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The role of action concepts in physical reasoning: insights from late childhood

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A fundamental component of human cognition is the ability to intuitively reason about behaviours of objects and systems in the physical world without resorting to explicit scientific knowledge. This skill was traditionally considered a symbolic process. However, in the last decades, there has been a shift towards ideas of embodiment, suggesting that accessing physical knowledge and predicting physical outcomes is grounded in bodily interactions with the environment. Infants and children, who learn mainly through their embodied experiences, serve as a model to probe the link between reasoning and physical concepts. Here, we tested school-aged children (5- to 15-year-olds) in online reasoning games that involve different physical action concepts such as supporting, launching and clearing. We assessed changes in children's performance and strategies over development and their relationships with the different action concepts. Children reasoned more accurately in problems that involved supporting actions compared to launching or clearing actions. Moreover, when children failed, they were more strategic in subsequent attempts when problems involved support rather than launching or clearing. Children improved with age, but improvements differed across action concepts. Our findings suggest that accessing physical knowledge and predicting physical events are affected by action concepts, and those effects change over development.
This article is part of the theme issue 'Minds in movement: embodied cognition in the age of artificial intelligence'.

Cite this article: Grandchamp des Raux H, Ghilardi T, Soderberg C, Ossmy O. 2024 The role of action concepts in physical reasoning: insights from late childhood. *Phil. Trans. R. Soc. B* **379**: 20230154.
https://doi.org/10.1098/rstb.2023.0154

Received: 16 August 2023
Accepted: 28 June 2024

One contribution of 14 to a theme issue 'Minds in movement: embodied cognition in the age of artificial intelligence'.

Subject Areas:
behaviour, cognition

Keywords:
physical reasoning, child development, action concepts, virtual tools, physical cognition, cognitive development

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Electronic supplementary material is available online at https://doi.org/10.6084/m9.figshare.c.7396503.

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1. Introduction

A fundamental aspect of human cognition is the ability to understand the physical properties of the world, regularities in everyday situations and typical human behaviour. These skills enable individuals to anticipate that an object will fall if dropped, or predict obstacles in their route. The pervasiveness nature of this understanding plays a critical role in humans' seamless interactions with the environment [1]. However, despite its ubiquity and apparent simplicity, physical reasoning ironically eludes straightforward scientific interpretation.

For example, consider a scenario where a cup is precariously perched on the edge of a table. Humans' understanding of physics immediately triggers an action to adjust the cup's position to prevent it from falling. This ability to tailor actions according to potential outcomes, even in novel scenarios, signifies the adaptive use of physical reasoning, which illustrates its pivotal role in the human cognitive framework [2,3].

(a) Perspectives on physical reasoning

A contentious debate in cognitive science has revolved around whether physical reasoning is based on abstract symbolic cognitive processes or whether it is fundamentally grounded in our bodily interactions with the environment [4–6]. In other words, is understanding physical laws and predicting physical events a result of rational, logic-based inferences, or is it honed through physical experience? This is not a trivial debate, and its outcomes could fundamentally influence the theoretical understanding of cognition, informing not only psychological research [7] but also applied fields such as artificial intelligence (AI) and robotics, where the replication of human-like physical reasoning remains a formidable challenge [8–10]. Despite considerable progress in building Bayesian models that are capable of human physical reasoning [11,12], these models still fall short when they need to perform and understand physical actions that humans take for granted [13,14].

Traditional research, driven by computational models, has leaned towards the view of physical reasoning as an integrated product of symbolic processes [10]. From this perspective, understanding physical laws and predicting physical events is built on a collection of learned rules and conventions, independent of the body's interaction with the environment [15,16]. However, over the past few decades, a prominent alternative perspective has emerged which argues that cognitive processes are fundamentally grounded in bodily experiences and interactions with the physical and social world [17–19]. For instance, predicting the trajectory of moving objects (e.g. a ball thrown towards them) is driven by the need to physically act upon this prediction (e.g. catch the ball [20]). Moreover, predicting physical events relates to individual variations in motor skills [21,22]. Seasoned athletes with robust physical prowess are more adept at foreseeing the course of a swiftly thrown ball, granting them a competitive edge in timely reactions [23,24]. This interplay between physical prediction and action allows humans to efficiently navigate through dynamic environments, adapt to novel scenarios, and react with precision and agility to unpredictable situations.

(b) Child development as a framework for physical reasoning

Developmental science, with its emphasis on the evolving nature of cognition across the lifespan, offers a unique lens through which physical reasoning can be examined. Long before infants acquire independent mobility or broad experience with their physical environment, they demonstrate intuitive physics [25,26]—a cognitive process involving the ability to reason about behaviours of objects and systems in a physical environment without resorting to explicit scientific knowledge. For example, infants in their first months of life look longer at scenes that violate gravity rules or other physical laws [25,27,28], suggesting they have an 'innate' understanding of the physical world, which develops further in their early years [29]. Infants can also predict object motion with their eyes or track objects when those are occluded as if they already possess some knowledge about basic principles of physics (e.g. object permanence [30,31]). This is supported by observations in different species, such as untaught physical knowledge exhibited by newborn chicks raised in controlled environments [32].

However, despite promising findings in laboratory settings [33], the innate view heavily leans on infants' studies quantifying looking-time differences when the stimuli violate physical laws. Although valuable, these investigations are limited in comprehensively assessing the practical manifestations of infants' physical actions and the extent to which these actions coalesce with physical knowledge [34]. Infants and young children, in their pursuit to comprehend and manipulate their surroundings, are heavily grounded in their sensory-motor experiences [35–39]. Indeed, studies in motor development show that infants internalize patterns and regularities as they navigate through the physical world [37,39,40]. For example, when infants first begin to locomote, they do not demonstrate physical understanding as they attempt impossible actions such as crossing wide gaps and descending steep slopes [40–42]. Over weeks of experience, reasoning becomes increasingly accurate until infants' attempts to descend steep slopes and high drop-offs, cross narrow bridges and ledges or squeeze through narrow doorways match the probability of crawling and walking successfully [35]. This developmental relationship between infants' reasoning and their own motor skills illustrates the embodiment of physical reasoning [38,43].

In older school-aged children, growing up in a different body affects their physical reasoning. For example, children with and without congenital limb differences who experience the physical world differently do not use the same 'obvious' strategies when solving virtual problems that approximate the physics of the real world [44]. Similar body differences affected adults' solutions in the same task, suggesting that tangible encounters with the environment influence their understanding of physical laws and how they predict physical events [44].

(c) Current study

Although current approaches have provided insights into how infants and children learn to access physical knowledge and form physical expectations, they remain limited in testing behaviours that involve more than just moving the eyes. To fill this knowledge gap, the current study aimed to link physical reasoning with physical action concepts.

Physical action concepts encompass stored knowledge that captures principles about the workings of actions in the physical world [44,45]. Specifically, we examined three physical action concepts. The first was 'supporting', which involves understanding the underlying principles of balance, weight distribution and structural integrity to maintain the functionality of a supported entity. Whether it be holding up a shelf, providing a base for an object to rest upon, or offering physical assistance to a person in need, the concept of supporting necessitates the application of force to sustain the target entity in a goal position. Supporting involves early developing motor skills that can be grasped through simple cause-and-effect interactions. For instance, a young child can use a ramp to guide a toy car to roll downhill or place a cushion as a barrier to prevent a ball from rolling off the edge [46,47]. Previous studies of perceptual search suggest that understanding of the support concept emerges around 3 years of age [48].

The second concept—'launching'—is the controlled release or projection of an object into motion through a propulsive force. This concept encompasses the application of force in a particular direction to initiate object movement and predicting its subsequent trajectory. Launching demands more refined motor skills and coordinated movements compared to supporting and therefore develops later (e.g. successfully hitting a stationary ball with a golf club [46,47,49]).

Finally, we examined the 'clearing' concept, which entails the act of removing or displacing objects, obstacles or clutter from a particular area to create a space that is free from obstruction. Clearing demands more advanced motor skills compared to launching and supporting because the child needs to anticipate the movement of multiple objects and their interactions and strategically move or relocate items according to this complex, multi-level anticipation (e.g. removing debris from a pathway [35,47,49]).

We encouraged school-aged children (5- to 15-year-olds) to play the 'Virtual Tools' physical reasoning games [9], which involve the aforementioned action concepts. Children were presented with dynamic two-dimensional virtual environments (figure 1*a*) containing various virtual objects and shaded areas. Although the design of the environment differs from game to game, the objective for each game remained the same: children were encouraged to select and place a blue 'tool' to bring a red object into the green goal area. Upon placing the tool in the scene, the static environment starts to move per the laws of physics (e.g. gravity and collision forces; figure 1*a*). To succeed, children must use their knowledge of real-world physical laws and predict environmental changes. For example, how objects interact once they have positioned and released their selected tool. Children also need to understand which action concept drives a successful interaction between the objects. Importantly, children were not asked to imagine or simulate motor actions corresponding to the different action concepts. This shift from passive observation in looking-time studies to active engagement in the Virtual Tools task not only enhances the measurement of physical reasoning by requiring children to apply their knowledge in novel scenarios, but it also bridges the gap between abstract cognitive processes and action concepts.

We used the Virtual Tools game as a model system to understand the relationships between reasoning and physical action concepts for several reasons. Most critically, as established in previous studies [9,44], the Virtual Tools game presents a diversity of physical reasoning problems that involve different physical action concepts and employ shared physical dynamics that approximate the real world. Therefore, it allows us to test children's knowledge of various physical action concepts [9,44,50]. Moreover, we aimed to fill a critical gap in the literature by testing older children (previous studies focused on infants and pre-schoolers) who had already acquired a variety of motor skills. Critically, virtual games eliminate the confounds of developmental improvements in manual dexterity and strength over this age range. With real three-dimensional objects, children might display the correct reasoning but still fail owing to lack of dexterity and strength [35,51]. In the virtual game, children are only required to place a single object in one mouse press. Thus, analyses could focus on developmental shifts in higher level reasoning.

Our main aim was to test how children's performance in the games changes over development and how these changes are affected by the physical action concepts. Performance was measured in success rate, number of attempts per game and duration of each attempt. Given that the tool's orientation cannot be altered, success hinges on the strategic combination of the tool selection and its placement. For most games, children had a spectrum of tool and placement combinations that led to success. We expected older children to achieve the goal more frequently, faster and with fewer attempts per game than younger children. To address our main aim, we examined performance separately in games that involved different concepts. We predicted better performance in games that involve actions that emerged earlier (e.g. supporting). We also predicted a stronger age effect in concepts that emerge later (e.g. clearing).

Finally, the ability to interpret and extract valuable insights from failed actions is also a key component of physical understanding [52]. Based on previous work, children do not solve Virtual Tools games on their first attempt [44]. Thus, we determined differences in children's attempts if they failed their first attempt. Specifically, for each game, we tested the average number of times they switched tools from one attempt to another and the average distance between tool placements across all their attempts. Frequent tool-switching and long tool-positioning distance indicate poor interpretation of outcomes in failed attempts. We predicted less switching and shorter distances in games that involve supporting and then launching and clearing. We also expected less switching and shorter distances with age.

2. Methods

(a) Participants

We tested 28 children from 5.05 to 15.05 years of age ($M = 9.96$ years; 13 girls; figure 1*c*). Children were recruited from advertisements, referrals and a pool of families who expressed interest in participating in online research through the Centre for Brain and Cognitive Development at Birkbeck, University of London. All the participants were typically developing children with normal vision. Participation was anonymous, and children were informed that they could withdraw at any time. The study was granted ethical approval by the Psychology Ethics Committee at Birkbeck, University of London (reference no. 2122028). The current report was pre-registered as part of a larger study that included a power analysis [53].

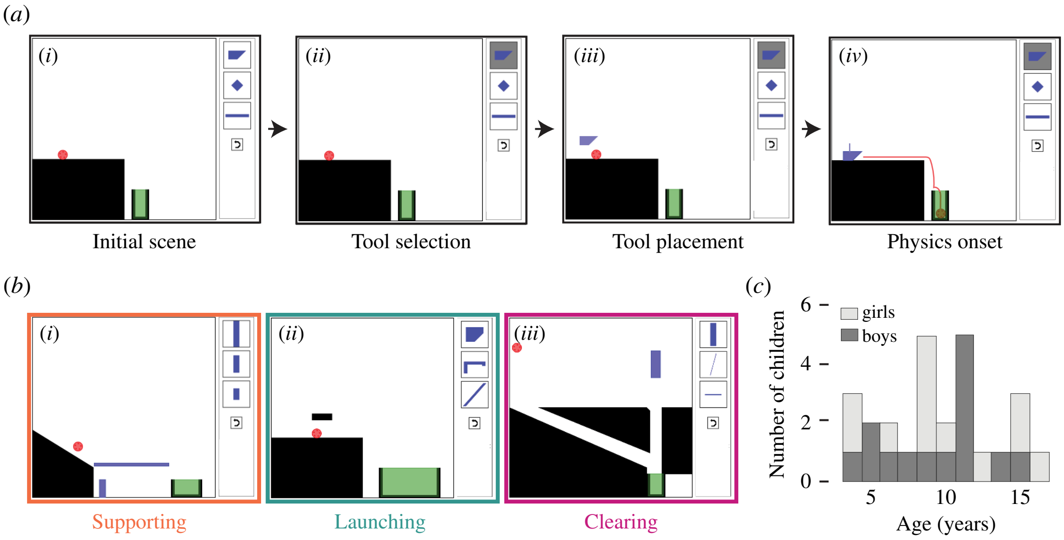

Figure 1. (*a*) Illustrative trial of the first Virtual Tools game children played (was not included in the analyses). The aim is to bring the red object into the green area using one of the three blue shapes (tools). (i) Once the initial scene appears, (ii) the child has to select a tool, and (iii) place it in the scene. Once the tool was placed, the laws of physics started (iv). (*b*) One exemplar game for each physical action concept: (i) supporting (using the tool to support the existing environment; orange box), (ii) launching (using the tool to initiate the movement of the red object; turquoise box), and (iii) clearing (using the tool to clear a blockage; magenta box). (*c*) Number of children tested per age and sex.

(b) Virtual Tools game

We used an online gaming framework developed by Allen *et al*. [9] named 'Virtual Tools' (figure 1*a*). The Virtual Tools task was used in previous research to assess physical reasoning in adults and children [9,44,50,54]. This framework consists of a series of games in which children are asked to select one of three tools and place it on the screen (in one click, there is no movement trajectory) to accomplish a goal condition—get a red object into a green goal area. The placement of the tool triggers a physical cascade, which approximates the physics of the real world, including gravity and object-to-object interactions [9,44,54]. Participants could attempt to place tools up to seven times without a time limit. The game was reset to its initial state after each failed attempt. If the attempt was successful, participants moved to the next game. For each attempt, we recorded which tool participants selected, where they placed it, when they placed it and whether they succeeded.

(c) Procedure

The experiment was available both in English and in French. It started with a brief introduction of the study and separated consent forms for parents and children. Recent published research [44] has shown that Virtual Tools is appropriate for children older than 5 years of age. In the current experiment, we also required parents to confirm that their children can play online games independently. After consent, children were given instructions about the rules of the game. Children were then familiarized with the experiment by practising in two initial games before the main part of the experiment began. Children then played 23 games and received visually presented feedback on their success (green tick or red cross) after each attempt. The first game out of the 23 games in the main part of the experiment included an elementary physical environment ('basic' game; figure 1*a*) and was not included in analyses that relate to physical action concepts. The electronic supplementary material, figure S1 shows the 22 games that were included in the analysis, split into the different physical action concepts.

(d) Physical action concepts

Although the goal was the same for each game, there were differences in environments and demands for actions (figure 1*b*). We split the games into three groups according to the physical action concept they involve. Based on previous data [9,44], we verified that the difficulty level of the games across action concepts did not differ for adults.

(i) Supporting

This group includes games that require the use of the tool to maintain local conditions and achieve the goal. The supporting games included environments in which gravity initiates the movement of the red object, and the tool must be used to support an *existing surface* to allow the red object to reach the goal (target green area). The environments of supporting games are shown in the electronic supplementary material, figure S1 (left column).

(ii) Launching

The launching group includes games in which the tool is used to *initiate the movement* of an object to satisfy the goal. In the launching games, participants had to place the tool so its interaction with the *stationary red object* would lead to a movement that ended in the target green area. See the electronic supplementary material, figure S1 (middle column) for all launching games.

(iii) Clearing

This group includes games in which the tool is used to clear a *moving* obstacle from blocking an already moving object from reaching the goal. In these games, gravity has already initiated the movements of the red object and another blue object in the environment, which blocks the target object from reaching the target green area. The participant is required to use the tool to prevent this blockage. Clearing games differ from supporting games mainly in what blocks the moving object from reaching its goal. If the blockage is caused by a removable obstacle, then it is a clearing game. If the blockage is caused by the lack of support from the existing environment, then it is a supporting game. The environments of clearing games are shown in the electronic supplementary material, figure S1 (right column).

(e) Attempt analysis

To assess how children interpret failed actions to improve subsequent performance, we determined how they attempted to solve each game by measuring (i) the percentage of tool-switching, and (ii) the average tool-positioning distance. In this analysis, we focused only on games in which the child failed to solve the game on the first try.

To calculate the percentage of tool switching, for each game and each attempt (starting from the second attempt), we compared whether the selected tool was identical to the one used in the previous attempt. For each game, we evaluated the percentage of attempts in which the selected tool was different. We then averaged the percentage of tool switching across all games within each physical action concept.

For the average tool-use positioning distance, we calculated for each game the average Euclidean distance in pixels between the positioning of the tool in each attempt and the previous attempt. For each game, we averaged this Euclidean distance across all attempts (starting from the second attempt), yielding an average tool-use positioning distance per game. Then, we averaged the positioning distance across all games within each physical action concept.

(f) Inferential statistical analysis

To investigate the role of action concepts in children's performance, we used one-way ANOVA to test differences between action concepts in each measure: success rate (proportion of successful solutions across games per participant), average number of attempts, average time per attempt, percentage of tool-switching and tool-positioning distance.

To test developmental changes and how they relate to action concepts, we used linear mixed-effects models [55,56], which test both fixed effects (the main effects we are interested in) and random effects (the variability among subjects). In each model, we included an interaction of action concept and age as fixed effects and incorporated a random intercept for each child. This approach is effective in addressing individual variances and in managing the correlations among repeated measures for each child, thereby providing a more accurate and comprehensive analysis of the role of age in the effects of action concept. Where the models showed significant interactions between action concepts and age, we estimated the beta coefficient (or slope) of age within each action concept and assessed whether these significantly differed from zero.

3. Results

(a) Success rate, attempts and duration

Children completed on average $M = 21.82$, s.d. = 1.59 games. Preliminary analyses showed no significant effect of sex, so we combined boys and girls in subsequent analyses. Overall, children were successful in $M = 71.15\%$ (s.d. = 16.61%) of the games and completed each game in $M = 3.77$ attempts (s.d. = 0.98), and each attempt lasted $M = 10.64$ s per attempt (s.d. = 5.82). As expected, children became more successful ($r_{26} = 0.69$, $p < 0.001$) and had less attempts ($r_{26} = -0.76$, $p < 0.001$; figure 2*b*) with age. However, children did not become significantly faster with age ($r_{26} = -0.14$, $p = 0.46$).

(b) Performance per physical action concept

Children performed differently in games involving different physical action concepts (figure 2). As expected, children were best in the supporting games as they succeeded in $M = 76.45\%$, s.d. = 17.54 of the games and had fewer attempts ($M = 3.29$, s.d. = 1.26). However, in contrast to our prediction, children were better in clearing ($M = 71.49\%$, s.d. = 25.19 success and had $M = 3.82$, s.d. = 1.40 attempts) compared to launching ($M = 56.73\%$, s.d. = 34.55 success and had $M = 4.62$, s.d. = 1.68 attempts). Two repeated-measures ANOVA on children's success rate and average number of attempts confirmed an effect of the physical

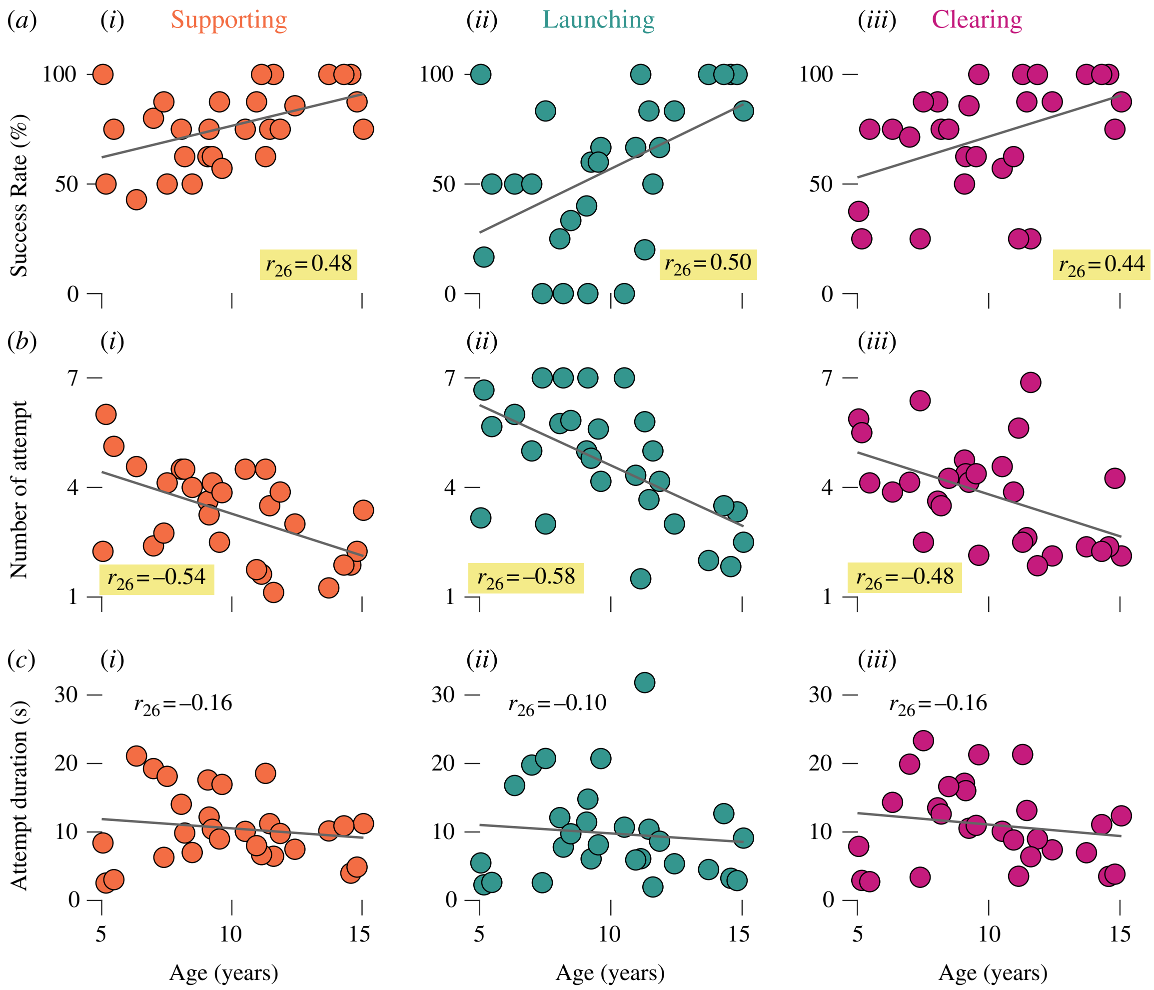

Figure 2. Scatterplots showing the correlation between children's age and their performance in games that involve supporting ((i) orange data points), launching ((ii) turquoise data points) and clearing ((iii) magenta data points). Yellow highlighting denotes significant correlations $ps < 0.05$. (*a*) Correlation between success rate and age. (*b*) Correlation between number of attempts and age. (*c*) Correlation between average attempt duration and age.

action concept ($F_{2,54} = 5.36$, $p < 0.01$ and $F_{2,54} = 8.50$, $p < 0.01$, respectively). Sidak-corrected post hoc comparison tests showed that supporting games were solved more frequently and in fewer attempts, $p < 0.01$ compared to launching games.

We did not find significant differences in the average duration per attempt across the different physical action concepts ($M_{\text{supporting}} = 10.54$, s.d.$_{\text{supporting}} = 5.08$ s; $M_{\text{launching}} = 9.80$, s.d.$_{\text{launching}} = 7.05$ s; $M_{\text{clearing}} = 11.09$, s.d.$_{\text{clearing}} = 6.05$ s). A repeated-measures ANOVA on the average attempt duration confirmed no effect of concept ($F_{2,54} = 2.10$, $p < 0.2$).

The scatter plots in figure 2*a,b* show that children were significantly more successful and had significantly fewer attempts with age in each one of the physical action concepts. Improvements in success rate were stronger in launching games ($r_{\text{launching, 26}} = 0.50$, $p < 0.01$) than in supporting and clearing games ($r_{\text{supporting, 26}} = 0.48$, $p < 0.01$, $r_{\text{clearing, 26}} = 0.44$, $p < 0.05$), and similarly, improvements in the average number of attempts were stronger in launching games ($r_{26} = -0.58$, $p < 0.01$), than supporting games ($r_{26} = -0.54$, $p < 0.01$) or clearing ($r_{26} = -0.48$, $p < 0.01$). Figure 2*c* shows that children became faster with age in all physical action concepts, but none of those changes was significant ($r_{\text{supporting, 26}} = -0.16$, $r_{\text{launching, 26}} = -0.10$, $r_{\text{clearing, 26}} = -0.16$; $ps > 0.05$).

When including interaction with age in our models, for success rate, we found a significant main effect of age ($\chi^2_1 = 5.75$, $p < 0.03$). Similarly, for the number of attempts, we found a significant main effect of age ($\chi^2_1 = 8.01$, $p < 0.01$). For time per attempt, we found no significant effects.

(c) Differences in strategy between action concepts

Finally, we examined differences in how children attempted to solve the games after failing in their first attempt (figure 3). As expected, children switched tools less in supporting games (children switched the tool in $M = 58.69\%$, s.d. = 30.60 of the attempts) than in launching games ($M = 63.00\%$, s.d. = 26.94) and clearing games ($M = 62.9\%$, s.d. = 22.04). However, these differences were not significant ($F_{2,54} = 0.47$, $p = 0.63$).

We determined the average distance of tool positionings per game across attempts (see Methods). As expected, this average tool-positioning distance was shortest in the supporting games ($M = 106.78$, s.d. = 70.92) then the launching games ($M = 126.83$, s.d. = 60.87) and finally the clearing games ($M = 155.24$, s.d. = 82.54). A repeated-measures ANOVA confirmed a significant effect of concept ($F_{2,54} = 5.38$, $p < 0.01$).

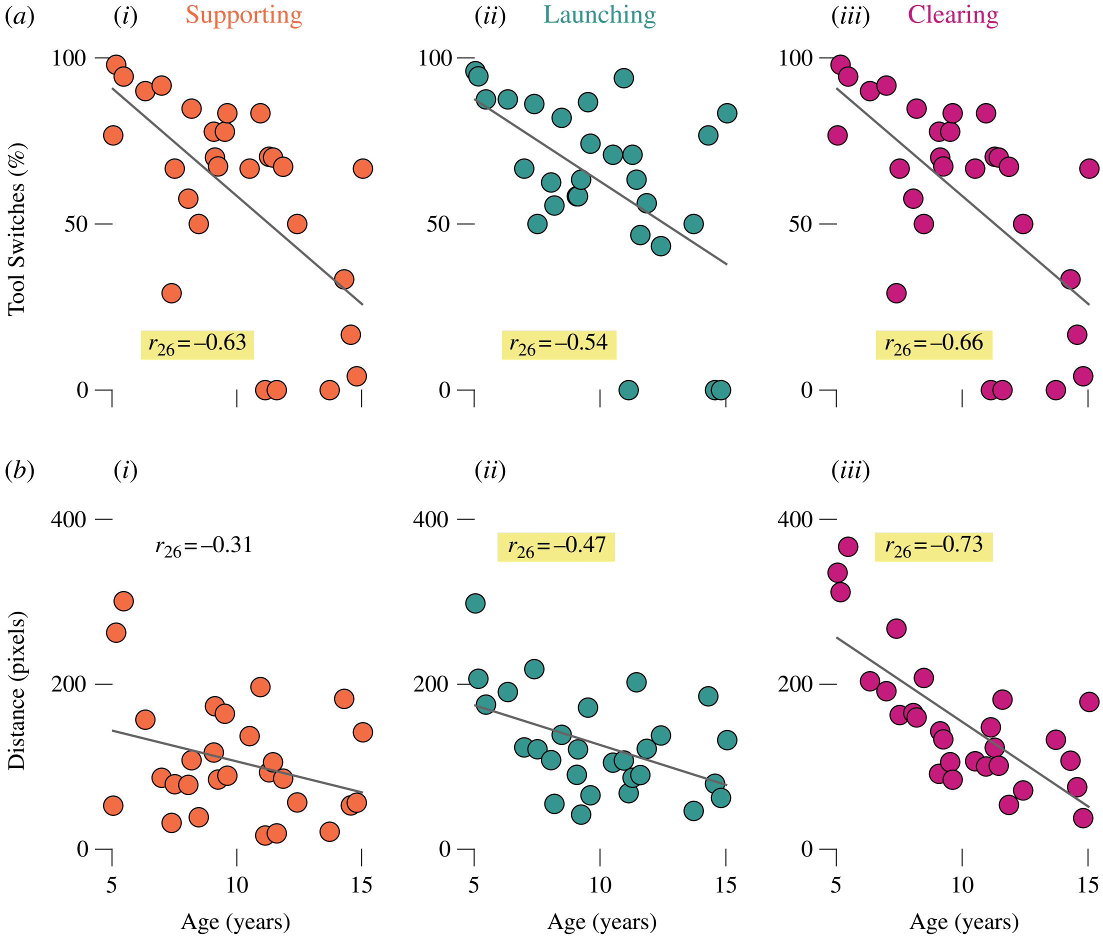

Figure 3. Scatterplots showing the correlation between children's age and their (*a*) average tool-switching and (*b*) average tool-positioning distance, for each physical action concept ((i) supporting; (ii) launching and (iii) clearing). When children failed in their first attempt, they had less tool switching and less distance between tool positionings with age. Yellow highlighting denotes significant correlations *ps* < 0.05.

Figure 3*a* shows the developmental changes in the percentage of tool switching and figure 3*b* in the average tool-positioning distance for each physical action concept. Children switched tools less with age, regardless of physical action concepts ($r_{\text{supporting, 26}} = -0.63$, $r_{\text{launching, 26}} = -0.54$, $r_{\text{clearing, 26}} = -0.66$; $ps < 0.01$). The average tool-positioning distance also significantly decreased with age in clearing and launching games, with a sharper decrease in clearing games ($r_{26} = -0.73$, $p < 0.001$) compared to launching games ($r_{26} = -0.47$, $p = 0.01$), but not in supporting games ($r_{26} = -0.31$, $p > 0.05$).

For our strategy measures, when including an interaction with age in our models, we found a significant relationship between tool switches and age ($\chi^2_1 = 12.31$, $p < 0.01$). For placement distance, we did find a significant relationship between distance and age ($\chi^2_1 = 27.07$, $p < 0.01$) and interaction between age and action concept ($\chi^2_1 = 8.29$, $p < 0.02$). The distance decreased with age in both the clearing and launching concepts (coefficient = −20.51, $t_{69.66} = -5.20$, $p < 0.01$ and coefficient = −9.66, $t_{69.66} = -2.45$, $p < 0.03$, respectively), but not in the supporting action concept group (coefficient = −7.48, $t_{69.66} = -1.90$, $p >$ 0.05).

4. Discussion

This study tested whether physical action concepts affect physical reasoning in school-aged children. To that end, we compared how children solved reasoning problems involving concepts such as supporting, launching and clearing. Findings show that children improve with age and their improvement is affected by the action concept. Moreover, when children failed in their first attempt, they had less tool switching and less distance between tool positioning in the supporting concept compared to the launching and clearing concepts, suggesting that their ability to interpret failed actions and adapt their physical prediction is also affected by the action concept. For one of the strategy measures, the linear mixed-effect model showed more efficient strategies in older children compared to younger ones in games involving clearing and launching but not in supporting. The physical action concepts correspond to motor skills that develop at different stages.

The foundational principle of physical reasoning is that humans share inherent intuitions about the physical world, encompassing rules of gravity, object persistence, collision dynamics and so on [25,27]. These intuitions serve as a common thread that runs through human cognition, shaping how people perceive, reason about and interact with their environment [26]. Despite variations in skills and environmental contexts, understanding physical laws and predicting physical events are believed to be consistent and deeply ingrained, driving the emergence of common patterns in how all humans navigate their surroundings [57]. Early developmental research used looking-time techniques to provide evidence for these intuitions in infants and young children [25,27,30]. In those studies, passive infants are considered to exhibit physical reasoning (e.g. object permanence or movement) when they exhibit prolonged attention towards scenes that defy the laws of physics.

However, physical knowledge and the ability to predict physical events serve the purpose of generating and directing behaviours including object manipulation or multi-step planning (e.g. retrieving items from a distant location using tools [39,58,59]). We argue that the Virtual Tools games involve more physical expectations and access to physical knowledge than looking-time tasks. While there is no substantial motor component in executing the action, it necessitates more sophisticated motor cognition because it involves abstracting and applying motor principles to virtual scenarios, which demands a higher level of cognitive engagement and predictive modelling. From this perspective, our findings expand looking-time studies by showing developmental improvement in physical reasoning in late childhood when children are required to actively predict the outcome of a physical simulation and not only observe it passively. Children were more successful with age in selecting tools and positioning them to create a desired sequence of object behaviours. Moreover, older children's actions after failures were more strategic than the younger ones, suggesting they are better at extracting valuable insights to improve prediction. In contrast to our expectations, children did not become significantly faster with age. This might relate to the lack of explicit instruction to complete the game rapidly.

Critical to the interest of this study, we show that children's physical prediction is affected by the concept of physical action. Children predicted more accurately the outcomes of supporting actions compared to launching or clearing actions. Similarly, when children failed in their first attempt, they were more strategic in subsequent attempts when supporting actions were involved. Previous work with adults [9] did not show similar differences across concepts. This discrepancy might suggest that the interplay between physical reasoning and physical action concepts evolves during late childhood, with children demonstrating a heightened sensitivity to the specific demands posed by different types of actions. This argument is supported by the significant interaction between the physical action concept and age, which is particularly evident in the strategy analysis. This interaction suggests that as children develop, their problem-solving abilities not only improve overall but their strategies to success vary according to the physical action concept presented.

The physical action concepts differ not only in the demands they pose but also in the development of corresponding motor skills [46,47,49]. Children are successful in using a ramp to guide a toy car to roll downhill (supporting action) before they learn to hit a golf ball (launching action) or remove obstacles (clearing action). Although children of school age have already acquired these skills, their embodied experience with each one of those action concepts differs. Research on balance control in infants supported this idea by showing that physical prediction depends on the amount of experience in a specific motor skill, with no automatic transfer effect to a later developing motor skill [43]. In older children, some studies suggest a similar association between motor and cognitive development in 6-year-old children in the domain of mathematical cognition [60–62]. Our findings may inform future research aiming to determine causality in the relationships between motor skills and physical reasoning. Motor training, for example, has beneficial effects on cognitive performance from infancy to late childhood [63–65], but we are not aware of any study that investigated whether motor training affects physical reasoning within different action concepts.

That said, our experiment does not directly address the question of embodiment, and our findings do not provide sufficient information into whether children were using motor simulation during the Virtual Tools game. Previous research using physical problem-solving tasks and tool use showed that children can use strategies involving clearing and supporting principles together with other types of strategies [66,67], but it is not clear to what extent children use their motor knowledge and incorporate it into the reasoning processes. Future studies should expand our findings by measuring children's motor skills, specifically using a test designed for school-aged children, such as the Bruininks-Oseretsky Test of Motor Proficiency, second edition (BOT-2) short form and control for general cognitive abilities.

Finally, findings are relevant to the AI and robotics communities that are interested in understanding how physical reasoning emerges from an embodied system. Research in AI is limited in using child behaviour as a guide [68–70]. Some previous research has presented computational models that demonstrate aspects of physical reasoning [10–12], including in the Virtual Tools task [9]. However, can this reasoning drive active behaviour? Our findings suggest that AI agents will assimilate reasoning in an implicit manner by having embodied experiences that improve the agents' environmental perception and give rise to physical action concepts. Such an approach will not only yield better algorithms but will also deepen our understanding of physical reasoning as a process that is, as suggested here, largely connected to interactions with the actual physical world.

Ethics. The study was granted ethical approval by the Psychology Ethics Committee at Birkbeck, University of London (reference no. 2122028).

Data accessibility. Data are provided via GithHub: https://github.com/Physical-Cognition-Lab/The-Role-of-Action-Concepts-in-Physical-Reasoning-Insight-from-Late-Childhood.

Electronic supplementary material available online [71].

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. H.Gd.R.: conceptualization, formal analysis, investigation, methodology, project administration, validation, writing—review and editing; T.G.: formal analysis, writing—review and editing; C.S.: methodology, validation, visualization; O.O.: conceptualization, funding acquisition, investigation, methodology, resources, supervision, validation, visualization, writing—original draft, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

Funding. Funding was received by the British Academy (BA Talent Award TDA21\210038), the Leverhulme Trust (grant no. RPG-2022-327), the UK Research and Innovation (ESRC New Investigator grant ES/W009242/1), the Waterloo Foundation (grant no. 917-4975) and the Wellcome Trust.

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