Developmental Review 81 (2026) 101279

Contents lists available at ScienceDirect

Developmental Review

journal homepage: www.elsevier.com/locate/dr

Beyond reach and grasp: the development of high-order planning for manual actions in typically developing children

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ARTICLE INFO

Keywords:
Action planning
Motor development
Systematic review
Manual actions
Infancy
Anticipatory planning
High-order planning

ABSTRACT

High-order action planning is the capacity to anticipate and organise two or more action steps before moving, requiring integration of cognitive, motor, and perceptual processes. High-order planning underpins goal-directed behaviour, enabling efficient problem-solving, skilled tool use, and adaptation to the environment. Developmental research shows that high-order planning skills emerge gradually in childhood, with adult-like responses appearing in older childhood, depending on the task. This systematic review investigates the development of high-order action planning in manual tasks from infancy to adolescence. Following the PRISMA 2020 guidelines, we searched PubMed and Scopus and identified 37 relevant studies after screening. Behavioural and kinematic differences during movement indicate that children as young as three years exhibit adult-like performance in high-order planning in tasks with low motor requirements and show degrees of adaptation in tasks that detect graded adjustments. Non-adult-like performance in young children appears more attributable to motor constraints than to a lack of planning ability. Children show high interindividual variance and occasionally non-linear development until around eight years. Recent research has begun to disentangle the development of action planning from the development of cognition. Findings show that high-order action planning is more closely associated with motor-related skills than with high-level, abstract planning and cognition. We argue that future research should focus on inter-individual variance and adopt real-time, multi-modal measures to reveal mechanisms underlying high-order action planning.

Introduction

Functional daily life demands humans to plan a sequence of steps with efficiency and minimal conscious effort. Planning is often conceptualised more broadly as a domain-general cognitive ability, supporting goal-directed behaviour across perceptual, motor, and abstract problem-solving contexts (e.g., Diamond, 2013; Keen, 2011). In the present review, however, we focus specifically on planning for multi-step, manual action sequences, which provides insight into how planning processes develop in the context of real-world actions. Such *high-order* action planning supports nearly all everyday skills children must master, e.g., feeding, dressing, playing and using tools. Acquiring this skill begins in early childhood (McCarty et al., 1999) and continues throughout development, as children learn to adapt their high-order action planning to an ever-changing environment (Lee et al., 2006). Tool-use tasks, for

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https://doi.org/10.1016/j.dr.2026.101279
Received 27 January 2026; Received in revised form 29 May 2026;
0273-2297/

example, provide a natural window into children's emerging high-order planning abilities: they require the coordination of perceptual, motor, and cognitive processes over time and across a sequence of action steps whose future states must be anticipated (Keen, 2011; Lockman, 2000). The choice of which hand grasps and wields an object, and the posture and velocity of that hand, are quantifiable, and research has revealed that these measures can be used to infer the degree to which a manual action was planned (e.g., Adalbjornsson et al., 2008; Manoel & Moreira, 2005; McCarty et al., 1999).

A seminal study by McCarty et al. (1999) tested high-order action planning in infants using a tool-use paradigm—spoon feeding. In such a paradigm, the focus is on trials when the handle is pointed away from infants' preferred hand, requiring them to select the non-preferred hand—a non-habitual action requiring planning for a 'future' secondary transport phase of moving the spoon toward the mouth—whereas a grip with the preferred hand results in an awkward feeding posture and reflects a lack of planning (Fig. 1). Importantly, the potential awkward posture is not visually apparent at the outset; efficient performance thus requires constructing a 'mental image' of the ideal future state and adjusting the initial grasp accordingly.

Planning is often described as a conflict between habitual and goal-directed behaviours (Stöckel et al., 2012). Habitual action can reduce cognitive effort relative to planning a goal-directed movement, but the latter may be more advantageous when the environment has changed. Adults readily adopt goal-directed actions in simple tasks (e.g., Rosenbaum et al., 1992), whereas young children rely more heavily on habitual grips (Stöckel et al., 2012). This distinction extends to action sequences of three or more orders, in which the individual must adapt the initial step to accommodate all subsequent action steps. In this review, the term *high-order planning* refers to planning for all actions that require *two or more steps*.

High-order planning and its emergence in children have been historically studied using the *end-state comfort effect* (ESC; Adalbjornsson et al., 2008; Rosenbaum et al., 1996, Rosenbaum et al., 2006, Rosenbaum et al., 2012), in which the actor sacrifices comfort at the first step of the action to enable a more functional, efficient last step (Rosenbaum et al., 1990). For example, consider an upturned glass on a table: righting the glass so that water can be poured efficiently typically requires a less-comfortable initial grip with the thumb pointing down, resulting in a more comfortable end grip (Fig. 1). A more abstract example is the bar-transport task (Rosenbaum et al., 1990), in which a horizontal bar rests on two plinths, and the participant must grasp it and insert one end into a vertical aperture. In critical trials, the end to be inserted points away from the dominant hand; ESC is therefore achieved when the participant adopts an *underhand* initial grip (Fig. 1). Measuring the frequency of ESC-adaptive actions across ages provides a window into the emergence of high-order action-planning abilities.

Traditionally, action-planning research has been outcome-oriented: researchers documented behaviours such as the posture of an initial grip (e.g., Lockman et al., 1984), or successful achievement of the action's goal. However, motion-tracking (MT) technology offered an alternative approach and has been used to measure kinematics and reveal differences between populations' reach trajectories as far back as the 1980's (e.g., MacKenzie et al., 1987). MT allows researchers to measure reaction times and motion times, and—through real-time sampling at frequent, regular intervals—accelerations and decelerations within reach and transport phases. One of the first studies to apply this technology to children completing manual tasks was Claxton et al. (2003). They measured reach kinematics of 10-month-old infants during an object-fitting task and demonstrated that the infants modified their reach according to the precision required for the fitting phase. An outcome-based approach that merely measured successful object fitting could not demonstrate anticipatory planning and prospective control in infants; MT therefore provided, for the first time, a window into the underlying mechanisms behind action planning.

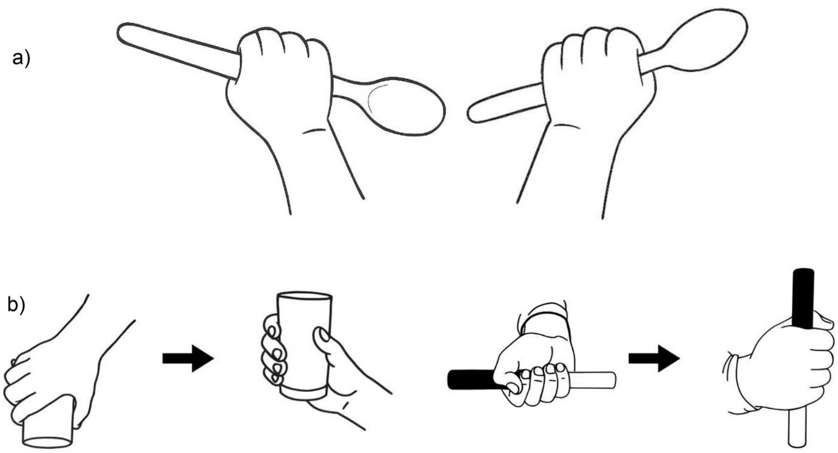

Fig. 1. Adaptive and non-adaptive grips.
Note: (a) Infants grip choices on a spoon when the handle points away from the preferred hand. Gripping with the preferred hand (left) indicates a failure to plan and adapt for a second-order action sequence; gripping with the non-preferred hand (right) provides more efficient transport. (b) Example initial grips adapting for ESC. The upturned-glass task (left) and bar-transport task (right). A less-comfortable, non-habitual initial grip on the object facilitates a more-comfortable end-state grip. Upper image adapted from *Problem solving in infancy: The emergence of an action plan* by McCarty et al., 1999, *Developmental Psychology*, 35(4), p. 1094 (10.1037/0012-1649.35.4.1091). Lower image adapted from *The development of tool use: Planning for end-state comfort* by Comalli et al., 2016, *Developmental Psychology*, 52(11), p. 1979 (10.1037/dev0000207).

At what age do children develop high-order action planning skills? Wunsch et al. (2013) conducted a systematic review of 13 studies on ESC in children and reported consistently low ESC rates in infants and toddlers aged three years and under (e.g., Adalbjornsson et al., 2008; Jovanovic & Schwarzer, 2011; Knudsen et al., 2012). For older children, however, findings were mixed: some studies reported near adult-like performance by eight years (e.g., Knudsen et al., 2012), whereas others observed clear immaturities at the same age (e.g., Crajé et al., 2010). The review concludes that task demands—such as precision and complexity—likely contribute to these discrepancies. Yet, why some paradigms elicited ESC in younger children than others remained an open question. The review also highlighted that interdependencies between action planning and cognition are poorly understood and warrant further investigation. Against this backdrop, the current review examines whether more recent research clarified the ontogeny of high-order planning in children, identified task properties that contribute to the age at which high-order-planning begin to appear, and—given advances in motion-tracking and other real-time data-capture technologies—provided new insights into the underlying processes and their relationship with cognitive functions.

More specifically, we aim to reveal how the last 12 years of research have addressed the following knowledge gaps: a) the age at which children acquire high-order-planning skills in manual actions, b) the effect of task complexity and context upon the emergence of high-order-planning in manual actions, and c) the relationships between high-order planning in manual actions and cognition in developing children.

Method

This systematic review was conducted in accordance with the PRISMA 2020 guidelines (Page, McKenzie, et al., 2021; Page, Moher, et al., 2021). Sources were identified via PubMed and Scopus searches conducted on 25 October 2025. To be eligible for the initial stage, reports were required to include at least one of the following terms in the title, abstract, or keywords: *"anticipatory planning", "action planning", "high-order planning", "object fitting", "object manipulation", "motor planning", "manual actions", "manual skills", "motor development", "action sequences", "planning sequences", "problem solving", "second-order planning", "tool use"*. In addition, the title, abstract or keywords needed to contain at least one of *"development", "infants"* or *"children"*. Only English-language studies with human child participants (16 years or younger) were included. To avoid overlap with a previous systematic review (Wunsch et al., 2013), entries published prior to 2013 and two studies from 2013 already reviewed (Jongbloed-Pereboom et al., 2013; Scharoun & Bryden, 2013), were excluded. Full search terms for each database are provided in the appendix.

The following reports were excluded: (a) reviews, (b) studies whose paradigms did not involve manual action (e.g., locomotion), (c) studies focused on the development of non-motor skills (e.g., tool innovation, tool selection, logical reasoning, observational learning), and (d) studies that did not investigate high-order planning (e.g., single-order reach-and-grasp or simple object-fitting tasks). For reports including both adults and children, only the results from children were included. For reports including groups of both typically developing (TD) and atypically developing (AD) children, *only the results from TD children were included*, as studies of children with developmental coordination disorder far outnumbered other clinical groups, and a recent systematic review already examined ESC in this population (Bhoyroo et al., 2020). These exclusions helped avoid unnecessary repetition and maintain the review's developmental focus.

Reports for which a full text was unavailable were discarded, and the remaining reports were manually screened using the same criteria. For each included report, metadata were extracted, including the experimental paradigm, number of trials, participant ages and sample sizes, outcome measures (e.g., task success, grip selection, kinematic data), and variables under test (Tables 1 and 2).

No formal assessment of study quality or risk of bias was conducted. The review therefore provides a descriptive synthesis of the available evidence rather than a critical appraisal of methodological quality; although all included reports were drawn from peer-reviewed journals, potential limitations in study design and reporting remain, and findings should be interpreted accordingly.

The purpose of this review was to examine developmental trends and identify themes in the interpretation of high-order action planning across childhood. Because studies investigated diverse outcomes and used varied capture and analysis techniques, a quantitative meta-analysis was unwarranted. All eligible studies were included in the synthesis, which adopts a narrative, thematic approach. Reports were labelled and categorised based on extracted metadata, summaries were assembled, and trends were identified.

Table 1
Distribution of high-order action-planning task types across included studies.

Task type	No. of studies	References
Transport (ESC)	11	Bäckström et al., 2021, 2025; Domellöf et al., 2020; Gottwald et al., 2017; Gottwald et al., 2019; Herbort et al., 2018; Jovanovic & Schwarzer, 2017a; Martel et al., 2020; Stöckel & Hughes, 2015; Toussaint et al., 2013; Wilmut et al., 2013
Upturned object (ESC)	7	Jongbloed-Pereboom et al., 2016; Jovanovic & Schwarzer, 2017b; Melzel & Paulus, 2022; Scharoun, Gonzalez, et al., 2018; Scharoun, Robinson, et al., 2018; Wunsch et al., 2015, Wunsch et al., 2016
Rotation (ESC)	17	Adams et al., 2016; Adams et al., 2017a, 2017b; Bäckström et al., 2021, 2025; Bhoyroo et al., 2018, 2019; Domellöf et al., 2020; Herbort et al., 2018; Fuelscher et al., 2016; Jongbloed-Pereboom et al., 2016; Krajenbrink et al., 2020; Krajenbrink, Lust, Beckers, & Steenbergen, 2021; Krajenbrink, Lust, & Steenbergen, 2021; Pratt et al., 2014; Wilmut & Byrne, 2014a, 2014b
Hammer (ESC)	5	Comalli et al., 2016; Golmakani et al., 2025; Jovanovic et al., 2021; Krajenbrink, Lust, & Steenbergen, 2021; Ossmy et al., 2022
Non-ESC	3	Cox & Smitsman, 2019; Melzel & Paulus, 2022; Niechwiej-Szwedo et al., 2025

Table 2
Authors, task categories, number of trials[a], primary measures, age groups (with count[b]) for all included studies.

Authors	Task(s)	No. Trials	Measure	Primary IV(s)	0–1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Toussaint et al., 2013	Transport	20	ESC	Task Demands						32		32								
Stöckel & Hughes, 2015	Transport	16	ESC	Task Demands						16	16	16	16	16						
Gottwald et al., 2017	Transport	48	Kinematics	Task Demands	37															
Jovanovic & Schwarzer, 2017a	Transport	4	ESC	Age			30		27											
Gottwald et al., 2019	Transport	18	Kinematics	Task Demands	61															
Martel et al., 2020	Transport	60	Kinematics	Age					10		10		10							
Wilmut et al., 2013	Transport	24	Kinematics	Clinical group								24								
Wunsch et al., 2015	Upturned object	8	ESC	Age			18				23		19							
Jovanovic & Schwarzer, 2017b	Upturned object	16	ESC	Context			39	31												
Scharoun, Robinson, et al., 2018	Upturned object	3	ESC	Gender and Age					No information on numbers or distribution, only age range											
Scharoun, Gonzalez, et al., 2018	Upturned object	48	ESC	Age							232									
Melzel & Paulus, 2022	Upturned, Insertion	16	ESC	Context		33	42		29	37		37						34		
Jongbloed-Pereboom et al., 2016	Rotation, Upturned object	3 + 12 + 12	ESC	Age and Task Demands				21		20		18		20				20		
Wunsch et al., 2016	Rotation, Transport	6 + 18 + 6	ESC	Task Demands			21	23	26	22	26	27	23	21						
Herbort et al., 2018	Rotation, Transport	60 + 12	ESC	Task Demands					24											
Bäckström et al., 2021	Rotation, Transport	24	Kinematics	Clinical group						12										
Bäckström et al., 2025	Rotation, Transport	24	Kinematics	Clinical group						17										
Domellöf et al., 2020	Rotation, Transport	20	Kinematics	Age						8				8						
Krajenbrink et al., 2020	Rotation	48	ESC	Age					35	39	37	35	54	45	41	25				
Wilmut & Byrne, 2014a	Rotation	11	ESC	Clinical group							20									
Wilmut & Byrne, 2014b	Rotation	36	ESC	Task Demands				20			20			20						
Pratt et al., 2014	Rotation	16	ESC	Clinical group							24									
Adams et al., 2016	Rotation	18 + 32	ESC	Clinical group						3										
Adams et al., 2017a	Rotation	18	ESC	Clinical group						30										
Adams et al., 2017b	Rotation	18	ESC	Clinical group						33										
Bhoyroo et al., 2018	Rotation	12	ESC	Clinical group								17								
Bhoyroo et al., 2019	Rotation	24	ESC	Clinical group							18									
Fuelscher et al., 2016	Rotation	36	ESC	Clinical group						12		18								
Krajenbrink, Lust, Beckers, & Steenbergen, 2021	Rotation	40	ESC	Clinical group						26										
Krajenbrink, Lust, & Steenbergen, 2021	Rotation, Hammer	18 + 18	ESC	Clinical group					9											
Comalli et al., 2016	Hammer	20 + 20	ESC	Age				52				13				13				
Ossmy et al., 2022	Hammer	60	ESC	Task Demands			32													
Golmakani et al., 2025	Hammer	60	ESC	Task Demands			23													
Paulus, 2016	Social	10 + 10 + 10	BSC	Context			20		20		23									
Jovanovic et al., 2021	Social, Hammer	18 + 18	BSC	Context					32											
Cox & Smitsman, 2019	Feeding	9 + 6 + 6	Hand selection	Context	21	19	26													
Niechwiej-Szwedo et al., 2025	Bead threading	30	Kinematics	Clinical group						58										

[a] Where the study employed multiple tasks, only high-order action-planning tasks are counted. Multiple values indicate separate included tasks.
[b] Where the study included both typically developing and clinical groups, only typically developing children are counted.

From these data, the narrative themes for the current review were derived.

Results

We first present the results of the search and a summary of the task paradigms and populations studied in each report.

Search results

After de-duplication, the database search yielded 4299 sources. Title and abstract screening reduced this to 206 records, of which all but 12 were successfully retrieved. Full-text assessment excluded a further 157 reports, leaving 37 sources for inclusion in the review (Fig. 2).

Ages of child participants

Child participants ranged from 14 months to 16 years. However, only four studies included participants under three years, and only four included participants over 12 (excluding adult controls; Table 2). Although most studies grouped participants by age and discussed age-related differences, only eight treated age as the main variable of interest. Instead, studies more often focused on the effects of other conditions, such as the cognitive or motor demands of the tasks (ten studies), the context in which the task is presented (five studies), or the difference between TD and AD groups (14 studies).

Paradigms

Rotation-based tasks, that require participants to grasp a bar, handle, knob or other object (e.g., sword - Crajé et al., 2010; Jongbloed-Pereboom et al., 2013) and rotate it from a home to a target orientation, were used in 17 studies (Tables 1 and 2). In critical trials, planning is evaluated by the extent to which the grip at the target orientation is more comfortable than the initial grip. When the target is far from the home orientation, success can be impossible unless the initial grip accounts for ESC. Eight studies adapted the basic principles of the handle-rotation task (Rosenbaum et al., 1990), which was in use prior to 2013, by replacing the bar with a knob or dial. Five of these studies (Bhoyroo et al., 2018, 2019; Fuelscher et al., 2016; Wilmut & Byrne, 2014a, 2014b) modified Haggard's (1998) octagon task for children, assessing sequences with one, two, and three target orientations; planning for ESC was indicated when the initial grasp accommodated all targets. Although the search terms used in the current review did not exclude tasks with more than two action steps, only this octagon task evaluated action sequences of three and four orders. Krajenbrink and colleagues (Krajenbrink et al., 2020; Krajenbrink, Lust, Beckers, & Steenbergen, 2021) introduced a similar hexagonal-knob paradigm for single-target, second-order planning, and Herbort et al. (2018) designed another simple dial-based task. All three approaches were motivated by the idea that a knob or dial can reveal planning skills that handle-rotation task may miss: whereas a handle affords only two grasps,

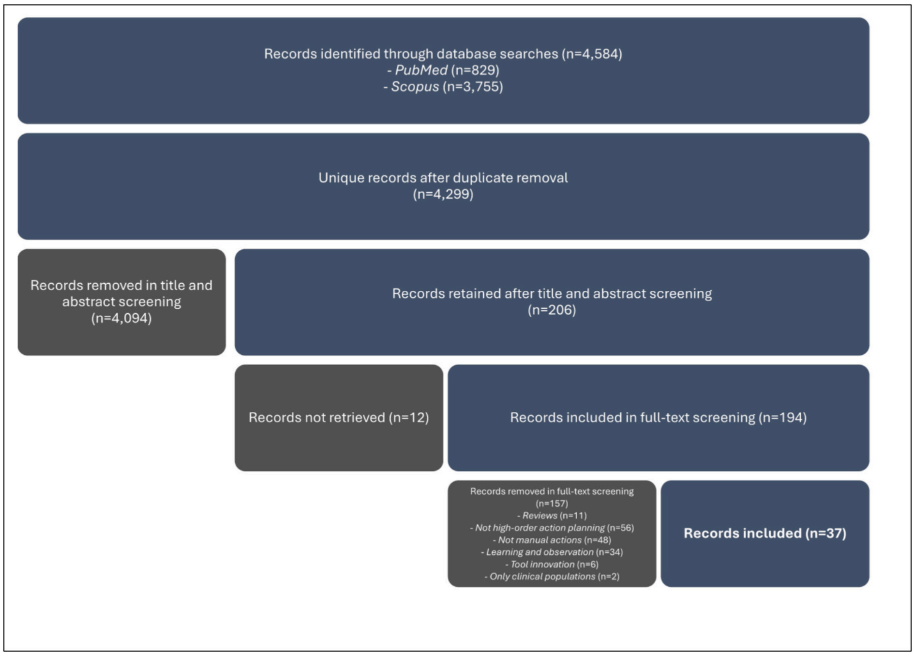

Fig. 2. The PRISMA Flowchart for the current review. We found 37 relevant studies after completing all steps.

a knob offers multiple possibilities, enabling detection of graded adjustments for ESC even when these adjustments are not fully adequate.

Eleven studies employed second-order transport-based paradigms (Tables 1 and 2), in which an object must be grasped and then transported. A novel paradigm in this category was introduced by Comalli et al. (2016), who devised a hammer task that is related to, but distinct from, the bar-transport task. As in the bar-transport task, the tool—a toy hammer—is presented on plinths, allowing an overhand or underhand grasp; in critical trials, when the hammer's handle points away from the dominant hand, an underhand grip indicates successful high-order planning. In the hammer task, the secondary action step is to pound down a peg. This paradigm was later readopted in three other studies in this review (Golmakani et al., 2025; Jovanovic et al., 2021; Ossmy et al., 2022), and one further study (Krajenbrink, Lust, & Steenbergen, 2021) recreated the rotation-based sword task, replacing the sword with a hammer. Because hammering is a higher-precision action than insertion, these researchers hypothesised that a hammering task would elicit a higher degree of planning for ESC than either the bar or sword task. Another novel paradigm employed by three studies (Bäckström et al., 2021, 2025; Domellöf et al., 2020) combined simultaneous transport and rotation of an asymmetrical peg.

Seven studies employed a second-order upturned-object paradigm (Tables 1 and 2), in which the object must be grasped and then turned to become functional (e.g., an upturned glass is turned right way up so that water can be poured into it). To achieve ESC—and thus indicate high-order planning—the upturned object must be grasped with the thumb pointing toward the functional end (Fig. 2).

Although the search terms for the current review were deliberately designed not to restrict inclusion to ESC studies, only two studies employed no ESC paradigm (Tables 1 and 2): Cox and Smitsman's (2019) experiment examined perseveration effects on hand selection in infants asked to grasp a spoon to feed themselves, and Niechwiej-Szwedo et al. (2025) employed a bead-threading paradigm. One further study (Melzel & Paulus, 2022) related performance in the upturned-cup task to performance on a non-ESC, second-order task.

Measures

For most studies (26 of 37), responses that adapted for ESC were the primary measure of successful action planning. Closely linked to ESC, two studies (Jovanovic et al., 2021; Paulus, 2016) used a social paradigm in which *beginning-state comfort* (BSC)—adapting the initial grip to accommodate the comfort of another person to whom the object is passed (Gonzalez et al., 2011)—was the primary measure. As an example of a BSC task, one employed by Jovanovic and colleagues required the participant to grasp a hairbrush, and then either use it to brush a toy lion (solitary condition) or pass it to the experimenter so they could brush the lion (social condition). An initial grip that adapted for BSC in the social condition required the participant to grasp the brush by its bristles, counter to the affordance and typical usage of the tool.

Kinematic data, specifically similarities or differences in kinematic responses between groups or conditions, were the primary measure in eight studies (Bäckström et al., 2021, 2025; Domellöf et al., 2020; Gottwald et al., 2017, 2019; Martel et al., 2020; Niechwiej-Szwedo et al., 2025; Wilmut et al., 2013). One study (Cox & Smitsman, 2019) used hand selection as an indicator of successful planning.

Advances in technology have enabled a multimodal approach to research into the development of high-order planning, capturing children's real-time responses via video capture and motion tracking (Golmakani et al., 2025; Gottwald et al., 2017; Ossmy et al., 2022), eye tracking (Golmakani et al., 2025; Ossmy et al., 2022), and electroencephalogram (EEG; Ossmy et al., 2022). Most studies measured ESC performance alongside additional measures that either indexed action planning through behaviours other than ESC and/or assessed perceptual, cognitive or motor skills distinct from manual action planning. We therefore judged the paradigms and measures to be too heterogeneous to justify a quantitative meta-analysis.

Discussion

Synthesising the findings across the included studies yields several interrelated themes that refine current accounts of how high-order action planning develops across childhood. First, we examine developmental trajectories in high-order planning behaviours, highlighting converging evidence that planning capacities emerge earlier than previously suggested. Across paradigms, children's grip choices often appear to reflect strategic trade-offs against motor ability rather than an absence of planning; planning *capacity* does not reliably translate into *overt* planning behaviours when task demands exceed motor constraints. Second, we consider efforts to dissociate manual action planning from general, abstract planning and high-level cognition, evaluating evidence for links with motor imagery, perspective taking, and executive problem-solving. Third, we integrate insights from studies using kinematic, eye-tracking, and neurophysiological measures, which reframe action planning from a discrete pre-movement decision to a dynamic, real-time process. Taken together, these themes motivate recommendations for future work, with particular emphasis on individual variability, task design, and multimodal measurement.

The ontogeny of high-order action-planning skills

A central question in this literature concerns the ontogeny of high-order action-planning abilities. Across paradigms, developmental trajectories are strongly moderated by motor demands: tasks with relatively low motor requirements tend to elicit adult-like responses earlier, with ceiling effects around six to eight years (Jongbloed-Pereboom et al., 2016; Krajenbrink et al., 2020), whereas tasks requiring more complex grip selection or coordinated rotations typically approach adult-like performance closer to eight to ten years (Jongbloed-Pereboom et al., 2016; Scharoun, Gonzalez, et al., 2018; Wunsch et al., 2016). Variants of the bar-transport task underscore this sensitivity showing that children can perform at adult levels under standard demands yet drop to chance when modest increases in precision or coordination are introduced, such as Stöckel and Hughes' (2015) use of pins that increased precision in the secondary transport phase.

Importantly, findings in younger children suggest latent planning. Studies that reduced motor requirements and quantified graded adaptation—specifically, the degree to which the participant rotated the wrist before grasping a dial (Herbort et al., 2018; Jovanovic & Schwarzer, 2017a; Krajenbrink et al., 2020; Martel et al., 2020)—rather than binary success-failure, show that children as young as three to six years partially adjusted initial grips or reaches in anticipation of downstream constraints. Thus, even when younger children fail on the most demanding trials, their initial actions often carry a signature of emerging high-order planning; consistent ESC responses may therefore lag behind the maturation of underlying planning processes.

At the same time, evidence from studies that analysed individual children (Comalli et al., 2016; Golmakani et al., 2025; Ossmy et al., 2022) reveals substantial interindividual variability in anticipatory behaviours, even within narrow age ranges. Such variability is not merely noise but reflects meaningful differences in developmental timing and strategy use across children, consistent with broader accounts of cognitive development that emphasise heterogeneous, context-sensitive trajectories (e.g., Diamond, 2013; Doebel, 2020). Although variability is also characteristic of other domains, such as executive function, it may be especially pronounced in action planning due to the interaction between cognitive, perceptual, and motor constraints.

One potential contributor to this variability is differences in learning across trials: in paradigms with repeated opportunities to act (e.g., Comalli et al., 2016), some children may more rapidly adjust their behaviour based on experienced discomfort or task demands, whereas others persist with habitual strategies. However, few studies in this review explicitly model trial-by-trial change, making it difficult to determine the extent to which observed variability reflects stable individual differences versus differences in learning rate.

In the bar-transport and hammer tasks, adaptive versus nonadaptive planning is indexed by adoption of a non-habitual underhand grip in critical trials, indicating adaptation for ESC. Adults produce ESC responses near-ceiling (Rosenbaum et al., 1996); infants typically do not, and children select "optimal" grips increasingly with age (Manoel & Moreira, 2005; McCarty et al., 1999). When children choose an apparently suboptimal grip, the key question is whether this reflects an absence of planning, or planning that is overridden by competing constraints. Across the reviewed studies, two factors repeatedly attenuated ESC even when children demonstrated planning in other contexts: habitual responding (Jongbloed-Pereboom et al., 2016; Jovanovic et al., 2021; Jovanovic & Schwarzer, 2017a, 2017b) and motor ability (Herbort et al., 2018; Wunsch et al., 2015).

Several studies implicate habitual grips and their inhibition. Jovanovic et al. (2021) attributed reduced ESC in their youngest participants to a stronger impulse toward habitual grips and/or an immature ability to *inhibit* this impulse; on this account, inhibitory control, rather than planning per se, may be the limiting factor in preschoolers, especially when familiar objects elicit strong habitual response tendencies. Consistent with this view, Jongbloed-Pereboom et al. (2016) reported stronger habitual responding for familiar functional objects (cups) than for more abstract objects (bars). Melzel and Paulus (2022) further linked performance on an ESC task to a high-order, non-ESC task in which success required participants to grasp a spoon by its bowl, thereby overriding the object's strongly afforded conventional use. More broadly, object affordances cue typical actions (e.g., Van Leeuwen et al., 1994), and repeated use can entrench conventional functions (functional fixedness; Pflüger et al., 2024). Together, these findings suggest that high-order planning processes may be present early, while flexible contextual adaptation and inhibition of habitual responses develop more gradually.

Adults also deviate from ESC when alternative efficiencies are available. In Jovanovic and Schwarzer's (2017a) grasp-height task, participants were required to transport a vertically oriented bar between a "home" shelf and a "target" shelf. Three-year-olds showed a *greater* ESC effect than adults when returning the bar from the target shelf to the home shelf, but this pattern does not imply superior planning. Adults often show reduced ESC here (Cohen & Rosenbaum, 2004; Weigelt & Schack, 2010) plausibly because they reuse the previously selected grip to reduce cognitive effort, even when this sacrifices end-state comfort—an effect that may be encouraged when motor demands are low. Children, by contrast, appeared not to deploy this recall-based shortcut and showed ESC in both conditions. Jovanovic and Schwarzer (2017b) similarly demonstrated that adults sometimes favour habitual grips even at the cost of end-state comfort, reinforcing the point that ESC is not invariably the "optimal" strategy when broader efficiency trade-offs are considered.

Finally, reduced ESC in younger children may reflect a realistic appraisal of motor constraints rather than insufficient planning. Wunsch et al. (2015) and Herbort et al. (2018) argue that children weigh the costs of initial-grip discomfort against end-grip discomfort and/or the feasibility of online correction, and these strategies compete with ESC. For dextrous adults, ESC is typically optimal (e.g., Rosenbaum et al., 1996), but for children with limited dexterity, an ESC grip may be suboptimal or even unattainable. On this account, apparent "errors" may reflect genuinely adaptive choices for the child's current motor repertoire. As dexterity increases, the balance of discomfort costs shift, such that age-related improvements in high-order tasks likely reflect coupled development in both motor control and planning. Importantly, such developmental change may not be strictly linear. Some accounts (Scharoun, Robinson, et al., 2018; Thibaut & Toussaint, 2010) propose periods of motor reorganisation, during which competing strategies are explored, and performance is temporarily destabilised, before more efficient coordination is achieved.

In summary, failure to exhibit adult-like grip-selection patterns does not, by itself, imply immature high-order planning. Children may be planning but constrained by habitual tendencies, limited inhibition, and/or motor capabilities, and may sometimes select grips that are truly optimal given their current action system. Furthermore, developmental trajectories may be heterogeneous and non-linear, reflecting both interindividual variability and potential periods of reorganisation.

Disentangling manual action planning from cognition

Spatial transformation processes, including mental rotation and perspective taking, likely play a central role in action planning, not only in high-order tasks but also in simpler, single-step actions. Developmental work on mental rotation in children (e.g., Frick et al., 2013) demonstrates that even relatively simple object transformations require the ability to mentally simulate spatial changes, a process that may also reinforce anticipatory adjustments in manual action tasks. From this perspective, high-order planning may place greater demands on processes already present in simpler actions, requiring not only the representation of a single future state but the coordination of multiple, sequentially linked transformations.

Several studies in the current review examined links between ESC and cognition, with a particular focus on imagery. Toussaint et al. (2013) related ESC performance to two mental-rotation tasks in six- and eight-year-olds, and found significant correlations with the "motor" task—mental rotation of a hand (Fig. 3)—in the younger group and a positive trend in the older group, but no association with the non-motor task—mental rotation of a numeral. Adams et al. (2017a, 2017b) found similar developmental associations between hand rotation and ESC tasks. In a larger sample, Wunsch et al. (2016) assessed 189 children across three ESC tasks and three cognitive tasks that each assessed an aspect of executive function, and found little evidence of broad cognitive coupling: only a single correlation emerged between bar-transport performance and a visuospatial subtest of the Wechsler Scale (Wechsler, 2003). Although Scharoun, Gonzalez, et al. (2018) attributed unstable ESC in younger children to inadequate internal models of the future state, their data provide limited support for a general cognitive deficit, and cross-task discrepancies remain unexplained. Moreover, Jovanovic and Schwarzer (2017a) observed reliable ESC even in three-year-olds on a low-motor-demand task, challenging the claim that early failures primarily reflect insufficient internal modelling. Taken together, the evidence suggests that modelling for high-order motor planning may follow a developmental trajectory that is at least partly dissociable from general cognitive modelling.

These spatial transformation demands become particularly salient in social contexts, such as tasks indexed by beginning-state comfort (BSC), in which the participant must adapt their action to accommodate another person. In such cases, successful performance likely requires *perspective transformation*—mentally simulating not only object rotation but also the orientation and action constraints of another individual. Classic work shows that children under five can solve perspective-taking problems, but their errors are often egocentric (Newcombe & Huttenlocher, 1992; Piaget & Inhelder, 1956). A similar egocentrism may constrain manual planning, with younger children privileging their own immediate viewpoint, suggesting a shared limitation across spatial, social, and motor domains. Within this review, Jovanovic et al. (2021) and Paulus (2016) reported better performance under solitary than social conditions, partly attributed to egocentrism, and Scharoun and Bryden (2013) also reported a different developmental pattern for BSC versus ESC. Evidence for a specific motor-imagery mechanism is mixed: Jovanovic et al. (2021), unlike Toussaint et al. (2013), found no definitive association between BSC and mental rotation of a hand. Taken together, these findings suggest that spatial transformation processes, including mental rotation and perspective taking, may constitute a shared mechanism underlying both simple and high-order manual planning, although their precise role—and interaction with motor and cognitive constraints—remains to be fully characterised.

Insights from multi-modal, real-time data

Historically, research on the development of manual action planning has prioritised behavioural outcomes—whether participants selected the expected grasp or achieved the task goal. Some studies additionally reported reaction or reaching times (e.g., Bard et al., 1990), and fewer employed motion-tracking to capture kinematics in real time (e.g., Claxton et al., 2003). The studies in the current

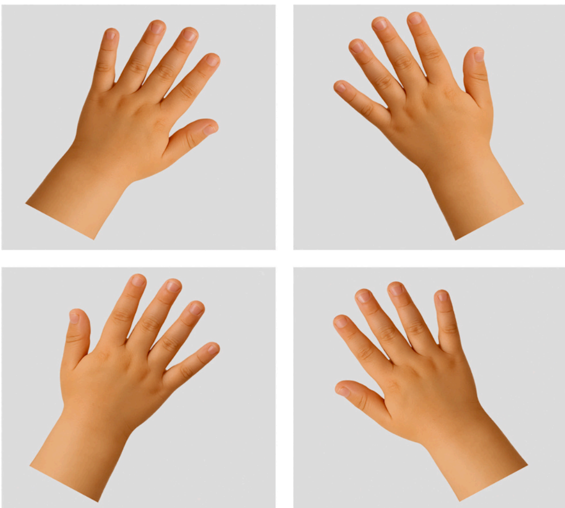

Fig. 3. The motor-imagery task; mental rotation of a hand (Toussaint et al., 2013). Participants must choose whether each rotated image is of a left or right hand.
Note: Adapted from *On the link between action planning and motor imagery: A developmental study* by Toussaint et al, 2013, *Experimental Brain Research*, 231(3), p. 334 (10.1007/s00221-013-3698-7).

review used kinematic measures to differentiate individuals who had effectively planned their actions from those who did not, and recent technological advances have further enabled the concurrent acquisition of real-time data streams, including video and EEG.

Motion-tracking evidence converges on a protracted developmental trajectory for the real-time organisation of multi-step actions. Experiments by Bäckström et al. (2021, 2025) and Domellöf et al. (2020) identified age-related differences in reach kinematics during high-order tasks, consistent with patterns observed in single-order object-fitting (e.g., Ossmy et al., 2020). Efficient performance required coordination of rotation and transport, yet even ten-year-olds did not exhibit adult-like efficiency; younger children produced more segmented movements, relying more heavily on feedback than feedforward control. Martel et al. (2020) reported similar developmental signatures. Extending these findings to infancy, Gottwald et al. (2017, 2019) combined motion tracking with video coding to show that infants modulate reach trajectories as a function of the precision required for a subsequent step. Whereas timing measures can indicate whether planning or movement phases differ in overall duration, they cannot localise where slowdowns occur within an action, underscoring the value of motion tracking for resolving fine-grained structure in executed movements.

Two studies probed underlying mechanisms in greater depth by integrating new technologies to capture real-time responses across multiple media (Golmakani et al., 2025; Ossmy et al., 2022). Building on Ossmy et al.'s (2020) multimodal synchronisation of video, motion tracking and eye tracking during a single-order object-fitting task—which revealed a real-time "cascade effect" from perception to motion tied to early gaze and a continuous feedback-feedforward interplay—Ossmy et al. (2022) extended the same approach to a high-order hammering task and added EEG (Fig. 4). Golmakani and colleagues synchronised eye-tracking and video data and confirmed the presence of the cascade effect across both the hammering task and less-structured play. These researchers' results indicate that cognitive processing operates as an intermediate stage between visual attention and movement onset within a successful planning cascade. Only in the past six years have the miniaturisation and flexibility of EEG and eye-tracking systems made such developmental research feasible in younger children, and continued technical advances are likely to accelerate their adoption.

Future work

Analyses at the level of individual children (Comalli et al., 2016; Golmakani et al., 2025; Ossmy et al., 2022) reveal substantial interindividual variability within age groups, with some children displaying markedly stronger adaptive planning than their peers. As noted above, such variability may reflect not only stable differences in developmental timing but also differences in learning across trials, an issue that remains largely untested in the current literature. Because developmental transitions occur at different times across children—and because high-order planning can be context-specific—broad age-binning risks obscuring genuine developmental change. Future research should therefore prioritise analytic approaches that model individual differences, accommodate high variance and incorporate trial-by-trial analyses to disentangle stable individual differences from learning effects, rather than treating within-age variability as noise.

Jovanovic and Schwarzer's (2017b) experiment dissociated an object's actual versus functional orientation; for example, a drinking glass's functional orientation positions its aperture at the top, while a pencil is functional when its tip points downwards, and each object was presented in its functional or opposite orientation. This experiment provides a promising route for probing inhibition of habitual grips, but its assumptions warrant closer scrutiny. For instance, three-year-olds may not yet know the conventional grip for a pencil or may lack the finger strength to execute it reliably; alternative grips can still satisfy functional goals despite reduced control. Similarly, the "habitual" grip for a trowel may depend on context (e.g., digging topsoil versus planting). It is therefore unclear which grips young children truly represent as habitual. Future studies should address this issue by selecting objects for which young children have a more stable, consistent experience.

Scharoun, Robinson, et al. (2018) reported gender differences in children aged seven to eleven on the upturned-cup task, with significant gender × age interaction despite no main effect of gender on ESC: boys showed a gradual increase in ESC responses,

Fig. 4. Simultaneous, real-time capture of video, motion-tracking data, eye-tracking data, and EEG (Ossmy et al., 2022).
Note: This figure is reprinted from *Real-time processes in the development of action planning* by Ossmy et al., 2022, *Current Biology*, p. 2 (10.1016/j.cub.2021.11.018), Reprinted with permission.

whereas girls exhibited a decrease around age seven followed by a rapid increase around nine, with both reaching adult-like responses by age ten. Thibaut and Toussaint (2010) similarly reported a dip in performance around age eight and proposed motor-system reorganisation, during which competing planning strategies may emerge before integration, although gender was not examined. These findings raise the possibility that non-linear developmental trajectories, reorganisation dynamics, and their behavioural signatures, might be gender-specific. This hypothesis requires targeted, adequately powered investigation.

Finally, studies combining synchronised, real-time data—video, motion tracking, eye tracking and EEG (Golmakani et al., 2025; Ossmy et al., 2020, 2022)—have reframed action planning from a top-down, pre-movement decision (McCarty et al., 1999), to a dynamic process in which anticipatory, feedforward planning is continuously shaped by bottom-up feedback and reciprocal interactions across perceptual, cognitive, and motor systems. Golmakani et al. (2025) demonstrated this "planning cascade" not only in structured, high-order tasks, but also in free-form play, suggesting a context-general process rather than a phenomenon restricted to explicit goal-directed contexts. Continued adaptation of multimodal designs is therefore likely to be a major driver of progress in the field.

Conclusion

This review addressed three questions: a) when high-order planning emerges in childhood; b) how task complexity and context shape the expression of high-order planning behaviours; and c) how high-order planning relates to cognitive functions during development. Evidence from the past twelve years indicates that children as young as three can plan action sequences of two orders or more and adjust their movements accordingly. Earlier inconsistencies (e.g., Wunsch et al., 2013) appear partly attributable to paradigm and measurement choices. Designs that reduce motor demands and quantify graded anticipatory adjustments (rather than relying on binary success-failure) more reliably reveal early high-order planning.

Across studies, the expression of high-order planning behaviours is strongly modulated by contextual and task constraints, including object affordances and familiarity (Jovanovic et al., 2021), internal modelling of future states (Scharoun, Gonzalez, et al., 2018), and the cognitive and motor load imposed by the task, relative to children's developing strength, dexterity and motor control (Krajenbrink et al., 2020). Critically, adult-like grip-selection patterns are not necessarily optimal for young children: in higher motor-threshold tasks, apparently "non-ESC" choices may reflect strategies that are genuinely adaptive given current motor constraints, rather than failures of planning.

At the neural level, action planning has been linked to distributed fronto-parietal networks involved in motor representation, action selection, and predictive control (e.g., Haggard, 1998; Jeannerod, 1994; Rosenbaum et al., 2012). Classic accounts propose that actions are guided by internally represented goals, with premotor and parietal circuits transforming object affordances into motor schemas, and that motor planning and imagery recruit overlapping neural systems (Jeannerod, 1994). Recent multimodal evidence, including "planning cascades" (Ossmy et al., 2022), further suggests that cognition can operate as an intermediate step linking perception to action in real time, and that high-order planning emerges from dynamic interactions between perceptual, motor, and cognitive systems, rather than from a single, discrete planning stage. This model is consistent with emerging accounts of the *predictive brain* (Friston, 2012), in which action is guided by anticipatory models that are continuously updated through sensory feedback. In this view, planning is not a discrete pre-movement computation but a dynamic, ongoing process shaped by reciprocal interactions between perception, *prediction*, and action. Developmental improvements in high-order planning may therefore reflect increasing precision, flexibility, and integration of these predictive processes.

At the same time, the limited and inconsistent associations between ESC/BSC and high-level cognition indicate that motor planning and cognitive functions may follow partially dissociable developmental trajectories. Progress will therefore depend on designs that are both replicable and sensitive to mechanism—particularly those that model individual variability, manipulate task constraints systematically, and integrate multimodal, real-time measurement.

More broadly, these findings raise questions about how high-order manual planning relates to general, abstract planning. Traditional accounts often treat planning as a domain-general capacity, supported by executive functions and internal modelling (e.g., Diamond, 2013; Keen, 2011; McCarty et al., 1999; Rosenbaum et al., 2012). High-order manual planning appears to emerge within a perception-action system that is tightly constrained by motor capabilities, task affordances, and real-time feedback, and therefore develops along a trajectory that is only partially aligned with more abstract forms of planning. Rather than reflecting a distinct planning ability, high-order manual planning may constitute a domain-specific instantiation of planning processes, grounded in sensorimotor experience and gradually integrated with other cognitive systems over development. These processes are supported by executive functions, such as inhibitory control, although the present findings suggest these play a modulatory rather than primary role. This perspective is consistent with evidence for weak or inconsistent associations between performance in tasks of high-order manual planning and tasks that assess executive function (Wunsch et al., 2016), alongside stronger links to motor-related processes such as motor imagery (Adams et al., 2017a, 2017b; Toussaint et al., 2013). Nonetheless, spatial transformation processes, such as mental rotation and perspective taking, may provide a key link between manual action planning and general planning abilities across domains. Understanding how manual-action-planning processes interact with more abstract forms of planning remains an important open question.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the ESRC New Investigator grant ES/W009242/1 and the Leverhulme Trust research grant RPG-2022-327 to OO.

Appendix A. Appendix: Search terms

The following advanced search term was used to acquire sources from Scopus:

TITLE-ABS-KEY (((“anticipatory planning”) OR (“tool use”) OR (“object fitting”) OR (“object manipulation”) OR (“motor planning”) OR (“motor development”) OR (“action planning”) OR (“manual skills”) OR (“problem solving”) OR (“manual actions”) OR (“action sequences”) OR (“planning sequences”) OR (“second-order planning”) OR (“high-order planning”)) AND ((development) OR (children) OR (infants))) AND PUBYEAR >2012 AND (LIMIT-TO (SUBJAREA, “PSYC”) OR LIMIT-TO (SUBJAREA, “NEUR”)) AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “ch”)) AND (LIMIT-TO (LANGUAGE, “English”)) AND (LIMIT-TO (EXACTKEYWORD, “Preschool Child”) OR LIMIT-TO (EXACTKEYWORD, “Child, Preschool”) OR LIMIT-TO (EXACTKEYWORD, “Child”) OR LIMIT-TO (EXACTKEYWORD, “Child Development”) OR LIMIT-TO (EXACTKEYWORD, “Motor Development”) OR LIMIT-TO (EXACT-KEYWORD, “Infant”)).

The following advanced search term was used to acquire sources from PubMed:

((“anticipatory planning”) OR (“tool use”) OR (“object fitting”) OR (“object manipulation”) OR (“motor planning”) OR (“motor development”) OR (“action planning”) OR (“manual skills”) OR (“problem solving”) OR (“manual actions”) OR (“action sequences”) OR (“planning sequences”) OR (“second-order planning”) OR (“high-order planning”)) AND ((development) OR (children) OR (infants))

In addition, the following filters were applied through the user interface:

Books and Documents, Clinical Study, Clinical Trial, Randomized Controlled Trial, English, Humans, Child: birth-18 years, Newborn: birth-1 month, Infant: birth-23 months, Infant: 1-23 months, Preschool Child: 2-5 years, Child: 6-12 years, Adolescent: 13-18 years, from 2013 to 3000/12/12.

Data availability

Data will be made available on request.

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