Jonassen, 2000; Mustakim et al., 2020; Simmons, 1992). Rule knowledge can be considered as domain-independent (Greiff et al., 2015) and mentally represented as a logical if-then-proposition (Arló-Costa & Levi, 1996). However, domain-specific rule knowledge can primarily be applied to a problem in this specific domain, for example in the gear domain. For instance, the domain-specific rule knowledge of turning direction can be applied to make gears turn in particular directions. Effectively applied domain-specific rule knowledge can be an integral part of successful problem-solving (Charlesworth & Leali, 2012; Milbourne & Wiebe, 2018).

Domain-specific rule knowledge can be stored in memory explicitly or implicitly (Reber & Kotovsky, 1997). A problem solver with explicit domain-specific rule knowledge can explain the rules, for example the turning direction of interconnected gears. A problem solver with implicit domain-specific rule knowledge knows about the turning direction of gears but is not able to explain it. Both explicit and implicit rule knowledge may be applied in problem-solving (Hamilton et al., 2007). Problem-solving without explicit knowledge is possible when using trial-and-error as a heuristic (Funke et al., 2018). Trial-and-error can be considered the lowest level of prior planning (Stern & Hertel, 2022), but can result in successful problem-solving by chance, lead to strategy formation, and generate implicit knowledge (Reber & Kotovsky, 1997; Tönnsen, 2021).

Domain-specific knowledge and domain-general cognitive abilities in problem-solving

Domain-specific knowledge and domain-general cognitive abilities in academic performance, including problem-solving, have been a much-investigated field for decades (Greene et al., 2018). However,

findings on the interaction of domain-specific knowledge and domain-general cognitive abilities in problem-solving are inconsistent (Chi et al., 1981; Chiappe & MacDonald, 2005; Greiff et al., 2014).

Domain-specific content knowledge in problem-solving

Studies using the expert-novice paradigm indicated that more domain-specific content knowledge (expertise) correlates with enhanced problem-solving abilities in the respective domain (e.g., Chi et al., 1981; Perkins & Salomon, 1989). Consequently, students' context familiarity of a problem may improve their problem-solving (Bibi et al., 2018). Content knowledge allows experts to pay attention to the deep structure of a problem, whereas novices are typically oriented towards surface features (Chi, 2006; Mayer, 1997). Moreover, a certain amount of domain-specific content knowledge may be necessary for an effective application of domain-general problem-solving strategies (Alexander & Judy, 1988), such as problem decomposition and solution search (Reif & Heller, 1982). A recent study with physics students indicated that problem-solving performance increased as a function of domain-specific content knowledge (Milbourne & Wiebe, 2018). Yet, findings from Sabella and Redish (2007) suggested that performance in problem-solving not only depends on the availability of domain-specific content knowledge but more on how and when it is activated. Thus, domain-specific content knowledge does not completely explain problem-solving performance (e.g., Schoenfeld, 1987), suggesting that other cognitive processes are involved.

Domain-general cognitive abilities in problem-solving

A number of previous studies indicated that higher-order cognition, such as fluid and crystallized intelligence, contributes to problem-solving performance (Funke, 2014; Greiff et al., 2014; Mehadi Rahman, 2019; Zook et al., 2004). Fluid intelligence might, for instance, support problem-solving performance when complex problems have to be segmented or inductive or deductive reasoning is required (Chiappe & MacDonald, 2005; O'Brien et al., 2023). Crystallized intelligence is considered an important factor in children's problem-solving, as it allows the retrieval of previously acquired information and experiences, but also as a prerequisite for the understanding of verbal problem statements (Stephan et al., 2022). Specifically, verbal abilities support action planning, which is a central part of problem-solving (Gunzenhauser et al., 2019).

The interrelation of domain-specific content knowledge and domain-general cognitive abilities in children

There are only a few studies focusing on the relationship between domain-specific content knowledge and domain-general cognitive abilities in children's problem-solving. Findings from English (1992) indicated that the amount of domain-specific content knowledge plays a crucial role in 4- to 9-year-olds for the application of meaningful solution strategies to combinatorial problems. Gilmore et al. (2018) suggested that domain-specific content knowledge regarding the structure of the number system best predicted arithmetic problem-solving, whereas domain-general cognitive abilities were weaker predictors in 8- to 10-year-old children. In contrast, Geary et al. (2017) found in a longitudinal study from grade one to grade eight that domain-general cognitive abilities were more important than domain-specific content knowledge for mathematics problem-solving in early grades, but domain-general abilities and domain-specific content knowledge were equally important in later grades.

Besides the mathematics domain, children's problem-solving has been studied in an early engineering framework (for an overview, Gold & Elicker, 2020; Lucas & Hanson, 2016; Strimel et al., 2018). A study by Spektor-Levy and Shechter (2022) has shown that engineering practices and problem-solving performance of 5- and 6-year-old preschoolers improved by simply providing them with construction

materials for free play at their daycare centre. However, few studies on children's engineering examined the role of domain-specific content knowledge for problem-solving. Reuter and Leuchter (2022a) investigated problem-solving with 4- to 7-year-olds in the domain of gears. The task involved connecting two gears fixed on a board so that they turn in the same direction. Based on the rule that adjacent gears turn in opposite directions, the children had to use an odd number of additional gears to successfully solve the problem (Reuter & Leuchter, 2022a). The results revealed no significant correlations between domain-specific rule knowledge (i.e., turning direction of adjacent gears) and quality of the problem solution (Reuter & Leuchter, 2022a).

Young children are likely to lack comprehensive content knowledge in various domains. However, they may have phenomenological primitives (diSessa, 1988) which they may have gained during playful experience (Weisberg et al., 2013). For example, the phenomenon of gears' turning direction and turning speed may have been achieved while playing with gears and the phenomenon of stability through block play. This experience may result in rule knowledge.

Children's domain-specific rule knowledge of gears' turning direction and turning speed

In the domain of gear-turning mechanisms, children may develop rule knowledge through playful experiences. The turning direction of adjacent connected gears is opposite. Thus, a target gear turns in the same direction as a driving gear when connected by an odd number of intermediate gears (Lehrer & Schauble, 1998). The turning speed of a gear around its own axis is size-dependent. Smaller gears turn faster around their own axis compared to larger gears (Reuter & Leuchter, 2021). Several studies have shown that children's domain-specific rule knowledge regarding gears' turning direction and turning speed develops during early school years and can be fostered through playful interventions (Lehrer & Schauble, 1998; Reuter & Leuchter, 2021, 2022a). In the study by Reuter and Leuchter (2021), most 7- and 8-year-olds had the correct domain-specific rule knowledge, whereas the majority of 5- and 6-year-olds did not. With respect to gears' turning speed, most children between 5 and 10 years of age had insufficient domain-specific rule knowledge (Reuter & Leuchter, 2021). However, studies by Reuter and Leuchter (2021, 2022b) indicated that 5- and 6-year-olds might acquire appropriate domain-specific rule knowledge about gears' turning direction and speed in short play-based interventions.

Children's domain-specific rule knowledge of building block constructions' stability

The stability of building blocks depends on the centre-of-mass principle, stating that a resting object is unstable when it is not supported (Weber & Leuchter, 2020). The geometric centre aligns with the centre-of-mass in symmetrical but not in asymmetrical constructions. Research indicated that asymmetrical building block constructions are more difficult to rate correctly than symmetrical building block constructions for 3- to 6-year-old children (Krist, 2010), indicating a lack of explicit stability knowledge. Additionally, Krist et al. (2005) found that 4- and 5-year-olds struggle to actively balance symmetrical building blocks on a beam scale, suggesting a lack of appropriate implicit knowledge. However, the development of stability knowledge between 4 and 8 years (Krist et al., 2005) can be fostered through interventions that address children's strategies to stabilize building blocks and their reasoning about it (Weber et al., 2020). These studies indicated that domain-specific rule knowledge can be learned implicitly and is accessible implicitly and explicitly.

Taken together, both the turning direction and speed of gears and the stability of building block constructions seem to be appropriate content domains to investigate the relationship between domain-specific rule knowledge and domain-general abilities for 6-to-8-year-olds' problem-solving. Thus, in the present study, we assessed problem-solving with tasks focusing on gears' turning direction and turning speed and building block constructions' stability.

The role of age and gender in problem-solving abilities

Problem-solving abilities significantly improve across childhood (Keen, 2011). Thornton (2009) attributed this learning development to children's active engagement with problem situations. Research suggested that problem-solving in children develops from trial-and-error procedures towards a more strategic and planful process with increasing age (Injoque-Ricle et al., 2014). However, age-related changes in problem-solving do not develop automatically but are driven by children's experiences in tool use, object manipulation and understanding of causal relations (Keen, 2011). Regarding general science understanding, a developmental boost occurs during early primary school age (Fitzgerald & Smith, 2016). Moreover, a previous study has shown that a developmental shift in the conceptual understanding of gears might occur between the ages of 6 and 7 years (Reuter & Leuchter, 2021). This was indicated by the fact that 7-year-olds were more likely than 6-year-olds to understand the content underlying gear problems (Reuter & Leuchter, 2021). While problem-solving strategies rely strongly on crystallized intelligence in older adults and on fluid intelligence in younger adults (Chen et al., 2017), less is known about early childhood.

Evidence for gender effects in problem-solving is heterogeneous, although there is some evidence that problem-solving performance varies between genders according to the problem domain (Walker et al., 2002; Zhu, 2007). Research suggested that female preschoolers are more competent in applying social problem-solving strategies than males (Walker et al., 2002). In contrast, male sixth graders were more strategic and successful in mathematical problem-solving (Zhu, 2007), although it was argued that gender differences in mathematical problem-solving resulted from stereotype threats depressing women's performance (Quinn & Spencer, 2001). In a science problem-solving study, male students were more successful because of their solution-seeking behaviour (Harskamp et al., 2008).

The present research

Our aim was to systematically investigate domain-specific rule knowledge and domain-general abilities in 6- to 8-year-old children's problem-solving. Therefore, we used three tablet-based *problem-solving tasks* in which participants had to solve construction problems with gears and building blocks according to well-defined goal requirements: (a) *carousel task*, (b) *propeller task* and (c) *stabilization task*. Additionally, three *rule knowledge tasks* assessed the domain-specific rule knowledge underlying the *problem-solving tasks*: (a) the *turning direction* of gears (rule: if adjacent connected gears turn, then their turning direction is opposite), (b) the *turning speed* of gears (rule: if a gear is larger than another gear, then it will turn comparably slower around its own axis) and (c) the stability of asymmetric building block constructions (rule: if the *centre-of-mass* of a building block construction is supported, it will remain stable). Furthermore, we measured two domain-general cognitive abilities: vocabulary as proxy for crystallized intelligence and reasoning as proxy for fluid intelligence. Our research questions were to test (1) whether problem-solving performance is more strongly related to (a) domain-specific rule knowledge or to (b) domain-general cognitive abilities (represented by crystallized and fluid intelligence and problem-solving in other domains; see Figure 2) and (2) whether age and gender have an impact on problem-solving performance.

METHODS

Participants

A power-analysis (parameters: $r = .25$, $\alpha = .05$, $1 - \beta = .90$) resulted in a required sample size of $n = 164$. The sample consisted of 215 children (age: 6–8 years, $M = 7.18$, $SD = 0.78$; 89 female) from public schools. Data collection took place at a workshop during a school holiday at the university. They participated voluntarily

and with written informed consent of their parents. The study was approved by the local ethics committee at the department of psychology (application #361). Ethnic background of participants was not recorded.

Design

We conducted a within-subject design, in which participants completed two sessions of approximately 30 min each with a 60-min break in between. Participants performed rule knowledge, vocabulary and reasoning tasks in the first session and problem-solving tasks (carousel, propeller and stabilization task) in the second session. In addition, children performed two tasks using analogue gear materials (cf. Schäfer et al., 2023a) in the second session, which are not subject of this study. Task order of the turning direction problem-solving task (carousel) and the turning speed problem-solving task (propeller) was counterbalanced, because they both belong to the gear domain. In relation to Bibi and Ahmad (2022), we presented non-routine problems since gears and building blocks are typically not used in goal-oriented problem-solving tasks, but as play materials. Trained experimenters explained and conducted the tasks in one-to-one settings with standardized procedures without providing feedback on response accuracy. All tasks were performed on a tablet application (cf. Schäfer et al., 2023a). Participants had sufficient time and instruction to get familiar with the task-specific tablet handling prior to each task. The procedure was video recorded.

Tests

The study comprised three rule knowledge tasks and three corresponding problem-solving tasks. All tasks started with one practice trial followed by the test trials (Figure 1).

Turning direction tasks

The *turning direction knowledge task* (Reuter & Leuchter, 2022b) contained six items with two to four connected gears of the same size. A driving gear was marked with a circular arrow indicating its turning direction. Participants were instructed to infer the turning direction(s) of the other connected gear(s) when the driving gear would turn in the direction specified by the arrow. Gears could neither be removed nor turned. Gears whose turning direction was estimated correctly were scored as one point each (0–13 points).

The *turning direction problem-solving task* (carousel task; Reuter & Leuchter, 2022b) contained a construction board with 20×14 plug-in options, and 14 gears of 4 different sizes arranged outside the board. The left lower corner of the board showed a fixed turnable driving gear and the upper right corner showed a fixed turnable target gear (i.e., a carousel). Participants were asked to build a connection between driving and target gear so that they turned in the same direction (goal state). Gears were moved via drag-and-drop and turned by circular swiping. Participants had up to 5 min to solve the task. Solution quality was ordinally scaled (0–4 points; see Table 1).

Turning speed tasks

The *turning speed knowledge task* (Reuter & Leuchter, 2022a) contained nine items with one to three connected gears of the same size in the upper half of the screen. In the lower half of the screen, three grey gears of different sizes were displayed. Participants had to pick the grey gear that would turn faster, slower or equally fast as the one(s) in the upper display. Gears could neither be removed nor turned. Gears whose turning speed was estimated correctly were scored as one point (0–9 points).

The *turning speed problem-solving task* (Propeller task; Reuter & Leuchter, 2019) contained a construction board with 20×14 plug-in options and 14 gears of 4 different sizes and 2 propellers

Tablet screenshots of the rule knowledge tasks and the problem-solving tasks

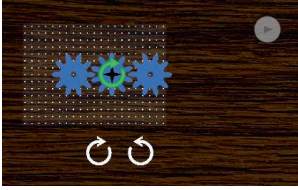
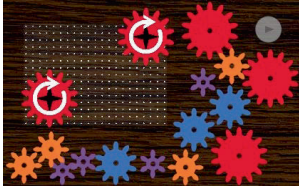
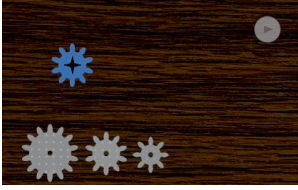
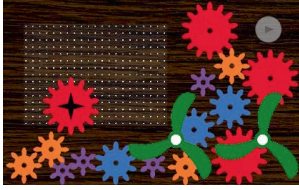
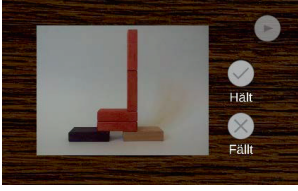
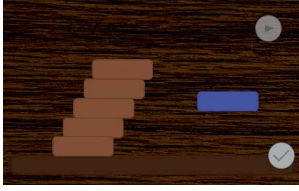
Rule knowledge tasks		Problem-solving tasks	
Turning direction knowledge		Turning direction problem-solving (carousel task)	
Turning speed knowledge		Turning speed problem-solving (propeller task)	
Centre-of-mass knowledge		Centre-of-mass problem-solving (stabilization task)	

FIGURE 1 Tablet screenshots of the rule knowledge tasks and the problem-solving tasks.

TABLE 1 Grading system for the solution quality in the turning direction problem-solving task (carousel task).

Coded score	Final state on the gear board
0	Neither the driving gear nor the target gear had another gear attached to it
1	Either the driving gear or the target gear had at least one other gear attached to it
2	At least one gear was attached to both the driving and target gear
3	Driving gear and target gear were connected, but the target gear was either turning in the wrong direction or it was blocked
4	Driving gear and target gear were connected and the target gear turned in the specified direction when the driving gear turned in the specified direction

arranged outside the board. The lower part of the board showed a fixed turnable driving gear. The propellers could be attached to all gears except of the driving gear. Participants were asked to make one propeller turn as fast as possible and another propeller turn as slow as possible when turning the driving gear, without both propellers touching each other (goal state). Gears were moved via drag-and-drop and turned by circular swiping. Participants had up to 5 min to solve the task. Solution quality was ordinally scaled as two variables that were added to a sum score (turning speed 0–3 points plus contact 0–2 points; see Table 2).

Centre-of-mass tasks

The *centre-of-mass knowledge task* (Weber & Leuchter, 2020) contained 16 items of asymmetrical building block constructions. Participants rated whether a construction would hold or collapse

TABLE 2 Grading system for the solution quality in the turning speed problem-solving task (propeller task).

Coded score	Coding variable	Final state on the gear board
0	Turning speed	At least one propeller was not attached on any gear
1	Turning speed	Both propellers were attached on gears of the same size
2	Turning speed	Both propellers were attached on different-sized gears, but not largest and smallest
3	Turning speed	One propeller was attached on the smallest gear and the other propeller was attached on the largest gear
0	Contact	Not both propellers were driven by the driving gear or not both propellers were attached to the centre of a gear wheel
1	Contact	The two propellers touched each other when turning the driving gear
2	Contact	The two propellers did not touch each other when turning the driving gear

Note: The sum of the values in turning speed and in contact represent the total score.

after removing one specific colour-coded building block. Correctly solved items were scored as one point (0–16 points).

The *stabilization problem-solving task* (based on Weber et al., 2020) contained eight items of an in-stable asymmetrical building block construction, which could be stabilized (goal state) by placing an additional building block via drag-and-drop. Once the participants added the building block correctly or after three attempts, they were presented the next item. Each participant had a start budget of 32 points. For each item that was not successfully solved after three attempts and for each used attempt, one point was subtracted ($\text{Score}_{\text{stabilization}} = 32 - n_{\text{attempts}} - n_{\text{unresolvedItems}}$), resulting in 0–24 points.

Domain-general measures

We assessed vocabulary and reasoning as domain-general indicators for intelligence that are known to contribute to problem-solving performance.

Vocabulary: We used the passive vocabulary task (WPPSI-IV, Petermann & Daseking, 2018) as an indicator of crystallized intelligence since vocabulary enables the problem solver to verbally understand problem requirements and is closely related to acquired general mental abilities (Jensen, 2001). Participants saw four images on the display and were asked to point to the image named by the experimenter. The task consisted of up to 35 items. After three consecutive failures, the task was aborted. Correctly solved items were scored as one point (0–35 points).

Reasoning: We used the figural reasoning task (WPPSI-IV, Petermann & Daseking, 2018) as an indicator of fluid intelligence (Beauducel et al., 2001). It included 26 items with a 2×2 matrix containing three images and one question mark. Participants selected one of four to five figurative response options to replace the question mark in a logically consistent manner. After three consecutive failures, the task was aborted. Correctly solved items were scored as one point (0–26 points).

Statistical analyses

Descriptives and correlations (Spearman's Rho) were calculated for performance in all tasks. Correlations between corresponding rule knowledge and problem-solving tasks indicate domain-specific associations. Correlations between different problem-solving tasks indicate domain-general associations since they represent higher-level domain-general problem-solving abilities (see Figure 2). Correlations of problem-solving tasks with vocabulary and reasoning also indicate domain-general associations,

Model of research questions

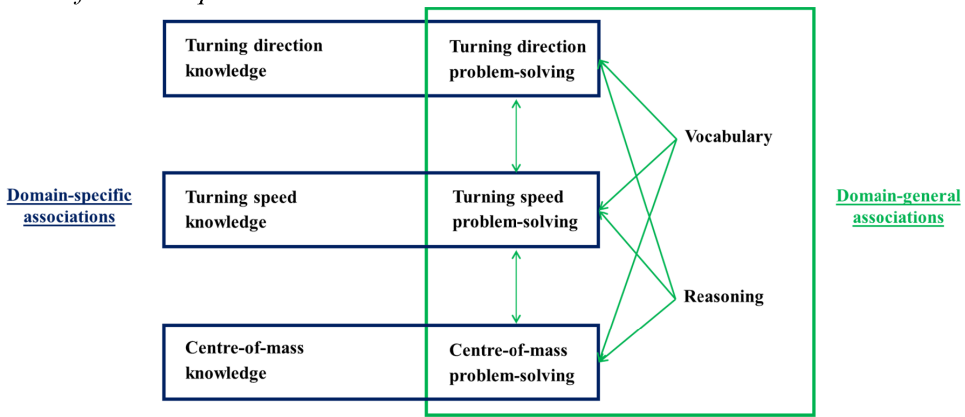


FIGURE 2 Model of research questions. Associations between tasks connected by a green arrow are domain-general. Associations of tasks in the same blue box are domain-specific.

because they may contribute to problem-solving across domains. Domain-specific and domain-general correlation strengths were compared according to Silver et al.'s (2004) method for correlations of independent groups.

The differential effects of domain-specific rule knowledge and domain-general abilities on problem-solving performance were analysed by a hierarchical ordinal logistic regression (proportional odds) for each problem-solving task as dependent variable (see Table 3). First, the domain-specific rule knowledge was the only included independent variable. Second, performances in other problem-solving tasks were added as independent variables. Third, vocabulary and reasoning were added as independent variables. Likelihood-ratio tests were conducted to control whether the added variables increased the variance explained by the model. We excluded all participants with at least one missing task ($n = 12$). Additionally, we calculated confirmatory factor analyses based on structural equation models (see Appendix B (Figures A1–A3, Table A4)).

Age and gender effects on problem-solving performance were analysed through ordinal logistic regressions. To keep regression coefficients comparable, we z-standardized all independent factors, except of gender which was dichotomously dummy-coded. All analyses were performed using R statistics software (version 4.3.0; R Core Team, 2023).

RESULTS

Unifactorial ordinal regressions exhibited that task order neither had significant effects on turning direction problem-solving (carousel task: $\beta_{to} = -0.09, p = .47$) nor on turning speed problem-solving (propeller task: $\beta_{to} = 0.01, p = .93$).

Correlations and their comparisons

Correlations between both turning direction tasks and both turning speed tasks were significant and not significant between both centre-of-mass tasks. All correlations between different problem-solving tasks and all correlations of domain-general measures and problem-solving tasks were significant (Table 4).

The comparison of correlations showed that the association between corresponding domain-specific knowledge and problem-solving tasks (turning direction, turning speed, centre-of-mass) were

TABLE 3 Dependent and independent variables of regression models.

Model	Turning direction knowledge	Turning speed knowledge	Centre-of-mass knowledge	Reasoning	Vocabulary	Turning direction problem-solving	Turning speed problem-solving	Centre-of-mass problem-solving
Turning Direction	IV			IV	IV	DV	IV	IV
Turning Speed		IV		IV	IV	IV	DV	IV
Centre-of-mass			IV	IV	IV	IV	IV	DV

Abbreviations: DV, dependent variable; empty = not integrated in the model; IV, independent variable.

descriptively smaller than the correlations between the problem-solving tasks and other measures (i.e., other problem-solving tasks, vocabulary and reasoning). In 8 out of 12 possible combinations, this difference was significant (see Table 5).

Regression analyses

For all three problem-solving tasks (see Tables 6–8), second-step regression models accounted for additional variance in the respective problem-solving performance compared to first-step models. Regarding performance on the turning direction and turning speed problem-solving tasks, domain-specific rule knowledge was no longer a significant predictor once performance on the other problem-solving tasks was included as predictors. For centre-of-mass problem-solving, domain-specific rule knowledge was not a significant predictor. The third step models, adding vocabulary and reasoning, again accounted for additional variance. Reasoning was a significant predictor of the turning direction of problem-solving performance. Vocabulary was a significant predictor of the turning speed problem-solving performance and the centre-of-mass problem-solving performance (see also regression analyses with an intelligence composite score (Appendix A (Tables A1–A3)) and confirmatory factor analyses (Appendix B)).

Age and gender effects

Ordinal regressions showed that both age and gender were significant predictors of problem-solving performance across all tasks (see Table 9). The impact of age and gender was similarly strong (age: $\chi^2(2) = 3.74\text{--}6.07$; gender: $\chi^2(2) = 2.50\text{--}4.05$) and in favour of older and male participants.

DISCUSSION

The aim of this study was to test whether children's problem-solving performance was more strongly related to their domain-specific rule knowledge or to domain-general cognitive abilities. We also investigated the effects of age and gender on problem-solving performance.

Problem-solving performance was correlated with both domain-specific rule knowledge and domain-general cognitive abilities. Children's domain-specific rule knowledge about gear-turning mechanisms was correlated with performance in the corresponding problem-solving tasks, while rule knowledge about stability was not. These findings are partially in line with the expert-novice paradigm, that emphasizes the importance of content knowledge for problem-solving (e.g., Chi et al., 1981; Perkins & Salomon, 1989). Regarding domain-general cognitive abilities, vocabulary and reasoning as indicators of intelligence were correlated with all problem-solving tasks and explained variance in problem-solving performance beyond domain-specific knowledge. This is consistent with studies by Greiff et al. (2015) and Stephan et al. (2022) demonstrating substantial effects of intelligence on problem-solving. Correlational and regression analyses revealed comparably stronger associations

TABLE 4 Correlations (Spearman's Rho) of all tasks.

Variable	Range	M	SD	1	2	3	4	5	6	7
1. Turning direction knowledge	0–13	7.77	3.19							
2. Turning direction problem-solving (carousel task)	0–4	3.06	1.18	.20**						
3. Turning speed knowledge	0–9	5.29	2.92	.14*	.26**					
4. Turning speed problem-solving (propeller task)	0–5	2.43	1.66	.29**	.46**	.22**				
5. Centre-of-mass knowledge	0–16	5.85	3.10	.05	-.02	.02	-.07			
6. Centre-of-mass problem-solving (stabilization task)	0–24	12.22	3.20	.30**	.28**	.24**	.36**	.00		
7. Vocabulary	0–35	27.02	4.44	.33**	.34**	.22**	.38**	-.04	.37**	
8. Reasoning	0–26	16.20	4.47	.38**	.43**	.21**	.34**	.00	.36**	.41**

* $p < .05$. ** $p < .01$.

TABLE 5 Comparison of domain-specific and domain-general problem-solving correlation strengths.

Correlated variable	Turning direction problem-solving (carousel task)	Turning speed problem-solving (propeller task)	Centre-of-mass problem-solving (stabilization task)	Reasoning	Vocabulary	Reference
	<i>z</i> (<i>p</i>)	<i>z</i> (<i>p</i>)	<i>z</i> (<i>p</i>)	<i>z</i> (<i>p</i>)	<i>z</i> (<i>p</i>)	
Turning direction problem-solving (carousel task)	–	3.47 (.00)	1.03 (.30)	3.24 (.00)	1.86 (.06)	Turning direction
Turning speed problem-solving (propeller task)	3.15 (.00)	–	1.76 (.08)	1.48 (.14)	2.00 (.04)	Turning speed
Centre-of-mass problem-solving (stabilization task)	2.92 (.00)	3.72 (.00)	–	3.85 (.00)	3.89 (.00)	Centre-of-mass

Note: Domain-specific correlations are compared with domain-general correlations. Positive *z*-values represent the domain-specific correlation to be weaker. *p*-Values indicate whether this difference is statistically significant.

TABLE 6 Ordinal logistic regression predicting performance on the turning direction problem-solving task (carousel task).

DV: Turning direction problem-solving performance (carousel task)			
Factor	Step 1	Step 2	Step 3
	Coef (SE)	Coef (SE)	Coef (SE)
Turning direction knowledge	.36** (.14)	.06 (.15)	-.11 (.16)
Turning speed problem-solving (propeller task)		.86** (.16)	.73** (.17)
Centre-of-mass problem-solving (stabilization task)		.21 (.15)	.09 (.16)
Vocabulary			.17 (.16)
Reasoning			.66** (.16)
Model parameters			
Log-likelihood	-247.54 (df=5)	-227.25 (df=7)	-217.19 (df=9)
R ²	.04	.23	.31
Observations	203	203	203

p* < .05. *p* < .01.

TABLE 7 Ordinal logistic regression predicting performance on the turning speed problem-solving task (propeller task).

DV: Turning speed problem-solving performance (propeller task)			
Factor	Step 1	Step 2	Step 3
	Coef (SE)	Coef (SE)	Coef (SE)
Turning speed knowledge	.36** (.13)	.15 (.13)	.12 (.13)
Turning direction problem-solving (carousel task)		.69** (.14)	.58** (.15)
Centre-of-mass problem-solving (stabilization task)		.48** (.13)	.36** (.14)
Vocabulary			.38** (.14)
Reasoning			.19 (.15)
Model parameters			
Log-Likelihood	-348.64 (df=6)	-325.51 (df=8)	-319.91 (df=10)
R ²	.04	.24	.29
Observations	203	203	203

p* < .05. *p* < .01.

TABLE 8 Ordinal logistic regression predicting performance on the centre-of-mass problem-solving task (stabilization task).

DV: Centre-of-mass problem-solving (stabilization task)			
Factor	Step 1	Step 2	Step 3
	Coef (SE)	Coef (SE)	Coef (SE)
Centre-of-mass knowledge	.03 (.12)	.09 (.12)	.10 (.13)
Turning direction problem-solving (carousel task)		.31* (.14)	.19 (.14)
Turning speed problem-solving (propeller task)		.52** (.14)	.37** (.14)
Vocabulary			.36* (.14)
Reasoning			.28 (.14)
Model parameters			
Log-likelihood	-510.11 (df = 16)	-494.48 (df = 18)	-487.63 (df = 20)
R ²	.00	.14	.20
Observations	203	203	203

* $p < .05$. ** $p < .01$.

TABLE 9 Ordinal logistic regression predicting performance on problem-solving tasks by age and gender.

Factor	Turning direction problem-solving (carousel task)	Turning speed problem-solving (propeller task)	Centre-of-mass problem-solving (stabilization task)
	Coef (SE)	Coef (SE)	Coef (SE)
Age	.53** (.14)	.81** (.14)	.84** (.14)
Gender	.69* (.28)	1.08** (.27)	.78** (.25)
Model parameters			
Log-likelihood	-239.96 (df = 6)	-324.69 (df = 7)	-484.95 (df = 17)
R ²	.11	.25	.22
Observations	203	203	203

* $p < .05$. ** $p < .01$.

between performance in different problem-solving tasks than between domain-specific knowledge and corresponding problem-solving performance. Moreover, comparisons of correlation strengths showed that performance in one specific problem-solving task was more strongly related to the performance in the other problem-solving tasks and to domain-general cognitive abilities than to the corresponding domain-specific rule knowledge. Additionally, for all problem-solving tasks (carousel, propeller, stabilization), effects of rule knowledge on performance became non-significant when including the other two problem-solving measures as independent variables in the regression analyses.

Taken together, our findings indicate that domain-specific rule knowledge played a minor role for 6- to 8-year-olds' science problem-solving performance, at least compared to domain-general abilities, such as intelligence and general problem-solving abilities. This finding is supported by the results of Geary et al. (2017), who found that domain-general cognitive abilities were more important than domain-specific knowledge for mathematics problem-solving in children. In contrast to our findings, English (1992) and Gilmore et al. (2018) found that content knowledge played a major role in combinatorial and arithmetic problem-solving. However, the relevance of domain-specific knowledge might increase as a function of age (cf. Geary et al., 2017).

We also found that age was a significant predictor of performance on all problem-solving tasks. Older children outperformed younger children, which is in line with previous research (Keen, 2011; Reuter & Leuchter, 2021; Thornton, 2009). Moreover, male children outperformed female ones on the

problem-solving tasks. This finding adds to previous research that pointed to gender differences in science problem-solving performance (e.g., Harskamp et al., 2008) and may be of importance for the development of STEM curricula that should provide equal learning opportunities for all children (Shechter et al., 2021). Further studies will be necessary to clarify the role of context factors, such as play materials available for girls and boys, and of task modality, such as spatial compared to verbal or figural tasks.

Taken together, the findings suggest that domain-specific rule knowledge plays a minor role for problem-solving performance in 6- to 8-year-old children, compared to domain-general abilities, such as vocabulary, reasoning and general problem-solving abilities. Two assumptions might explain these results.

First, children might have solved the problems through trial-and-error irrespective of whether they had rule knowledge or not, so that rule knowledge would have been irrelevant (Funke et al., 2018; Tönnsen, 2021). Trial-and-error might be helpful for children without domain-specific rule knowledge and for children who are incapable to retrieve it (Sabella & Redish, 2007; Tuminaro & Redish, 2007). Furthermore, the environment of our problem-solving tasks was playful and might thus have led children to try different solution pathways by trial-and-error, because they assumed that their performance on the tasks was not relevant. However, participants who did not have solid domain-specific rule knowledge prior to problem-solving might have acquired this knowledge during the problem-solving process (Tönnsen, 2021). In particular, trial-and-error might integrate implicit rule knowledge which is, however, hardly assessable (Funke et al., 2018). To gain more insights into whether rule knowledge is acquired during trial-and-error, microgenetic studies (cf. Siegler, 2007) are a promising approach. Moreover, the relevance of domain-specific knowledge may depend on individual problem-solving strategies. Thus, applied strategies should be analysed in future studies, for example based on number and timing of gear and block manipulations.

Second, children who have domain-specific rule knowledge might fail to apply it. This failure might depend on more general cognitive skills, for example executive functioning (Dixon & Johnson, 2012; Schäfer et al., 2023b), which continuously develop till late adolescence (Wiebe & Karbach, 2017). Children's limited working memory capacity might affect their problem-solving performance, because the problems required the maintenance of the objects' continuously changing constellations, such as the interrelations of the gears or of the building blocks. Deficits in executive functioning might also affect the capability to remember previous errors systematically, leading children to commit the same errors repeatedly, thus hindering learning from errors. This explanation is in line with the finding that working memory capacity mediates implicit learning in problem-solving (Reber & Kotovsky, 1997).

Limitations and future research

Although we gained new insights into children's problem-solving, the rule knowledge tasks applied may not fully capture all necessary aspects of the respective domain-specific knowledge. We tested domain-specific rule knowledge and corresponding problem-solving in only two domains (gears and building blocks), revealing a minor role of domain-specific rule knowledge. However, the prominent role of domain-specific knowledge in problem-solving, observed in expert-novice studies (Perkins & Salomon, 1989), might be latently inherent at age 6–8 years.

To study the development of relations between domain-specific rule knowledge, domain-general cognitive abilities and problem-solving, a longitudinal design is promising. Generalizing our findings requires similar research in other domains. Assessing rule knowledge before and after problem-solving could illuminate the acquisition of rule knowledge during problem-solving.

Our results highlight vocabulary and reasoning as central domain-general aspects of problem-solving (cf. Greiff et al., 2015). However, given that Bühner et al. (2008) found effects of working memory on problem-solving abilities, the assessment of a broader set of cognitive abilities would allow more specific conclusions. Verbal presentation of our problem-solving tasks, requiring children to maintain instructions for several minutes, may be affected by intelligence and working memory.

Additionally, given the spatial representation and goal-oriented nature of our tasks, spatial abilities and inhibition are worth further investigation (Dixon & Johnson, 2012; Oostermeijer et al., 2014).

CONCLUSION

Our study indicates a major role of domain-general cognitive abilities in 6- to 8-year-old children's science problem-solving. We found that domain-general cognitive abilities had a stronger association with problem-solving abilities in three different problems than domain-specific rule knowledge. This suggests the importance of studying problem-solving even in participants lacking substantial domain-specific rule knowledge, thus extending beyond the expert-novice paradigm. Regarding educational settings, assessing problem-solving in the classroom can be valuable, especially when problem-solving is part of the curriculum.

AUTHOR CONTRIBUTIONS

Jonas Schäfer: Conceptualization; data curation; formal analysis; investigation; methodology; visualization; writing – original draft; writing – review and editing; software; validation. **Timo Reuter:** Conceptualization; investigation; writing – review and editing; methodology. **Julia Karbach:** Conceptualization; resources; writing – review and editing. **Miriam Leuchter:** Conceptualization; funding acquisition; project administration; resources; supervision; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors do not report any conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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APPENDIX A

REGRESSION ANALYSES WITH A COMPOSITE FACTOR OF INTELLIGENCE

TABLE A1 Ordinal logistic regression predicting performance on the turning direction problem-solving task (carousel task).

DV: Turning direction problem-solving performance (carousel task)			
Factor	Step 1	Step 2	Step 3
	Coef (SE)	Coef (SE)	Coef (SE)
Turning direction knowledge	.36** (.14)	.06 (.15)	-.08 (.16)
Turning speed problem-solving (propeller task)		.86** (.16)	.71** (.16)
Centre-of-mass problem-solving (stabilization task)		.21 (.15)	.08 (.16)
Intelligence			.40** (.10)
Model parameters			
Log-likelihood	-247.54 (df = 5)	-227.25 (df = 7)	-219.28 (df = 8)
R ²	.04	.23	.29
Observations	203	203	203

Note: The factor Intelligence represents the sum of the standardized scores of vocabulary and reasoning.

* $p < .05$. ** $p < .01$.

TABLE A2 Ordinal logistic regression predicting performance on the turning speed problem-solving task (propeller task).

DV: Turning speed problem-solving performance (propeller task)			
Factor	Step 1	Step 2	Step 3
	Coef (SE)	Coef (SE)	Coef (SE)
Turning speed knowledge	.36** (.13)	.15 (.13)	.12 (.13)
Turning direction problem-solving (carousel task)		.69** (.14)	.56** (.14)
Centre-of-mass problem-solving (stabilization task)		.48** (.13)	.36** (.14)
Intelligence			.29** (.09)
Model parameters			
Log-likelihood	-348.64 (df = 6)	-325.51 (df = 8)	-320.25 (df = 9)
R ²	.04	.24	.29
Observations	203	203	203

Note: The factor Intelligence represents the sum of the standardized scores of vocabulary and reasoning.

* $p < .05$. ** $p < .01$.

TABLE A3 Ordinal logistic regression predicting performance on the centre-of-mass problem-solving task (stabilization task).

DV: Centre-of-mass problem-solving (stabilization task)			
Factor	Step 1	Step 2	Step 3
	Coef (SE)	Coef (SE)	Coef (SE)
Centre-of-mass knowledge	.03 (.12)	.09 (.12)	.09 (.13)
Turning direction problem-solving (carousel task)		.31* (.14)	.19 (.14)
Turning speed problem-solving (propeller task)		.52** (.14)	.38** (.14)
Intelligence			.32** (.09)
Model parameters			
Log-likelihood	-510.11 (df=16)	-494.48 (df=18)	-487.69 (df=19)
R ²	.00	.14	.20
Observations	203	203	203

Note: The factor Intelligence represents the sum of the standardized scores of vocabulary and reasoning.

* $p < .05$. ** $p < .01$.

APPENDIX B

CONFIRMATORY FACTOR ANALYSES

Confirmatory factor analysis for the performance in turning direction problem-solving (carousel task)

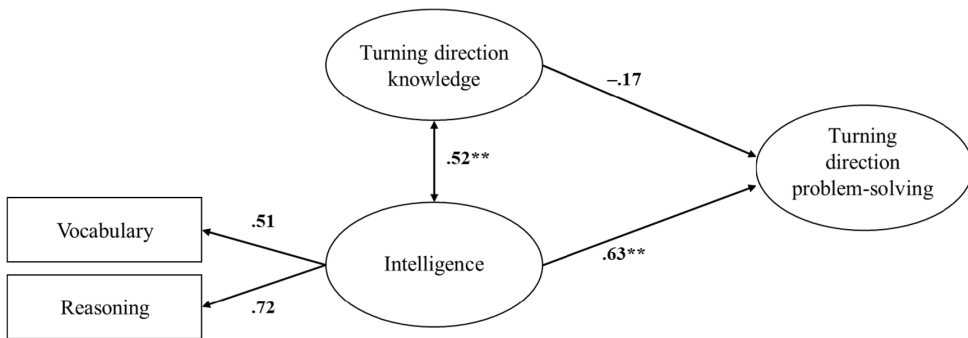


FIGURE A1 Confirmatory factor analysis for the performance in turning direction problem-solving (carousel task). * $p < .05$; ** $p < .01$; Unidirectional arrows between latent factors represent regressions, bidirectional arrows represent correlations. Path values represent the standardized estimates. Domain-specific knowledge and problem-solving are defined as single-indicator latent factors (Hayduk & Littvay, 2012).

Confirmatory factor analysis for the performance in turning speed problem-solving (*propeller task*)

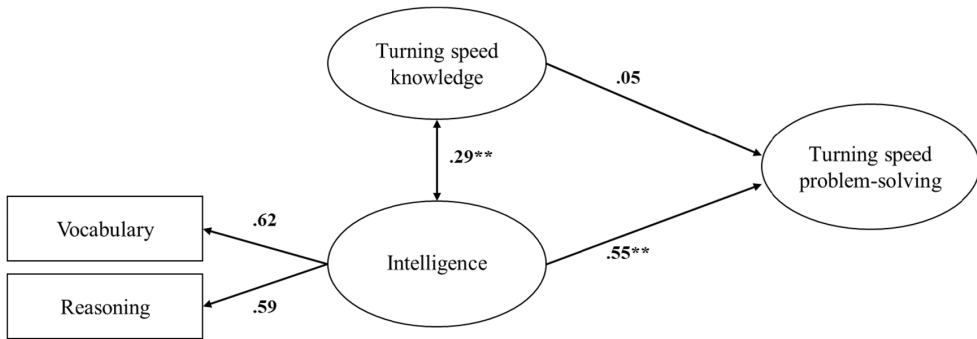


FIGURE A2 Confirmatory factor analysis for the performance in turning speed problem-solving (*propeller task*). * $p < .05$; ** $p < .01$; Unidirectional arrows between latent factors represent regressions, bidirectional arrows represent correlations. Path values represent the standardized estimates. Domain-specific knowledge and problem-solving are defined as single-indicator latent factors (Hayduk & Littvay, 2012).

Confirmatory factor analysis for the performance in turning direction problem-solving (*stabilization task*)

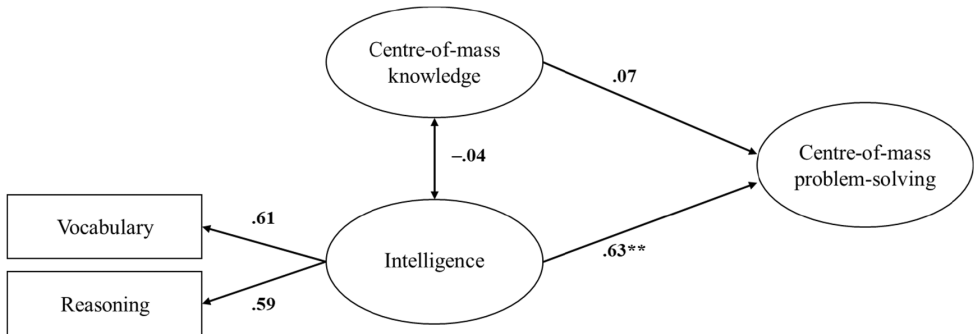


FIGURE A3 Confirmatory factor analysis for the performance in turning direction problem-solving (*stabilization task*). * $p < .05$; ** $p < .01$; Unidirectional arrows between latent factors represent regressions, bidirectional arrows represent correlations. Path values represent the standardized estimates. Domain-specific knowledge and problem-solving are defined as single-indicator latent factors (Hayduk & Littvay, 2012).

TABLE A4 Model fit indices of the confirmatory factor analyses.

Model	χ^2 (df)	p	CFI	TLI	RMSEA (90% CI)	SRMR
Turning direction problem-solving (carousel task)	.26 (1)	.61	1.00	1.04	.00 (.00–.15)	.01
Turning speed problem-solving (propeller task)	.01 (1)	.94	1.00	1.08	.00 (.00–.05)	.00
Centre-of-mass problem-solving (stabilization task)	.18 (1)	.18	.99	.92	.06 (.00–.21)	.02

Note: Model fit indices are evaluated according to Beauducel and Wittmann (2005).