



Object play and problem solving in infancy: Insights into tool use

Lauriane Rat-Fischer, Kim Plunkett, Auguste M P von Bayern, Alex Kacelnik

► To cite this version:

Lauriane Rat-Fischer, Kim Plunkett, Auguste M P von Bayern, Alex Kacelnik. Object play and problem solving in infancy: Insights into tool use. *Journal of Experimental Child Psychology*, 2024, 244, pp.105957. <10.1016/j.jecp.2024.105957>. <hal-04589873>

HAL Id: hal-04589873

<https://hal.science/hal-04589873v1>

Submitted on 27 May 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY-NC 4.0 - Attribution - Non-commercial use - International License



Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

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



Object play and problem solving in infancy: Insights into tool use



Lauriane Rat-Fischer^{a,*}, Kim Plunkett^b, Auguste M.P. von Bayern^c,
Alex Kacelnik^a

^a Department of Biology, University of Oxford, Oxford OX1 3RB, UK

^b Department of Experimental Psychology, University of Oxford, Oxford OX2 6GG, UK

^c Max-Planck-Institute for Biological Intelligence, Eberhard-Gwinner-Street, 82319 Seewiesen, Germany

ARTICLE INFO

Article history:

Received 9 July 2023

Revised 12 April 2024

Keywords:

Tool use

Problem solving

Means-end

Object-oriented play

Development

Infancy

ABSTRACT

Tool use is primarily, but not exclusively, present in species with otherwise advanced cognitive traits. However, the interaction between such traits and conspecific inter-individual variation in the presence, complexity, or intensity of tool use is far from being established. We addressed this matter among human infants, seeking factors that relate to differences in tool use. We examined, both correlationally and experimentally, whether the propensity to engage in object combinations predicts performance in means-end problem-solving tasks involving or not involving the use of a tool. We tested 71 infants aged 15, 18, 21, and 24 months, dividing them into two subgroups: one exposed to an adult demonstrating object-object combinations (i.e., “prompting” infants to combine objects together) and another with comparable social exposure but where the adult demonstrated single-object manipulations. We found a correlation between the combined level of spontaneous and prompted object combinations and problem-solving performance regardless of the involvement of tools in the problem. However, we did not find differences in tool-use performance between the two demonstration subgroups. The correlational analysis suggests that complexity of play, as measured by the frequency of combining objects, is linked to infants’ problem-solving skills rather than being specifically associated with tool use, as previously suggested in the literature.

© 2024 The Authors. Published by Elsevier Inc. This is an open access article under the CC BY-NC license (<http://creativecommons.org/licenses/by-nc/4.0/>).

* Corresponding author at: Max Planck Institute for Biological Intelligence, 82152 Planegg, Germany.

E-mail address: l.ratfischer@parisnanterre.fr (L. Rat-Fischer).

Introduction

Tool use has long been seen as a correlate of intelligence and “a royal road to the study of problem solving” (Keen, 2011, p. 2). The study of the acquisition of tool-use competence attracts interest from various disciplines such as developmental psychology (e.g., Deák, 2014), comparative cognition (e.g., Meulman et al., 2013), neurosciences (e.g., Osiurak et al., 2018), and developmental robotics (e.g., Guerin et al., 2013). There is no doubt that all animal species in which tool use plays a role show an intricate interaction among innate propensities, nervous system maturation, programmed receptivity to ontogenetic experience, and individual contingencies, and for this reason the development of tool-use competence remains only partly understood. Our aim was to contribute to the understanding of some of these interactions in human infants.

The use of tools emerges in the second year of life (Lockman, 2000), beginning with tools that align with infants' everyday cultural exposure such as using spoons for self-feeding (Claxton et al., 2009; Connolly & Dalgleish, 1989; Kaur et al., 2020; McCarty et al., 1999, 2001), using tools for hammering (e.g., Kahrs et al., 2014; McCarty et al., 2001), and brushing hairs (McCarty et al., 2001). The ability to solve means–end problems by using novel tools usually develops later, in the second half of the second year of life. Means–end problem solving involves the execution of a planned sequence of actions in order to achieve a goal (e.g., Babik et al., 2019; Willatts, 1999), and examples widely used in the literature require the use of a rake, a stick, or a hook to bring an out-of-reach toy within reach when the toy is initially separated in space from the tool (e.g., Bates et al., 1980; Brown, 1990; Fagard et al., 2016; Rat-Fischer et al., 2012; van Leeuwen et al., 1994).

Several factors have been suggested to play a role in the developmental process leading to tool use in infants, particularly sensorimotor and social experiences and the general maturation of cognitive skills (Keen, 2011; Schubotz et al., 2023). We briefly review these three factors here. First, recent work has highlighted that the way infants interact with objects and surfaces may shape the motor bases of their tool use (see reviews by Lockman, 2000; Lockman & Kahrs, 2017; Needham, 2016; Schubotz et al., 2023). Learning about objects' affordance is a crucial aspect of this development (we use *affordance* in the sense introduced by Gibson (1966, 1979) to address an agent's possibilities for physical interactions with objects in the environment, thereby being a joint property of subject and object). By interacting with objects, infants learn to perform actions that efficiently alter the relation of objects with their environment and other objects, ultimately gaining competences that are part of being competent with tools (Lockman, 2000; Lockman & Kahrs, 2017; Needham, 2016; Schubotz et al., 2023). Second, social interactions affect infants' action repertoires and consequently their understanding of actions' consequences. This is probably why direct demonstrations, scaffolding, and repeated passive observations of tool-use events during development have observable effects on the onset of tool use (e.g., Elsner, 2007, 2009; Esseily et al., 2013, 2015; Somogyi & Esseily, 2014). Finally, a third main factor is the development of infants' general cognitive capacities. As cognitive capacities mature over the first 2 years of life, infants gradually develop the ability to reason and to form representations relevant for tool use, in particular the ability to notice, remember, and abstractly generalize different types of object functions (Deák, 2014). As specified by Deák (2014), the term *function* employed here is more advanced than the term *affordance* proposed by Gibson (1966, 1979) in that it implies an instrumental object use codified by culture or habit.

The main epistemic challenge to disentangle the extent to which social interactions, sensorimotor experience, and cognitive maturation contribute to the development of tool use is the ethical impossibility of devising developmental experiments in humans, which would involve selectively depriving or enriching infants' experience just to assess different factors' contribution to the emergence of tool use. One alternative, however, is conducting correlational analyses of individual differences in the timing of competences. This can be supplemented with short-term mild interventions that may help to uncover causal links between different aspects of experience and performance. The current study used both approaches to investigate tool-use development over infants' second year of life, focusing on their experience with objects while controlling, to some extent, for cognitive and social factors. More specifically, we focused on how infants' object-oriented play relates to the development of tool-use competences using Wynberg et al.'s (2022) definition of object-oriented play as being “focused on

objects or materials and their sensorimotor or intentional affordances” and involving “the sensorimotor exploration, physical manipulation, or mental manipulation of objects and/or materials” (p. 216). Object play is one of the most prominent activities infants engage in during early childhood. Researchers from many disciplines have argued that object-oriented play exposes and promotes the development of physical competences in both human and nonhuman animals (see reviews by Bjorklund & Gardiner, 2011; Burghardt, 2005; Cenni, 2022; Needham, 2016; Wynberg et al., 2022). In particular, the complex play behavior of combining objects with each other or (to some extent) with various substrates (i.e., surfaces) has been pointed out as a precursor of tool use (e.g., Auersperg et al., 2015; Hayashi & Matsuzawa, 2003; see reviews by Hayashi et al., 2006; O'Hara & Auersperg, 2017). We summarize some of these ideas in the next few paragraphs.

Infants explore objects in increasingly complex ways over the first 2 years of life. After a first period in which they focus on single objects' properties, from 6 to 10 months they start combining objects with substrates while showing an increasing sensitivity to the properties of both the object and the substrate (e.g., Bourgeois et al., 2005; Fontenelle et al., 2007; Palmer, 1989). Object-object combinations (also called “relational acts”; Fenson et al., 1976; see also the literature review on play classifications by Fanning et al., 2021) start at about 9 months and increase in number and complexity over the second year of life. Fenson et al. (1976) reported that infants continuously perform “simple” combinations (involving nonfunctional combinations between two objects such as touching an object with another) from 9 to 20 months, with a peak at 9 months. This peak is followed by an increase in accommodative combinations (involving appropriate [i.e., functional/conventional] combinations between two objects, e.g., lid on pot, cup on saucer, spoon in cup; Fanning et al., 2021; Fenson et al., 1976) at 13 to 20 months, a behavior also accompanied by the growing emergence of symbolic acts. Construction skills, such as stacking, nesting, and affixing objects together, also gradually develop from 10 to 24 months, with individual differences emerging in the developmental trajectories of such combinatorial behaviors (Marcinowski et al., 2019).

Developmental studies investigating the relationship between individual differences in combinatorial activities and tool use are available, but only in older children (e.g., Gredlein & Bjorklund, 2005; Sylva, 1977). In the study by Gredlein and Bjorklund (2005), 3-year-old boys displayed significantly more object combinations, such as stacking, securing, and connecting objects together, than girls of the same age. The authors further found that boys performed better than girls on a tool-choice task in which children needed to select the appropriate tool from a set of six alternatives (with only one being functional) to retrieve a toy. Gredlein and Bjorklund (2005) further linked the two behaviors, showing that the amount of time boys, but not girls, spent in object combinations during the free-play sessions predicted their performance in the tool-choice task.

Data from comparative psychology highlight the potential link between object combinations and the later emergence of tool use. For example, Vauclair and Bard (1983) reported that human infants performed more complex manipulatory behaviors (such as bimanual explorations, exploring objects while holding them, and combining objects together) than juveniles from species that show less flexible tool use as adults such as chimpanzees (*Pan troglodytes*) and bonobos (*Pan paniscus*). A longitudinal study investigating object manipulation in three mother-reared, captive infant chimpanzees showed that the first tool-use behaviors appeared at approximately 21 months of age, 4 months after a dramatic increase in object-object combinations (Hayashi & Matsuzawa, 2003). Longitudinal observations of the proficient tool-using capuchin monkeys (*Sapajus apella*) both in captivity (Fragaszy & Adam-Curtis, 1991) and in the wild (de Resende et al., 2008) showed that juveniles undergo a long period of object and substrate exploration before they eventually learn to use objects to crack nuts for self-feeding. These exploratory behaviors start from simple manipulation of objects to more and more complex combinations such as rubbing and hitting and then inserting and hitting objects against various substrates. Similarly, juveniles of the New Caledonian crow (*Corvus moneduloides*), a species renowned for its capacity to manufacture and use tools in the wild and in captivity (e.g., Kacelnik et al., 2006), start exploring and combining available objects with the substrate soon after leaving the nest. The quantity of combinatorial behavior gradually increases over subsequent weeks until crows eventually start using stick-like objects as tools to retrieve food from crevices (Kenward et al., 2006). All these comparative studies point toward a similar pattern in the development of tool

manipulation, going from simple manipulation to object combinations until the use of tools, both in closely related species such as nonhuman primates and in more distant species such as birds.

To our knowledge, no study so far has investigated the direct association between object combinations and tool use in infants over the second year of life. In the current study, we investigated the potential correlation between individual combinatorial activity and tool performance in four different age groups: 15 months (before single-tool problems involving a spatial gap are usually solved), 18 months, 21 months, and 24 months (when the spontaneous use of single tools gradually develops with inter-individual differences). As outlined above, this age period is particularly important for the emergence of infants' capacity to solve means–end problems involving the use of novel tools such as retrieving an out-of-reach toy with a single tool. The tool-choice task used in earlier studies on this topic (Chen & Siegler, 2000; Gredlein & Bjorklund, 2005) is usually solved later, from 24 to 36 months (Brown, 1990; Keen, 2011), and only after the infants have acquired the ability to solve novel single-tool tasks.

We examined a potential causal link between object combinations and tool performance using both an experimental approach and a correlational approach. To this effect, we first measured infants' spontaneous combinatorial activity with an object play set inspired by the one created by Auersperg and colleagues (2015) for use with birds after adapting it for babies. With this play set, Auersperg et al. (2015) reported that more complex and structured object combinations prevailed in the two tool-using bird species tested (New Caledonian crows and Goffin cockatoos), but not in four other non-tool-using species, and this applied in both the corvid and psittacid families. Drawing parallels in the association of object combination and tool-related competences between species differing in tool use and problem-solving performance may provide insights on how object play and tool use interact through developmental ages in humans. After this first measure of spontaneous combinatorial activity, we assigned infants to one of two demonstration subgroups. In the first subgroup, we “prompted” infants to combine objects with other objects (pushing/pulling an object with another) or with a fixed feature of the substrate (e.g., inserting an object into a tube or a hole) by exposing them to demonstrations by an experimenter. The second subgroup served as a control; it was matched for social interactions but exposed only to single-object combinations and manipulations (pushing/pulling an object with the finger and scratching an object against the ground). After being exposed to the demonstration, infants were given the opportunity to freely interact with the play set again to verify the effects of the demonstrations on infants' propensity to perform object combinations while also considering potential effects of individual factors such as age, sex, and linguistic group. After this first play session, we measured infants' ability to solve novel means–end tool tasks, comparing infants from the two demonstration subgroups on their capacity to solve tool tasks. Thus, we could detect correlations between initial spontaneous combinatorial behaviors and problem solving and also could expose the effect of the experimental treatment of the two subgroups. We predicted that if performing object combinations affects variance in tool-related performance, infants in the object–object combinations subgroup would outperform infants in the control subgroup in tool-related tasks. Because both tool and combinatorial behaviors undergo developmental changes across the second year of life, we expected this relation to vary across the age groups, in particular in the younger group that was not yet expected to solve tool tasks at the time of exposure.

In addition, to investigate whether object combinations are specifically linked to tool use (e.g., Cheyne & Rubin, 1983; Gredlein & Bjorklund, 2005) rather than to means–end problem-solving ability in general (Lockman, 2000), we measured infants' performance in not only tool-related but also non-tool-related means–end tasks. The most frequently studied non-tool means–end tasks in the literature are the cloth task and the string-pulling task. In the cloth task, infants must pull a piece of cloth to retrieve an out-of-reach toy. They usually solve it at 9 or 10 months of age (Bates et al., 1980; Willatts, 1984, 1999). In the string-pulling task, infants need to pull a string connected to an out-of-reach toy to bring it within reach, and they usually solve it at 10 to 12 months of age (e.g., Uzgiris & Hunt, 1975). However, it is difficult to compare infants' performance in tool tasks with that on means–end tasks like the cloth and string-pulling tasks because they do not align in complexity. Whereas in the cloth and string-pulling tasks only one action is necessary to retrieve the toy (i.e., pulling a piece of cloth or a string spatially connected to the goal object), using tools typically involves at least two actions in addition to identifying the tool as a potential means for bringing

the (non-connected) goal object into reach: (a) directing the tool toward the object and (b) performing the retrieval gesture in an appropriate manner. Thus, we designed a series of non-tool problem-solving tasks so as to have either a similar sequence of actions or a similar number of actions as the tool tasks. The goal was always similar: to retrieve a toy placed within an apparatus out of the infants' direct reach. Previous studies investigating the link between object combinations and tool use frequently focused only on tool-use problems, ruling out the possibility that object combinations may correlate with a wider range of problem-solving skills and not specifically with tool use.

Method

Participants

Infants were recruited from a database of local families who had expressed interest in taking part in studies of infant development. A total of 101 healthy full-term infants aged 15, 18, 21, and 24 months participated in the study. Of these, 30 infants were excluded from the final sample for one of the following reasons [with age group(s) in months as subscripts]: not playing during the play session ($n_{21m} = 3$); not completing the problem-solving session, that is, at least four tasks from the eight problem-solving battery of tasks (this was usually due to fussiness or lack of interest; $n_{15m} = 3$, $n_{18m} = 16$, $n_{21m} = 5$, $n_{24m} = 1$); experimental error ($n_{18m} = 1$); or extreme shyness (refusal to participate or interact with the experimenter; $n_{15m} = 1$). These strict exclusion criteria, defined a priori, were used to (a) be able to assess the effect of the demonstration on infants' play behavior before and after the demonstration and (b) ensure that all infants participated in at least one tool task and one non-tool task (the order of presentation of the tasks was randomized within groups). The final sample consisted of 71 infants, pseudo-randomly assigned between the demonstration subgroups (ComplexComb and SimpleComb subgroups; see "Procedure" section for details about the demonstrations), matched for age, sex, and linguistic context (monolingual or plurilingual. (For a detailed description, see [Table S1](#) in the online [Supplementary Material](#), which is referred to as "SupplInfo" hereafter). Sex was matched between groups because some studies have found sex differences in infants' play style ([Gredlein & Bjorklund, 2005](#)) and in tool use ([Chen & Siegler, 2000](#)). The linguistic context was also matched between groups because studies have shown that bilingualism provides an advantage over monolingualism in various cognitive skills recruited during problem-solving tasks (see [Quinteros Baumgart & Billick, 2018](#), for a review in infants, although some studies, like the *meta-analysis* by [de Bruin et al., 2014](#), question the strength of these findings). This balance of linguistic context was possible because our recruitment area included families of multiple nationalities, so that about half ($n = 33$ of 71) of the infants lived in a family speaking more than one language. We categorized infants as plurilingual if they heard a second language for more than 20% of the overall heard speech, as reported by their parents.

All parents gave written informed consent about the study and about their children being video-recorded during the study. This study received ethics clearance from the University of Oxford Central University research ethics committee.

Design and materials

Each infant experienced a play session designed to quantify spontaneous object combination intensity with a play set and a problem-solving session to measure infants' abilities to solve various means-end tasks involving or not involving the use of tools.

Play set

The play set contained a mixture of loose objects and fixed features ([Fig. 1](#)). The objects consisted of wooden balles, cubes, rings, sticks, and plastic cups of different sizes and colors (the wooden objects were painted with childproof, nontoxic, water-based acrylic red, green, and brown paint). The fixed features consisted of four 50 x 50-cm activity plates with holes, affixed poles, and both horizontal and vertical tubes with which the objects could be combined (e.g. touching or inserted). After the

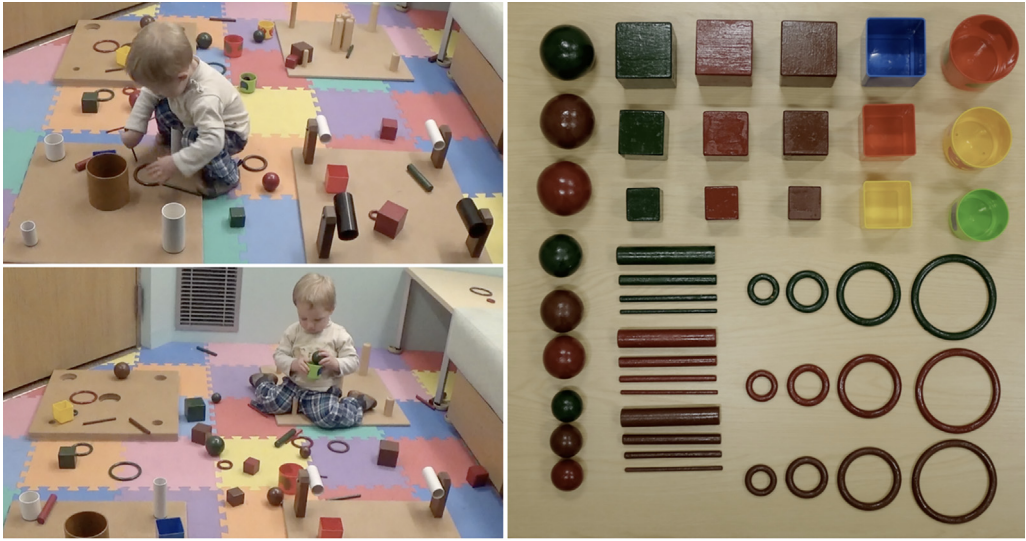


Fig. 1. Top left: An 18-month-old infant playing with the play set, performing a single-object manipulation, that is, rubbing a single stick against one of the four platforms. Bottom left: The same infant performing an object-object combination, that is, inserting a ball into a plastic cup. Right: Detail of all wooden and plastic objects used during the play phase.

infant and caregiver entered the room, the experimenter positioned the four activity plates on the floor in a random rectangular arrangement at approximately 40 cm from one another (Fig. 1). The objects were then randomly scattered over this arrangement. This play set was inspired by the one created by [Auersperg and colleagues \(2015\)](#) for use with birds after adapting it for babies, adding a few additional objects (squared and round plastic cups of different sizes and colors), and adding some interactive features on the activity plates. The motivation to present objects of different sizes, colors, and shapes was to give infants the opportunity to explore and perform many different kinds of behavior, including combinations with other objects and with features from the platform. [Auersperg et al. \(2015\)](#) used a detailed ethogram that included object manipulations and combinations and thus is suitable to make inter- and intra-species comparisons. Given that the ethogram was conceived for birds, we adapted it for human infants (see [Table S4](#) in SupplInfo and the “Data coding and analyses” section below).

Problem-solving tasks

To test infants’ means-end problem-solving abilities, we designed a battery of eight means-end tasks, all involving the execution of a planned sequence leading to the extraction of an attractive toy. To keep infants’ interest in the target across trials and tasks, we used various toys representing animals of different colors and lighting effects, small cars or little wind-up toys, and varied their use on each trial depending on the infants’ interest. All tasks are described in detail and illustrated in [Table S3](#) in the SupplInfo, but we briefly describe them here. Five of the eight tasks involved the use of tools, four of which involved the use of a single tool, thus referred to as “single-tool tasks”. In the rake task, infants needed to use a rake to retrieve an out-of-reach toy placed inside a wide transparent box (Fig. 2, bottom right). Initially, both the rake and the toy were inserted inside the box, with a spatial gap of about 10 cm to the side (right or left depending on the trial) between the rake and the toy. In the slit box task (tool version; see below for the non-tool version), infants needed to horizontally push a toy with a stick through a slit on the side of a transparent box. In the trail box task, infants needed to horizontally push a toy with a stick through a slit on the top of a transparent box. In the tube-pulling task, infants needed to use a hook to pull out a toy placed inside of an opaque horizontal tube (with one end of the tube being closed). The fifth tool task involved the use of several tools in



Fig. 2. Illustrations of the priming step (left pictures) and transfer step (right pictures) of a non-tool task (top pictures) and a tool task (bottom pictures) from the problem-solving session. Top left: An 18-month-old girl spontaneously opening a box to retrieve a toy previously placed inside. In this priming version of the task, two locks are present, but neither one blocks the opening of the lid. Top right: The same girl facing the transfer version of the box (same box but with one of the locks in a blocking position). The girl is moving one of the locks (in this case the non-blocking one to her right) while trying to open the box. Bottom left: A 24-month-old girl pulling the handle of a rake to retrieve a toy attached to it. Bottom right: The same girl manipulating the rake while looking at the toy (not attached to it).

association, referred to as the “associative tool task” (following the definition by [Shumaker et al., 2011](#)). In this task, infants needed to push a toy out of a transparent horizontal tube (with both sides being opened) by inserting two or three short wooden blocks in sequence. We designed this associative tool task so as to be harder than single-tool tasks because it involved the combination of several tools in sequence. Finally, we designed three problem-solving tasks that did not involve the use of tools but were meant to be equivalent in terms of cognitive difficulty, goal to be achieved (i.e., retrieve an out-of-reach toy), number of actions needed to solve the task, and level of motor dexterity. Using tools in extracting tasks typically involves at least two actions: directing the tool toward the object and performing the retrieval gesture in an appropriate manner; thus, our non-tool tasks also involved at least two actions. In the box opening task, infants needed to first remove a latch on the box and then lift its transparent lid to retrieve an out-of-reach toy ([Fig. 2](#), top right); in the slit box task (non-tool version), infants needed to slide an obstructing door to the right before being able to push a toy to the left through a horizontal slit until it fell out of the box; finally, in the tube tilting task, infants needed to remove a wooden block from under a horizontal opaque tube in order to tilt the tube, which made the toy fall out of the tube.

To mitigate potential age and/or inter-individual differences in infants’ problem-solving performance attributable to their prior experience with objects and material properties, we added a priming step for each task. An example of such inter-individual differences is a difference in the amount of

experience with transparent materials given that some apparatuses involved transparent Perspex parts. During the priming step, infants needed to learn how to extract an attractive toy from the apparatus with a single-step (non-tool) manipulation, thereby learning about the basic principle of the task. In the priming step of the rake task, for example, infants learned to retrieve a toy by pulling the handle of the rake to retrieve the toy directly taped to it (Fig. 2, bottom left). In the (non-tool) box opening task, infants first learned that the box (not blocked by a locker) could be opened by lifting its transparent lid. The priming step of each task is described in detail in Table S3.

Procedure

Upon arrival, infants were given a short warm-up phase in the lab reception, during which the experimenter offered various toys and played with the infants to give them an opportunity to familiarize themselves with the experimenter and the environment. In parallel, the caregivers were given information and consent forms and were explained the overall procedure.

The test began with a 15-min play session, immediately followed by a problem-solving session (~20–30 min; Fig. 3). To reduce potential stress, the caregivers were present during the whole experiment but were asked to interfere as little as possible except for occasionally verbally encouraging the infants to interact with the objects and/or retrieve the toy from the apparatuses without showing or telling them how to solve the task.

Play session

We conducted the 15-min play session in a small testing room. It began when the infants first started to interact with the play set. After 5 min of free play with the objects and features (pre-demonstration phase), infants in the ComplexComb subgroup were given 5 min of demonstrations by an experimenter performing object–object combinations and object combinations with features on the platforms. These combinations included pushing or pulling another object with a stick and inserting any kind of small objects into holes, vertical and horizontal tubes attached to the platforms (see Table S2 in the SupplInfo for a detailed description of each type of action performed by the experimenter). These behaviors were chosen because of their prevalence in species that perform well in physical cognition and tool-use tasks (e.g., Auersperg et al., 2015; Hayashi & Matsuzawa, 2003). The demonstrations were intended to potentially increase combinatorial activity by the infants through providing either behavioral models or motivational incentives given that 8- to 24-month-old infants imitate object-directed actions performed by adults in free-play situations (e.g., Koterba & Iverson,

	1. Play session			2. Problem-solving session (2 different sets of 4 tasks)	
	Pre-demo	Demonstration	Post-demo	Priming phase	Transfer phase
ComplexComb subgroup (min n=8 per age group)	5min of free play	5 min of complex combinatorial demonstrations	5min of free play	Infants are asked to extract a reward using a single-step action	If the priming phase of a task is completed, modification of the task to test for transfer of knowledge
SimpleComb subgroup (min n=8 per age group)		5 min of simple actions and simple combinatorial demonstrations		(e.g. open a box, pull the handle of a rake to which a toy is attached)	(e.g. use a rake or a stick to push/pull a toy, remove a blocking object to open a box)

Fig. 3. Overview of the procedure (from left to right) for each demonstration subgroup (ComplexComb and SimpleComb). The demonstration (demo) refers to the phase in which objects are being manipulated by the experimenter (either with a single-object manipulation or with object–object combinations; see below). Babies were allowed and encouraged to play over the three phases of the play session.

2009; Williamson & Brand, 2014). The demonstration per se, or the infants' own induced activity through the demonstration, could then have a causal impact on performance in the follow-up tests. Infants in the SimpleComb subgroup were given the same amount of free play and object demonstrations, but the experimenter manipulated single objects alone or in interaction with the ground, pushing or pulling toys directly with the fingers (i.e., object–body combination) and rubbing sticks against the ground (i.e. object–substrate combination). This reproduced the pushing or pulling demonstrated in the ComplexComb subgroup but without combining objects (see Table S2 for a detailed description of the manipulations). This also served to match the demonstration subgroups for social interaction while exposing the significance of object combinations. To standardize the quantity of demonstrations seen by each infant, we made sure that the infant paid attention to at least 10 instances of each type of demonstrated action (Table S2). Thus, demonstrations that were clearly outside of the infants' visual field when being performed by the demonstrator were repeated when the infants were paying attention again. During the demonstrations, the experimenter verbally attracted the infants' attention toward the actions she was performing (e.g., “Look. I take this. I am doing this”), and also verbally encouraged the infants to imitate these actions (e.g., “Can you do that?”). Infants were allowed to interact with the demonstrator as well as with the play set. Thus, the demonstrator did not continuously perform the actions over the 5 min of the demonstration phase but paused after some actions to give the infants the opportunity to copy the demonstrated action (or to perform other actions). After the demonstrations, infants' free play was recorded for an additional 5 min (post-demonstration phase) to examine possible differences between the two subgroups. Over the 15-min play session, infants were vocally encouraged to freely interact with the play set but were not forced to play; they were free to sit back and/or interact with their caregiver at any time. In the rare cases where infants did not play either during the whole session or both during and after the demonstration period, the infants were excluded from the final sample ($n = 3$ of 101; see “Participants” section). This exclusion criterion was used because of the impossibility to assess the effect of the demonstration or relate play activity with performance in problem-solving tasks.

Problem-solving session

After the play session, the infant and caregiver were transferred to another room. For all but one of the problem-solving tasks, the infant sat in the lap of the caregiver in front of a table and the experimenter sat opposite, facing the infant. Tasks were presented on top of the table except for the trail task, which took place directly on the floor because the testing box was too high for the infants to see the toy inside the box when presented on the table. All trials were prepared behind an opaque screen to prevent infants from observing the experimenter. During the trial, the screen was positioned between the experimenter and the apparatus to prevent the experimenter from looking at the toy (but not at the infants), potentially providing infants with directional cues. Because the procedure was relatively long (15-min play session followed by the problem-solving tasks), we divided the battery of tasks into two predetermined sets of four. Set A contained one single-tool task, the associative tool task, and two non-tool tasks (see Table S3 for a detailed description, and see Fig. 6 in Results for the name of the tasks in each set). Set B contained three single-tool tasks and one non-tool task (Table S3). Given that most of these tasks were being used for the first time in infants, their distribution between the two sets was arbitrary (see in particular the result and discussion of the associative tool task). The order in which tasks were presented and the attribution of sets to participants (A or B) were counterbalanced within each age group and demonstration subgroup. Furthermore, infants who were still motivated to participate after completing one set were given additional tasks from the other set until they refused to participate ($n_{15m} = 0$, $n_{18m} = 1$, $n_{21m} = 1$, and $n_{24m} = 6$ infants). These additional data were included in the infants' problem-solving performance analyses.

As mentioned earlier, each task involved two steps: a *priming* step and a *transfer* step (see Table S3 for details). The completion criterion of the priming step consisted of three successes in a row, with a demonstration of the solution when the infant failed to solve the task. Thus, infants had a minimum of three trials (if they succeeded from the first trial) and a maximum of five trials (if they succeeded at the third trial after demonstration) (see SupplInfo and “Data coding and analyses” section for more details). If an infant did not solve the task after three trials each followed by a demonstration, the transfer version of the task was omitted (assuming that the infant would have failed this version given

that it was more complex than the priming version). For infants who completed the priming step of a given task, the experimenter modified the apparatus for the transfer step. The goal of the task remained the same as during priming, but the task now required using a tool (single-tool task), combining several tools (associative tool task), or removing a physical blockade impeding the priming solution (non-tool task). In the rake task, for instance, the toy was placed to the left or right of the rake so that just pulling the handle would not work; instead, the rake needed to be placed behind the object before pulling (Fig. 3, bottom right). Infants were given about 1 min per trial and up to five trials, and the success criterion was three successes in a row. Thus, infants had a minimum of three trials and a maximum of five trials. During this step, the solution was never demonstrated.

Data coding and analyses

We filmed all sessions and analyzed infants' behavior from the videos using BORIS (Behavioral Observation Research Interactive Software; Friard & Gamba, 2016).

We adapted the ethogram from Auersperg et al. (2015) for human infants, classifying and quantifying manipulations into the following classes: (1) non-combinatorial actions (e.g., touching, pushing, shaking, or picking an object with the hand, symbolic acts such as drinking from a cup or pretending to drive with a ring), (2) simple combinations (e.g. hitting, rubbing, or scratching an object against the ground, touching the substrate, a platform feature, or an object with another object [without moving it], stacking an object on top of another or on a platform feature, symbolic acts such as putting a cup on the head like a hat or brushing hairs with a stick), (3) social actions (not used in the analysis; e.g., giving an object to the experimenter or the caregiver), and (4) complex combinations (i.e., actions demonstrated in the ComplexComb subgroup: e.g., inserting, dipping, or probing an object into a tube/hole or another object, pushing or pulling an object with another) (see Table S4). We extracted the following variables from the coding of the play session: session duration, total time around and within the play set, total manipulation time with objects in the play set, number and nature of non-combinatorial actions, and number and nature of combinations (simple combinations and complex combinations). We conducted a series of generalized linear mixed models (GLMMs) to evaluate infants' spontaneous level of object combinations (simple and complex combinations before the demonstration) as well as to investigate any potential effects of the two demonstration types on their combination levels during and after the demonstration. In these models, we also controlled for individual differences (age, sex, and linguistic context).

For the means-end problem solving, we analyzed infants' performance on two levels: "basic" and "advanced". The basic level corresponded to infants' performance at the priming step of each task because it involved no tool use and required only one simple action to be solved. Spontaneous success was scored as 0, success after demonstration as 1, and failure after two demonstrations as 2 (see additional details in the SuppInfo). We initially expected all priming steps to be relatively easy for all age groups, with older infants solving them spontaneously and younger infants solving them with the assistance of demonstrations. Because this was not what we observed during the experimentations, we statistically compared the performance between the priming steps of different tasks by means of multiple Wilcoxon and Mann-Whitney tests with Bonferroni correction (seven different primings leading to 21 comparisons, $\alpha = .05/21 = .002$). The use of paired versus non-paired tests depended on whether the two compared priming steps were from the same task set (i.e., same infants performing both primings; Wilcoxon) or a different task set (i.e., primings performed by different infants; Mann-Whitney). Note that there were only seven priming steps because two of the eight problem-solving tasks had the same priming but a different transfer step (one to be solved with a tool and the other without a tool, with both tasks being in a different task set). This analysis showed that three of the seven priming tasks were more difficult to solve than the other four (see Results). Thus, we decided to run an additional GLM analysis to check for a potential effect of the demonstrations on the performance in the three more difficult priming tasks and for an effect of individual factors (age and sex).

The "advanced" level of problem solving corresponded to infants' performance at the transfer step of each task. We conducted a binomial GLMM on performance for each task (success or failure based on the success criteria described above), evaluating the potential effects of the following factors:

demonstration subgroups, type of task (single-tool, associative tool, or non-tool), age, sex, and a series of interactions between these factors (see details in Results). In this model, infants had as many performance scores as the number of tasks from their set. For example, if an infant completed Set A, the infant had four scores: one score for the single-tool task, one score for the associative tool task, and two scores for the two non-tool tasks from this set. Thus, infants were added as a random factor into the model to account for the repeated-measure dependencies, and the type of task was included in the factors of the model.

A final correlational analysis was conducted to investigate whether infants who combined more during the whole play session (independently of the demonstration subgroup) performed better in the problem-solving tasks. We used two mixed logistic regressions (one for single-tool and one for non-tool tasks). The dependent variable was the performance in the type of task (either single-tool or non-tool). For example, if an infant did not solve any single-tool task, the score was 0, and if the infant solved one or more, the score was 1. The independent variables in the model were the proportion of simple and complex combinations performed during each phase of the play session (pre-, during, or post-demonstration). This allowed us to differentiate between infants who spontaneously combined more from the beginning of the session and infants who imitated the combinations displayed by the experimenter. Because of the high variability in quantity of each type of combinations performed during the play sessions, all variables were normalized before running the models (see details in the SupplInfo).

An independent observer (blind to the experimental hypotheses) coded about 28% of the data, that is, 20 of 71 babies (10 from each demonstration subgroup). The correlation between the two observers was excellent for all variables (intra-class correlations used for the continuous variables ranged from .86 to .98, and the unweighted Cohen's kappa was .91 for the performance in the battery of tasks, all $p < .001$) (see details for each variable in the SupplInfo).

All statistics were performed using R 4.0.1 and RStudio 1.3.959 for Mac computers. For mixed models, we used the “lme4” package developed by [Bates, Maechler, Bolker, & Walker, 2015](#) with the *lmer* or *glmer* function depending on the nature of the dependent variable (linear or binomial, respectively). For GLMMs, model selections were conducted using a manual backward stepwise procedure based on minimum Akaike information criterion (AIC) values and starting with a global model containing a priori selected variables and interactions of interest, as suggested in [Grueber et al. \(2011\)](#). For GLMs, we used the automatized *stepAIC* function from the “MASS” package instead of a manual procedure. We specify both the variables from the full model and the ones selected in the final best model, both in Results and/or in [Table S5](#) of the SupplInfo. As suggested in [Thomas et al. \(2017\)](#), we only report the main effects when they are not involved in any significant higher-order interaction(s). We calculated the significance of random effects using the method proposed in [Zuur et al. \(2009\)](#). When reporting our results, we also report the mean and standard error ($M \pm SE$) when a result has not been displayed in a figure. Additional details about the analyses can be found in the SupplInfo.

Results

Play session

Quantification of play

Before examining infants' propensity to combine objects, we quantified duration and number of object manipulations. We checked whether these quantities varied across age groups, demonstration subgroups, phase (pre-, during, or post-demonstration), sex, and all two-term interactions between age, subgroups, and phase. This analysis was conducted to check whether the number of object combinations needed to be weighted by number or duration of manipulations in further analyses. Duration and number of manipulations were significantly but weakly correlated ($r = .27$, $p < .05$) because a single action could entail a variable time holding or examining each object. For this reason, we analyzed both dependent variables, but because the results were similar, we report the model with the number of actions as the dependent variable. The outputs of both models, however, can be found in the SupplInfo (GLMM1 and GLMM2 in [Table S5](#)). The final model, chosen through the model

selection process (GLMM2 in Table S5), included phase, demonstration subgroup, and sex and included none of the interactions.

Phase had a significant effect on number of actions. Infants performed more actions before ($M = 56.5 \pm 2.7$) and during ($M = 55.3 \pm 2.9$) the demonstration than after the demonstration ($M = 47.1 \pm 2.7$; $Z_{\text{pre-post}} = 3.30$, $p < .01$, $Z_{\text{ExpPhase-post}} = 2.82$, $p < .05$) (GLMM2 in Table S5). In addition, there was an effect of sex, with boys performing significantly more actions than girls ($z = 2.36$, $p < .05$) (Fig. 4; see also GLMM2 in Table S5).

We did not, however, find a significant effect of demonstration subgroup on the total number of actions ($M_{\text{ComplexComb}} = 168.9 \pm 8.9$; $M_{\text{SimpleComb}} = 149.1 \pm 9.6$, $t = -1.72$, $p = .09$) (GLMM2 in Table S5) or a significant interaction between type of demonstration and experimental phase.

Because the duration of the phases, although programmed to be 5 min each, could vary slightly, we assessed the correlation between total number of actions and number of actions per minute in each phase. This correlation was extremely high ($r = 1$, $p < .001$). This means that the number of actions reflects the actual rate of activity and not variation in opportunity through differences in phase duration. For this reason, in further models we did not correct the quantity of combinations by phase duration.

The significant drop in activity in the last (post-demonstration) phase could be due to fatigue or loss of interest. The fact that the demonstrator stopped interacting with the toys could also have had an inhibitory effect. Because of this “phase” effect, in models comparing the quantity of combinations between the play and problem-solving session, we weighted the dependent variables by the number of actions per phase of each participant. Because during the play session boys played significantly more than girls, we further investigated whether this relates to differences in simple, complex, and/or non-combinatorial actions (see GLMM3 in next section). Finally, there was no significant effect of age in this model; infants in all age groups manipulated the toys to a similar extent.

Quantification of combinatorial activity

To evaluate infants' propensity to perform object combinations, we ran a mixed model analysis with a binomial distribution on the proportion of type of combination (simple or complex) weighted by the total number of actions. The following variables were included before model selection: demonstration subgroup (ComplexComb or SimpleComb), phase (pre-, during, or post-demonstration), type of combinations (simple or complex), sex, age, and various preselected two- and three-term

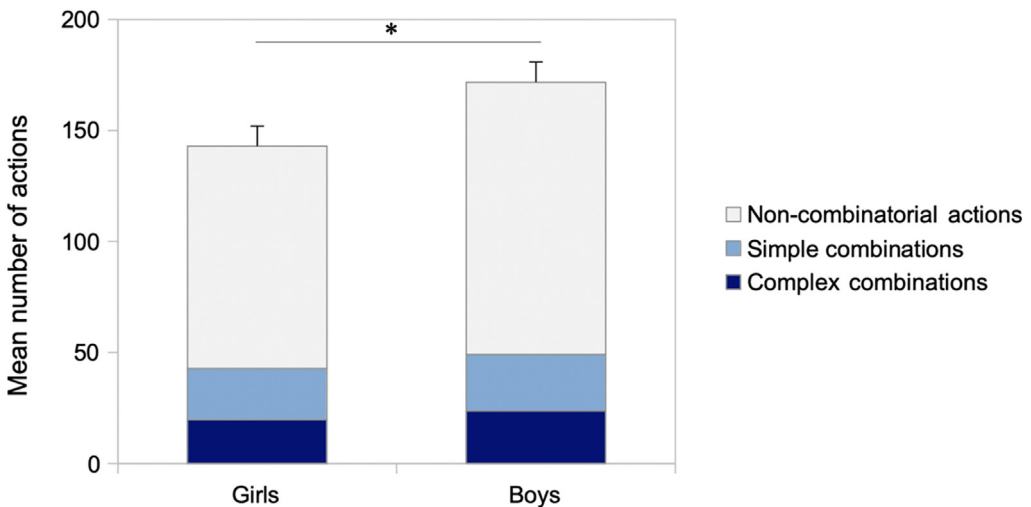


Fig. 4. Mean number of actions per infant over the play session as a function of sex and type of actions. Error bars show standard errors of total actions. * $p < .05$ (Generalized Linear Mixed Model [GLMM] 2).

interactions defined as predictors (see full model details, GLMM3 in Table S5). None of the factors or interactions was excluded through the model selection process.

Type of demonstration had a significant impact on infants' object combinations. First, there was a significant three-term interaction among type of combination performed by infants, demonstration subgroup, and phase (Fig. 5). Before the demonstration, both subgroups performed object combinations to a similar level ($z = 0.97, p = .99$) and did not differ in the proportion of type of combination performed (simple or complex). During the demonstration, infants in the ComplexComb subgroup performed more complex combinations ($z = -8.05, p < .001$) and marginally fewer simple combinations than infants in the SimpleComb subgroup ($z = 2.89, p = .06$). This was related mainly to changes within the ComplexComb subgroup that increased the proportion of complex combinations during and after the demonstration ($z = -14.57, p < .001$; $z = 8.72, p < .001$) and decreased that of simple combinations ($z = 7.00, p < .001$) with respect to the same group prior to the demonstration. In contrast, within the SimpleComb group there was no detectable effect of demonstration on proportion of object combinations. Finally, after the demonstration, the ComplexComb subgroup displayed a significantly higher proportion of complex combinations than the other subgroup ($z = -4.87, p < .001$), whereas the subgroups did not differ in the proportion of simple combinations ($z = 0.19, p = 1.00$). There was also a within-group effect; the proportion of complex combinations was significantly lower after the demonstration than during the demonstration ($z = 6.23, p < .001$) (Fig. 5).

Combination type (complex or simple), demonstration subgroup (ComplexComb or SimpleComb), and age had a significant three-way interaction. There was a higher proportion of complex combinations in the ComplexComb subgroup than in the SimpleComb subgroup at 15, 18, and 24 months of age, but not at 21 months ($M_{ComplexComb15} = 21.7 \pm 4.4, M_{SimpleComb15} = 11.3 \pm 4.0, z_{15} = -3.36, p < .01$; $M_{ComplexComb18} = 31.0 \pm 3.9, M_{SimpleComb18} = 12.1 \pm 3.6, z_{18} = -4.24, p < .001$; $M_{ComplexComb21} = 29.0 \pm 4.9, M_{SimpleComb21} = 20.4 \pm 7.2, z_{21} = -1.53, p = .58$; $M_{ComplexComb24} = 33.7 \pm 6.1, M_{SimpleComb24} = 16 \pm 3.8, z_{24} = -3.06, p < .05$). The means at 21 months suggest that in this age group infants performed more complex combinations in both groups, including the SimpleComb group. Although the difference is not significant, the mean quantity of object combinations in the two groups follows the same trend as in the other age groups. In contrast, there were no overall demonstration subgroup differences between any of the age groups in the propensity to perform simple combinations (all contrast p values $> .05$). This result confirms that the complexity of the combinations demonstrated by the

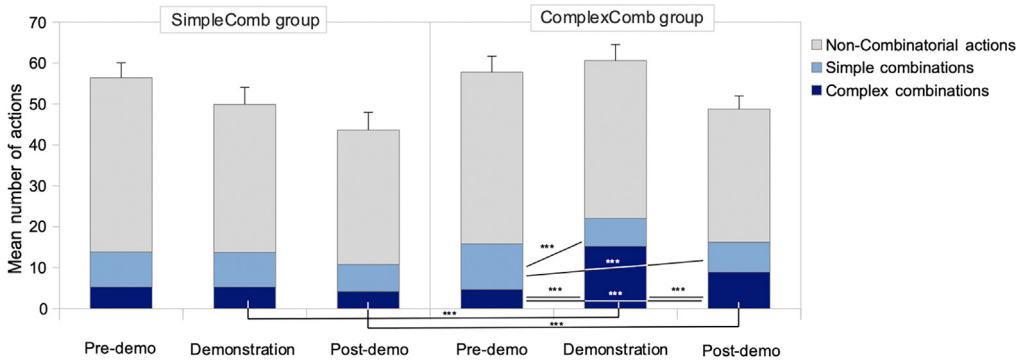


Fig. 5. Number and type of actions in each demonstration subgroup (SimpleComb and ComplexComb) pooled across all ages. Non-combinatorial actions are included to display the proportion of combinations with respect to total actions. Error bars show standard error of total actions. All significant differences are shown by asterisks ($***p < .001$). The two connecting lines and asterisks below the graphs illustrate all significant intergroup comparisons. Infants from the ComplexComb group displayed more complex combinations during and after demonstration than infants from the SimpleComb group. The five connecting lines along with asterisks inside the graph illustrate all the significant intragroup comparisons. The differences were found only in the ComplexComb group (right); infants displayed more complex combinations during the demonstration phase than before and after the demonstration, and they displayed more complex combinations after the demonstration than before the demonstration. demo, demonstration.

experimenter likely played a role on the infants' motivation to copy these actions, at least in three of the four ages tested.

To examine whether boys and girls differed in their play style, we examined the interaction between type of combination performed and sex. We found that boys significantly performed simple and complex combinatorial actions in a similar proportion ($z = 1.72, p = .26$), whereas girls had a higher proportion of simple combinatorial actions than complex ones ($z = 3.06, p < .01$) (Fig. 4). This did not seem to be mediated by total number of combinatorial actions, (see GLMM4 in Table S5 and para. 1.2 in SupplInfo) but instead seemed to be mediated by the fact that boys engage in more non-combinatorial behavior, thereby affecting the observed proportions (Fig. 4).

In conclusion, and perhaps surprisingly, we did not find evidence for a difference in combinatorial activity between age groups. However, the demonstration did affect propensity to combine; infants exposed to complex combinations performed more of them during and after the demonstration. In contrast, infants exposed to simple combinations did not perform more simple combinations during or after the demonstration. Thus, demonstrations had both simultaneous and lagging influence on infants' behavior, but only for the complex combinations.

Problem-solving session

Priming step

Difference of complexity between the priming step of each task. To check for differences in difficulty between the priming step of each task, we conducted Bonferroni-corrected multiple two by two comparisons using the following scores: spontaneous success (scored as 0), success after demonstration (scored as 1), and failure after two demonstrations (scored as 2). Spontaneous success in the priming step was much lower in the associative, slit box, and trail box tasks than in the other tasks (Fig. 6; see also Table S6 in SupplInfo). In contrast,

the rates of success after demonstration and of failure were higher. The difference in performance between tasks may reflect differences in cognitive processing requirements, in motor difficulty, or in engagement.

Main factors influencing the basic level of problem-solving (i.e., priming step). To test whether unintended factors (i.e., age, sex, and demonstration subgroups) explained infants' performance at the

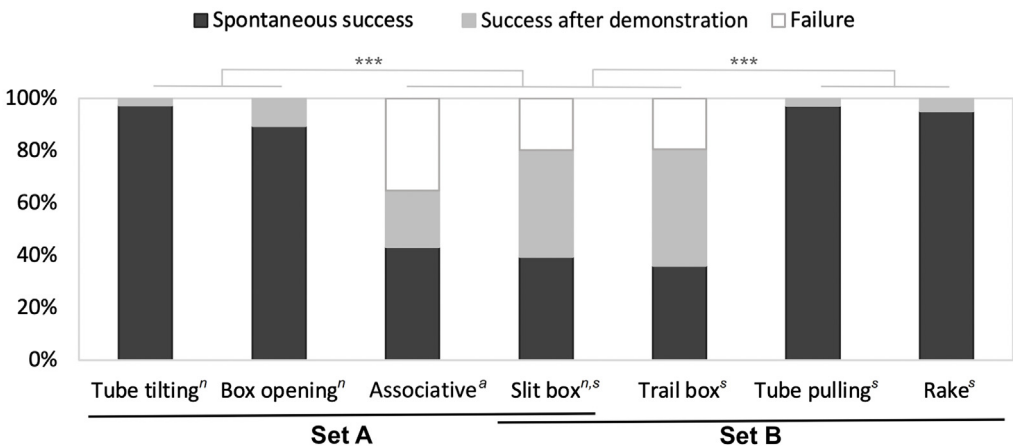


Fig. 6. Proportion of infants succeeding in the (non-tool) priming step of each task spontaneously, after demonstration, or never (i.e., not solving the task in the testing session). *** $p < .001$. Because the slit box task had both a tool version and a non-tool version, but with an identical priming step, it was present in both Set A (tool version) and Set B (non-tool version). No task involved tools during the priming step, so superscripts (n = non-tool task, s = single-tool task, a = associative tool task) indicate the kind of task to follow in the transfer step. See descriptions and illustrations in the SupplInfo.

priming step of the three tasks with most failures, we ran a GLM1 with these predictors on infants' mean performance in these three tasks. We calculated the performance based on the score (0, 1, or 2) described above. Subgroup was excluded through the model selection process, and sex had a small, nonreliable effect ($p = .07$), but age was a significant factor ($p < .001$; see GLM1 in Table S5). This effect was principally due to the two younger age groups failing significantly more than the two older ones ($M_{15} = 1.44 \pm 0.13$, $M_{18} = 1.13 \pm 0.13$, $M_{21} = 0.50 \pm 0.12$, $M_{24} = 0.27 \pm 0.10$, $z_{21-15} = -4.96$, $p < .001$, $z_{21-18} = -3.67$, $p < .01$, $z_{24-15} = -6.77$, $p < .001$, $z_{24-18} = -5.25$, $p < .001$; no differences between 15 and 18 months or between 21 and 24 months, respectively, all $ps > .05$).

In summary, in the priming step four of the seven tasks were solved by nearly all infants, whereas the remaining three tasks were mostly solved by infants of the two older age groups.

Transfer step: Effect of combinatorial demonstration on problem-solving performance

To test for the effect of the two demonstration subgroups, we used success or failure on each task as the dependent variable (with success corresponding to three consecutive successful trials; see Method). Our initial GLMM included the following predictors: demonstration subgroup (ComplexComb or SimpleComb), type of task (single-tool, associative tool, or non-tool tasks), age, sex, and the interactions between age and demonstration subgroups and between age and type of task, with infant as a random factor. After model selection, the final model included only age and type of task as main predictors (GLMM5 in Table S5). The interaction between age and type of task was also dropped during the model selection process.

As with priming, performance at the transfer step significantly improved across age groups, with 21- and 24-month-olds performing better than 18-month-olds ($M_{18} = 0.33 \pm 0.05$, $M_{21} = 0.65 \pm 0.06$, $M_{24} = 0.68 \pm 0.05$, $z_{21-18} = 3.51$, $p < .01$, $z_{24-18} = 4.15$, $p < .001$), and all other age groups performing better than 15-month-olds ($M_{15} = 0.15 \pm 0.04$, $z_{18-15} = 2.58$, $p < .05$, $z_{21-15} = 5.30$, $p < .001$, $z_{24-15} = 5.88$, $p < .001$). There was also a significant effect of type of tasks, with a lower performance in single-tool tasks than on associative tool and non-tool tasks ($z_{\text{seq-single-tool}} = 2.42$, $p < .05$, $z_{\text{non-tool vs. single-tool}} = 4.36$, $p < .001$) (Fig. 7).

In summary, we found no differences in problem-solving performance between demonstration subgroups. Infants' performance was worse in the single-tool tasks than in the associative and non-tool tasks, and neither demonstration nor age affected this difference. This confirms that infants have

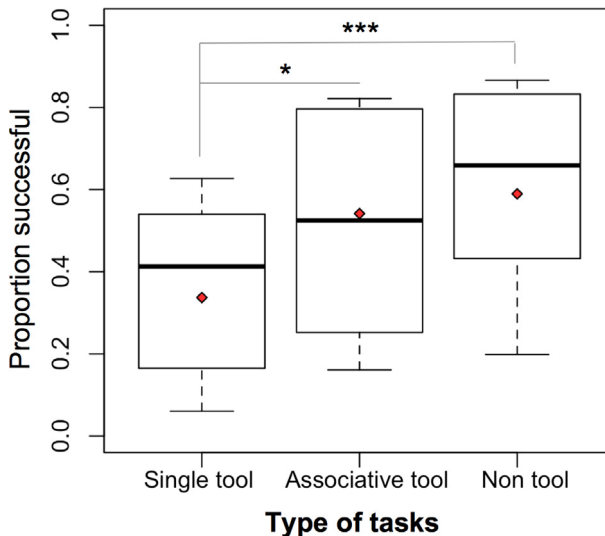


Fig. 7. Proportion of successful infants (all age groups and demonstration subgroups combined) in each type of task. Points show the mean, and horizontal lines show the median. * $p < .05$; *** $p < .001$.

more difficulties in solving novel means–end tasks involving the use of tools until at least the end of the second year of life, in comparison with non-tool means–end tasks (see also Discussion below). The difference found between the single-tool and associative tool tasks may seem counterintuitive at first sight given that combining several tools should require more advanced planning skills than using a single tool, but the effect is probably artifactual. We designed the associative tool task (Table S3) so as to be harder than single-tool tasks because it involved the combination of several tools to be solved. However, the task did not work as expected. A large proportion of infants, when failing to reach the toy, seemed to switch their goal; instead of trying to retrieve the toy, they tried to insert as many blocks as possible inside the tube—leading to serendipitous success on many occasions. Many infants became uninterested in the toy even after a successful trial; instead, they kept inserting either blocks or the toy itself into the tube. Because of this, in the following series of models, we dismissed this task and analyzed the link between infants' combinatorial activity and problem-solving performance only in the single- and non-tool tasks.

Link between combinatorial activity and problem-solving performance

In this last section we investigated whether infants' combinatorial activity during the three phases of free play (i.e., before, during, and after the demonstrations) predicted success or failure in tool and non-tool tasks independent of the demonstration types. We ran logistic regressions (LRs; LR1 and LR2 models in Table S5) on infants' success in at least one task of each type (i.e., single-tool or non-tool task) as a function of number and types of combinations (i.e., complex or simple) performed during the three phases of the play session. Because the number of actions differed significantly between phases (see “Quantification of combinatorial activity” section), we systematically weighted the quantity of combinatorial actions by the total number of actions of each subject and phase. Age was not included because the proportion of actions that were combinations did not differ significantly between age groups (GLMM3 in Table S5; see also “Quantification of combinatorial activity” section). These models were run on both types of tasks (single-tool and non-tool tasks) separately.

Single-tool tasks

Performance on tool tasks was significantly correlated with propensity to perform complex combinations; the greater the number of combinations during (but not before and after) the demonstration, the better was performance in the tool tasks ($p = .05$, LR1, Table S5 in SupplInfo; see also Fig. 8, left).

Non-tool tasks

Similar to the model with tool tasks, the more complex combinations infants performed during the demonstration, the better their performance in non-tool tasks was ($p < .01$ for LR2 on 71 infants, Table S5; see also Fig. 8, right). No other factors were significant.

In summary, inter-individual differences in spontaneous complex combination behavior before the demonstration did not predict performance in either tool or non-tool problem-solving tasks, but complex combinations during the demonstration were positively associated with success in both tool and non-tool tasks. This result includes both infants who combined more by observation (i.e., infants who copied more the complex combinations performed by the experimenter) and infants who spontaneously combined more regardless of the demonstration subgroup.

Discussion

This study was triggered by the expectation that infants who display greater propensity to combine objects would show an enhanced performance in solving problems involving physical manipulations. Furthermore, we also expected that more complex combinations, either spontaneous or socially prompted, would selectively predict greater tool-use competence. These hypothetical associations may be expected for a variety of reasons. Empirically, comparative studies contrasting different species that vary in propensity to use tools have found tool use to be more frequent in species perceived as being cognitively advanced such as primates, corvids, and parrots. This suggests the possibility that

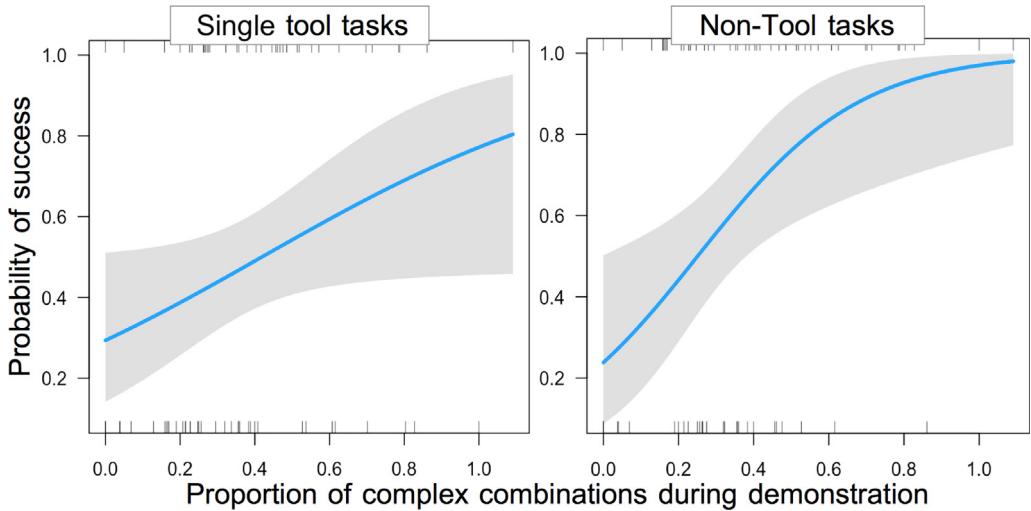


Fig. 8. Probability of success in each type of task as a function of number of complex combinations over the total number of actions during the demonstration.

such associations may also be present in within-species inter-individual variation, including individual differences in combinatorial activities and tool use in children (Gredlein & Bjorklund, 2005). There are also theoretical possible reasons. Tool use by definition involves using objects to exert influence on other objects, and the propensity to generate complex nonfunctional object interactions may be higher in individuals more capable of using objects functionally as tools to achieve goals. It is also reasonable to expect causal relations; combining objects in complex ways may offer the opportunity to acquire skills that remain available when a functional need presents itself.

We examined the relation between object play and the development of physical problem solving in infants with an emphasis on distinguishing between tool-related and non-tool-related competences. We explored these potential associations correlationally by seeking to expose whether spontaneous infant playing (before the experimenter's demonstrations) predicts inter-individual variance in physical problem solving as well as experimentally by exposing infants to either simple or complex combinatorial activity by a demonstrator and exploring whether such demonstrations induce variance in infants' play and problem-solving performance. Regarding the experimental approach, we found no detectable differences in problem-solving performance between infants who were prompted to perform complex combinations and those who were not. The correlational approach, on the other hand, revealed a correlation between infants' inclination to combine objects and their proficiency in means-end problem-solving tasks regardless of whether the task involved the use of tools or not. Furthermore, this result includes not only infants who combined more spontaneously (before demonstration) but also infants who were prompted during the demonstration phase to perform complex combinations. We next summarize results from the play and problem-solving sessions separately and then evaluate their significance regarding the hypothesized link between tool use and combinatorial behavior.

During the play session, infants of all ages performed both simple and complex combinations spontaneously, and the total number of combinations did not differ significantly between age groups. We did expect to find an age effect both as a general effect of development and because of preexisting empirical reports. Previous research has found that object combination typically begins at 9 to 12 months of age (Vauclair & Bard, 1983; see Needham & Nelson, 2023, for a review) and continues developing throughout the second year of life with the emergence of symbolic acts and construction skills (Fenson et al., 1976; Marcinowski et al., 2019). In fact, we detected symbolic and construction acts at all the tested ages (e.g., symbolic acts were present in approximately 11%, 47%, 13%, and 22% of infants across our four age groups—15-, 18-, 21-, and 24-month-olds, respectively). The fact

that infants of various ages exhibited similar levels of spontaneous engagement in both simple and complex combinations during play sessions suggests a continuity in developmental trajectories rather than distinct age-related stages. Despite initial expectations based on previous literature, our study highlights the early emergence and persistent presence of complex combinations across infancy, underscoring the need for further investigation into the nuanced progression of cognitive and motor skills during this critical period of development.

Consistent with previous work on imitation of play during the second year of life (Koterba & Iverson, 2009; Williamson & Brand, 2014), we found an effect of type of demonstration; infants exposed to complex combinations (i.e., pushing or pulling an object with another and inserting objects into others or features of the play set) increased their level of combinatorial activity with respect to their own baseline while the demonstration took place, and this effect persisted after the demonstration. In contrast, infants exposed to simpler object combinations (i.e., pushing an object with the finger and scratching an object against the ground) did not significantly increase their propensity to either imitate these actions or perform more complex combinations.

As mentioned earlier, it is frequently assumed that tool-related tasks are intrinsically more difficult than non-tool tasks, and there is evidence supporting this in children (Meulman et al., 2013). Indeed, success in our tool tasks was poorer than in tasks equated on goals, number of steps, and motor dexterity but not requiring tools. This extra difficulty could be due to many factors, including the need to use an external object splitting attention between tool and goal, the need to identify the affordances of the tool, and/or the need to integrate the control of the tool with control of one's own body (Smitsman & Corbetta, 2010). Another contributing factor is that the probability of discovering a solution through random exploration is lower in tool tasks without necessarily requiring higher cognitive competence. Tool tasks may be solved only if appropriate actions are performed in a correct sequence—grasping the tool, placing it in contact with the target, and then moving the target object with it exploiting the (folk) physics of solids' interactions. In contrast, in non-tool tasks, random manipulation of bits of the apparatus may lead to a solution, and reinforcement learning may do the rest.

This debate is consistent with the view that tool-related behavior (or “tooling”; Frigaszy & Mangalam, 2018) may be fundamental for comparative cognition research not just because it requires especially advanced cognition but also because it makes cognition more observationally accessible. For example, Keen (2011) called tool use “a royal road to the study of problem-solving” (p. 2), arguing that it more easily reflects infants' capacity to reason about the task, and Bluff, Weir, & Rutz, 2007 wrote, “While tool-related behavior is not necessarily associated with unusually sophisticated cognition, it is likely to be unusually revealing about the cognitive processes and the level of understanding involved in animals' manipulation of physical objects” (p. 1).

In the current study, exposure to complex combinations did not lead to detectable differences in performance in either tool or non-tool tasks. We also found no correlation between spontaneous propensity to combine objects (i.e., before demonstration) and performance in the tasks. The absence of a detectable effect of our brief demonstrations on problem solving is interesting but should not be interpreted as children being refractory to social influences in this respect given that their sensitivity may have been masked by a number of factors. For instance, although the number of combinations did not vary much with age, performance in tool use improved. This would be in line with the sensorimotor perspective on the development of tool use (Lockman, 2000; Lockman & Kahrs, 2017), which postulates that the motor origins of tool use are reaching maturity by the end of the first year of life. Revealing a causal link between early combinatorial intensity and later problem-solving performance in tool-related tasks may require longer longitudinal studies exploring combinatorial activity during the second half of the first year in relation to tool use at the end of the second year. It is also possible that there is no strong relation between object combinations and tool use until as late as the end of the second year given that Gredlein and Bjorklund (2005) found that the amount of time boys spent in object combinations (stacking or connecting objects together) during a free-play session did predict performance in a tool choice task at 3 years of age.

It is also possible that inter-individual variance in combinatorial activity before demonstration swamped the impact of experimental treatment given that combinatorial activity did predict problem-solving performance in both tool and non-tool tasks when participants were pooled across demonstration subgroups. Notice that this last result includes infants who combined more either

by being prompted or spontaneously, that is regardless of demonstration subgroup. This highlights the necessity, in the study of the development of learning, to take into account the interaction between an infant's own sensorimotor development and the social context of play activities, as stressed by Wynberg et al. (2022).

The wider implication is that complexity of play may be a better predictor of means–end problem-solving ability in general than of tool-use competence specifically, a possibility that is not exposed in protocols using exclusively tool-related tasks (e.g., Gredlein & Bjorklund, 2005, although the authors did mention that, based on other play variables, more advanced styles of play may reflect higher advanced cognitive skills [p. 225]). Significantly for our current study, Pepler and Ross (1981) found a link between diversity in the objects with which 3- and 4-year-old children played and the number of strategies used to solve a set of problems. As noted by Riede et al. (2018), this shared diversity in innovativeness and active exploration is associated with infants' creativity, a cognitive trait likely to affect various forms of reasoning. Taken together, our main result joins the growing body of literature suggesting that early exploratory play correlates with cognitive development (Chu & Schulz, 2020; Hutt & Bhavani, 1972; Muentener et al., 2018; Singer et al., 2006).

The fact that we found no sex differences in either object combinations or tool-use performance contrasts with studies reporting that 3-year-old boys spontaneously performed better than girls on a tool-retrieval task (Chen & Siegler, 2000; Gredlein & Bjorklund, 2005). Gredlein and Bjorklund (2005) further found that boys performed more combinatorial actions than girls, with a positive correlation between tool-use performance and number of combinatorial actions. The authors proposed that sex differences in play styles may have been selected over the course of human evolution to prepare boys and girls for adult life in traditional environments. In our study, however, although boys performed significantly more actions than girls, there was no sex difference in the propensity to combine objects—in terms of either proportion or absolute quantity—and no difference in the nature of the combinations performed (simple or complex). Given that the infants we tested were 12 to 18 months younger than children from the above-cited experiments, two obvious candidate explanations emerge. Perhaps the sex biases in play and tool use are indeed rooted in our evolutionary heritage, but they only develop after the onset of tool use—that is, after the end of the second year of life. However, a major confounding factor is that older children had more exposure to social and cultural environments, hence the reported differences may reflect those environmental influences rather than evolutionary adaptations. As mentioned by Lonsdorf (2017) in her review of behavioral sex differences in primates, distinguishing between biological and social factors in human development poses a considerable challenge.

In summary, we found that complexity of play, measured by the propensity to combine objects both spontaneously and by observation, predicts the capacity to solve means–end problems in general rather than just tool-use competences. By linking infants' spontaneous and socially influenced play styles to their performance in a battery of tool and non-tool problem-solving tasks, our study aligns with the approach to tool-use development that considers sensorimotor, social, and cognitive aspects together. Isolating single factors influencing infants' sociocognitive development can be very informative, but such factors act through their developmental interactions, and the relation between complex object manipulations and tool-use competence might not be revealed until longer-term developmental studies become available.

CRedit authorship contribution statement

Lauriane Rat-Fischer: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Kim Plunkett:** Validation, Supervision, Resources. **Auguste M.P. von Bayern:** Validation, Conceptualization. **Alex Kacelnik:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization.

Data availability

Data will be made available on request.

Acknowledgments

We thank Amanda Griffins and Irina Lepadatu for participant recruitment and all the families who took part in the study. We thank Angèle Castets for double coding of a significant fraction of the data. We thank Tony Price and John Hogg from the mechanical workshop of the Department of Zoology at the University of Oxford for the building of eight baby-friendly apparatuses. We thank three anonymous reviewers and the editor for their constructive feedback and suggestions, which significantly enhanced the scientific rigor and presentation of this work. This project was funded by a postdoctoral fellowship from the Fyssen Foundation to L.R-F. Support through the ANR Labex IAST to L.R-F. is also gratefully acknowledged. A.K. was sponsored by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy (EXC 2002/1, "Science of Intelligence". Project 390523135). Funding sources had no involvement in the conduct of the research and/or preparation of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jecp.2024.105957>.

References

- Auersperg, A. M. I., van Horik, J. O., Bugnyar, T., Kacelnik, A., Emery, N. J., & von Bayern, A. M. P. (2015). Combinatory actions during object play in psittaciformes (*Diopsittaca nobilis*, *Pionites melanocephala*, *Cacatua goffini*) and corvids (*Corvus corax*, *C. monedula*, *C. moneduloides*) (*Corvus*). *Journal of Comparative Psychology*, 129(1), 62–71. <https://doi.org/10.1037/a0038314>.
- Babik, I., Cunha, A. B., Ross, S. M., Logan, S. W., Galloway, J. C., & Lobo, M. A. (2019). Means-end problem solving in infancy: Development, emergence of intentionality, and transfer of knowledge. *Developmental Psychobiology*, 61(2), 191–202. <https://doi.org/10.1002/dev.21798>.
- Bates, D., Maechler, M., Bolker, B. M., & Walker, S. (2015). *lme4: Linear mixed-effects models using Eigen and S4*. R package Version 1 <http://CRAN.R-project.org/package=lme4>.
- Bates, E., Carlsonluden, V., & Bretherton, I. (1980). Perceptual aspects of tool using in infancy. *Infant Behavioural Development*, 3, 127–140. [https://doi.org/10.1016/S0163-6383\(80\)80017-8](https://doi.org/10.1016/S0163-6383(80)80017-8).
- Bjorklund, D. F., & Gardiner, A. K. (2011). Object play and tool use: Developmental and evolutionary perspectives. In A. D. Pellegrini (Ed.), *Oxford handbook of play* (pp. 153–171). Oxford University Press.
- Bourgeois, K. S., Khawar, A. W., Neal, S. A., & Lockman, J. J. (2005). Infant manual exploration of objects, surfaces, and their interrelations. *Infancy*, 8(3), 233–252. https://doi.org/10.1207/s15327078in0803_3.
- Brown, A. L. (1990). Domain-specific principles affect learning and transfer in children. *Cognitive Science*, 14(1), 107–133. https://doi.org/10.1207/s15516709cog1401_6.
- Burghardt, G. M. (2005). *The genesis of animal play: Testing the limits*. MIT Press.
- Cenni, C. (2022). *On the proximate links between object play and tool use in the context of stone handling behavior in Balinese long-tailed macaques*. Lethbridge, Alberta, Canada: University of Lethbridge. Doctoral thesis.
- Chen, Z., & Siegler, R. S. (2000). Across the great divide: Bridging the gap between understanding of toddlers' and older children's thinking. *Monographs of the Society for Research in Child Development*, 65(2), v–96. <https://doi.org/10.1111/1540-5834.00072>.
- Cheyne, J. A., & Rubin, K. H. (1983). Playful precursors of problem solving in preschoolers. *Developmental Psychology*, 19(4), 577–584. <https://doi.org/10.1037/0012-1649.19.4.577>.
- Chu, J., & Schulz, L. E. (2020). Play, curiosity, and cognition. *Annual Review of Developmental Psychology*, 2, 317–343. <https://doi.org/10.1146/annurev-devpsych-070120-014806>.
- Claxton, L. J., McCarty, M. E., & Keen, R. (2009). Self-directed action affects planning in tool-use tasks with toddlers. *Infant Behavior and Development*, 32(2), 230–233. <https://doi.org/10.1016/j.infbeh.2008.12.004>.
- Connolly, K., & Dalgleish, M. (1989). The emergence of a tool-using skill in infancy. *Developmental Psychology*, 25(6), 894–912. <https://doi.org/10.1037/0012-1649.25.6.894>.
- de Bruin, A., Treccani, B., & Della Sala, S. (2014). Cognitive advantage in bilingualism: An example of publication bias? *Psychological Science*, 26, 1–9. <https://doi.org/10.1177/0956797614557866>.
- de Resende, B. D., Ottoni, E. B., & Fragaszy, D. M. (2008). Ontogeny of manipulative behavior and nut-cracking in young tufted capuchin monkeys (*Cebus apella*): A perception-action perspective. *Developmental Science*, 11, 828–840. <https://doi.org/10.1111/j.1467-7687.2008.00731.x>.
- Deák, G. O. (2014). Development of adaptive tool-use in early childhood: Sensorimotor, social, and conceptual factors. In J. B. Benson (Ed.), *Advances in child development and behavior* (Vol. 46, pp. 149–181). Elsevier.
- Elsner, B. (2007). Infants' imitation of goal-directed actions: The role of movements and action effects. *Acta Psychologica*, 124, 44–59. <https://doi.org/10.1016/j.actpsy.2006.09.006>.
- Elsner, B. (2009). Tools and goals: A social-cognition perspective on infant learning of object function. In T. Striano & V. Reid (Eds.), *Social cognition: Development, neuroscience and autism* (pp. 144–156). John Wiley-Blackwell.
- Esseily, R., Rat-Fischer, L., O'Regan, J. K., & Fagard, J. (2013). Understanding the experimenter's intention enables 16-month-olds to successfully perform a novel tool use action. *Cognitive Development*, 28(1), 1–9. <https://doi.org/10.1016/j.cogdev.2012.10.001>.

- Esseily, R., Rat-Fischer, L., Somogyi, E., O'Regan, J. K., & Fagard, J. (2015). Humor production may enhance observational learning of a new tool use action in 18-month-old infants. *Cognition and Emotion*, 30(4), 817–825. <https://doi.org/10.1080/02699931.2015.1036840>.
- Fagard, J., Rat-Fischer, L., Esseily, R., Somogyi, E., & O'Regan, J. K. (2016). What does it take for an infant to learn how to use a tool by observation? *Frontiers in Psychology*, 7, Article, 267. <https://doi.org/10.3389/fpsyg.2016.00267>.
- Fanning, P. A., Sparaci, L., Dissanayake, C., Hocking, D. R., & Vivanti, G. (2021). Functional play in young children with autism and Williams syndrome: A cross-syndrome comparison. *Child Neuropsychology*, 27(1), 125–149. <https://doi.org/10.1080/09297049.2020.1804846>.
- Fenson, L., Kagan, J., Kearsley, R. B., & Zelazo, P. R. (1976). The developmental progression of manipulative play in the first two years. *Child Development*, 47(1), 232–236. <https://doi.org/10.2307/1128304>.
- Fontenelle, S. A., Kahrs, B. A., Neal, S. A., Newton, A. T., & Lockman, J. J. (2007). Infant manual exploration of composite substrates. *Journal of Experimental Child Psychology*, 98(3), 153–167. <https://doi.org/10.1016/j.jecp.2007.07.001>.
- Fragaszy, D. M., & Adam-Curtis, L. E. (1991). Generative aspects of manipulation in tufted capuchin monkeys (*Cebus apella*). *Journal of Comparative Psychology*, 4, 387–397. <https://doi.org/10.1037/0735-7036.105.4.387>.
- Fragaszy, D. M., & Mangalam, M. (2018). Tooling. *Advances in the Study of Behavior*, 50, 177–241. <https://doi.org/10.1016/bs.asb.2018.01>.
- Friard, O., & Gamba, M. (2016). BORIS: A free, versatile open-source event-logging software for video/audio coding and live observations. *Methods in Ecology and Evolution*, 7(11), 1325–1330. <https://doi.org/10.1111/2041-210X.12584>.
- Gibson, J. J. (1966). *The senses considered as perceptual systems*. Houghton Mifflin.
- Gibson, J. J. (1979). *The ecological approach to perception*. Psychology Press.
- Gredlein, J. M., & Bjorklund, D. F. (2005). Sex differences in young children's use of tools in a problem-solving task. *Human Nature*, 16(2), 211–232. <https://doi.org/10.1007/s12110-005-1004-5>.
- Grueber, C. E., Nakagawa, S., Laws, R. J., & Jamieson, I. G. (2011). Multimodel inference in ecology and evolution: Challenges and solutions. *Journal of Evolutionary Biology*, 24, 699–711. <https://doi.org/10.1111/j.1420-9101.2010.02210.x>.
- Guerin, F., Krüger, N., & Kraft, D. (2013). A survey of the ontogeny of tool use: From sensorimotor experience to planning. *IEEE Transactions on Autonomous Mental Development*, 5(1), 18–45. <https://doi.org/10.1109/TAMD.2012.2209879>.
- Hayashi, M., & Matsuzawa, T. (2003). Cognitive development in object manipulation by infant chimpanzees. *Animal Cognition*, 6, 225–233. <https://doi.org/10.1007/s10071-003-0185-8>.
- Bluff, L.A., Weir, A.A.S., & Rutz, C. (2007). Tool-related cognition in New Caledonian crows. *KIP Articles*, Article 5333. https://digitalcommons.usf.edu/kip_articles/5333.
- Hayashi, M., Takeshita, H., & Matsuzawa, T. (2006). Cognitive development in apes and humans assessed by object manipulation. In T. Matsuzawa, M. Tomonaga, & M. Tanaka (Eds.), *Cognitive development in chimpanzees*. Springer. https://doi.org/10.1007/4-431-30248-4_24.
- Hutt, C., & Bhavani, R. (1972). Predictions from play. *Nature*, 237, 171–172. <https://doi.org/10.1038/237171b0>.
- Kacelnik, A., Chappell, J., Kenward, B., & Weir, A. A. S. (2006). Cognitive adaptations for tool-related behavior in New Caledonian crows. In E. A. Wasserman & T. R. Zentall (Eds.), *Comparative cognition: Experimental explorations of animal intelligence* (pp. 515–528). Oxford University Press. <https://doi.org/10.1093/acprof:oso/9780195377804.003.0027>.
- Kahrs, B. A., Jung, W. P., & Lockman, J. J. (2014). When does tool use become distinctively human? *Hammering in young children*. *Child Development*, 85(3), 1050–1061. <https://doi.org/10.1111/cdev.12179>.
- Kaur, M., Detherage, A., & Needham, A. W. (2020). Unconventional tool use in infants: Using a familiar tool in a novel way in the second year of life. *Cognitive Development*, 54, 100881. <https://doi.org/10.1016/j.cogdev.2020.100881>.
- Keen, R. (2011). The development of problem solving in young children: A critical cognitive skill. *Annual Review of Psychology*, 62, 1–21. <https://doi.org/10.1146/annurev.psych.031809.130730>.
- Kenward, B., Rutz, C., Weir, A. A. S., & Kacelnik, A. (2006). Development of tool use in New Caledonian crows: Inherited action patterns and social influence. *Animal Behaviour*, 72, 1329–1343. <https://doi.org/10.1016/j.anbehav.2006.04.007>.
- Koterba, E. A., & Iverson, J. M. (2009). Investigating motionese: The effect of infant-directed action on infants' attention and object exploration. *Infant Behavior and Development*, 32, 437–444. <https://doi.org/10.1016/j.infbeh.2009.07.003>.
- Lockman, J. J. (2000). A perception–action perspective on tool use development. *Child Development*, 71(1), 137–144. <https://doi.org/10.1111/1467-8624.00127>.
- Lockman, J. J., & Kahrs, B. (2017). New insights into the development of human tool use. *Current Directions in Psychological Science*, 26(4), 330–334. <https://doi.org/10.1177/0963721417692035>.
- Lonsdorf, E. V. (2017). Sex differences in nonhuman primate behavioral development. *Journal of Neuroscience Research*, 95, 213–221. <https://doi.org/10.1002/jnr.23862>.
- Marcinowski, E. C., Nelson, E., Campbell, J. M., & Michel, G. F. (2019). The development of object construction from infancy through toddlerhood. *Infancy*, 24(3), 368–391. <https://doi.org/10.1111/inf.12284>.
- McCarty, M. E., Clifton, R. K., & Collard, R. R. (1999). Problem solving in infancy: The emergence of an action plan. *Developmental Psychology*, 35(4), 1091. <https://doi.org/10.1037/0012-1649.35.4.1091>.
- McCarty, M. E., Clifton, R. K., & Collard, R. R. (2001). The beginnings of tool use by infants and toddlers. *Infancy*, 2(2), 233–256. https://doi.org/10.1207/S15327078IN0202_8.
- Meulman, E. J. M., Seed, A. M., & Mann, J. (2013). If at first you don't succeed ... : Studies of ontogeny shed light on the cognitive demands of habitual tool use. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 368, 20130050. <https://doi.org/10.1098/rstb.2013.0050>.
- Muentener, P., Herrig, E., & Schulz, L. (2018). The efficiency of infants' exploratory play is related to longer-term cognitive development. *Frontiers in Psychology*, 9, 635. <https://doi.org/10.3389/fpsyg.2018.00635>.
- Needham, A. W., & Nelson, E. L. (2023). How babies use their hands to learn about objects: Exploration, reach-to-grasp, manipulation, and tool use. *Wiley Interdisciplinary Reviews: Cognitive Science*, 14(6)e1661. <https://doi.org/10.1002/wcs.1661>.
- Needham, A. W. (2016). Learning about objects in infancy. *Routledge*. <https://doi.org/10.4324/9781315628783>.
- O'Hara, M., & Auersperg, A. M. I. (2017). Object play in parrots and corvids. *Current Opinions in Behavioral Sciences*, 16, 119–125. <https://doi.org/10.1016/j.cobeha.2017.05.008>.

- Osiurak, F., Navarro, J., & Reynaud, E. (2018). How our cognition shapes and is shaped by technology: A common framework for understanding human tool-use interactions in the past, present, and future. *Frontiers in Psychology*, 9, 293. <https://doi.org/10.3389/fpsyg.2018.00293>.
- Palmer, C. F. (1989). The discriminating nature of infants' exploratory actions. *Developmental Psychology*, 25(6), 885–893. <https://doi.org/10.1037/0012-1649.25.6.885>.
- Pepler, D. J., & Ross, H. S. (1981). The effects of play on convergent and divergent problem solving. *Child Development*, 52, 1202–1210. <https://doi.org/10.2307/1129507>.
- Quinteros Baumgart, C., & Billick, S. B. (2018). Positive cognitive effects of bilingualism and multilingualism on cerebral function: A review. *Psychiatric Quarterly*, 89, 273–283. <https://doi.org/10.1007/s11126-017-9532-9>.
- Rat-Fischer, L., O'Regan, J. K., & Fagard, J. (2012). The emergence of tool use during the second year of life. *Journal of Experimental Child Psychology*, 113(3), 440–446. <https://doi.org/10.1016/j.jecp.2012.06.001>.
- Riede, F., Johannsen, N. N., Högborg, A., Nowell, A., & Lombard, M. (2018). The role of play objects and object play in human cognitive evolution and innovation. *Evolutionary Anthropology*, 27, 46–59. <https://doi.org/10.1002/evan.21555>.
- Schubotz, R. I., Ebel, S. J., Elsner, B., Weiss, P. H., & Wörgötter, F. (2023). Tool mastering today—An interdisciplinary perspective. *Frontiers in Psychology*, 14, 1191792. <https://doi.org/10.3389/fpsyg.2023.1191792>.
- Shumaker, R. W., Walkup, K. R., & Beck, B. B. (2011). *Animal tool behavior: The use and manufacture of tools by animals*. Johns Hopkins University Press.
- Singer, D., Golinkoff, R., & Hirsh-Pasek, K. (2006). *Play = Learning: How play motivates and enhances children's cognitive and social-emotional growth*. Oxford University Press.
- Smitsman, A. W., & Corbetta, D. (2010). Action in infancy: Perspectives, concepts, and challenges. In G. Bremner & T. Wachs (Eds.), *Blackwell handbook of infant development* (2nd ed.). <https://doi.org/10.1002/9781444327564.ch5>.
- Somogyi, E., & Esseily, R. (2014). Mimicry enhances observational learning in 16-month-old infants. *PLoS One*, 9(12)e113695. <https://doi.org/10.1371/journal.pone.0113695>.
- Sylva, K. (1977). Play and learning. In B. Tizard & D. Harvey (Eds.), *Biology of play* (pp. 59–73). SIMP/Heinemann.
- Thomas, R. J., Lello, J., Medeiros, M., Pollard, A., Robinson, P., Seward, A., Smith, J., Vafidis, J., & Vaughan, I. (2017). *Data analysis with R statistical software: A guidebook for scientists*. Eco-explore.
- Uzgiris, I. C., & Hunt, J. M. (1975). *Assessment in infancy: Ordinal Scales of Psychological Development*. University of Illinois Press.
- van Leeuwen, L., Smitsman, A., & van Leeuwen, C. (1994). Affordances, perceptual complexity, and the development of tool use. *Journal of Experimental Psychology: Human Perception and Performance*, 20(1), 174–191. <https://doi.org/10.1037/0096-1523.20.1.174>.
- Vauclair, J., & Bard, K. A. (1983). Development of manipulations with objects in ape and human infants. *Journal of Human Evolution*, 12, 631–645. [https://doi.org/10.1016/S0047-2484\(83\)80003-7](https://doi.org/10.1016/S0047-2484(83)80003-7).
- Willatts, P. (1984). The Stage-IV infant's solution of problems requiring the use of supports. *Infant Behavior and Development*, 7, 125–134. [https://doi.org/10.1016/S0163-6383\(84\)80053-3](https://doi.org/10.1016/S0163-6383(84)80053-3).
- Willatts, P. (1999). Pulling a support to retrieve a distant object. *Developmental Psychology*, 35(3), 651–667. <https://doi.org/10.1037/0012-1649.35.3.651>.
- Williamson, R. A., & Brand, R. J. (2014). Child-directed action promotes 2-year-olds' imitation. *Journal of Experimental Child Psychology*, 118(1), 119–126. <https://doi.org/10.1016/j.jecp.2013.08.005>.
- Wynberg, E. R., Boland, A., Raijmakers, M. E. J., & van der Veen, C. (2022). Towards a comprehensive view of object-oriented play. *Educational Psychology Review*, 34, 197–228. <https://doi.org/10.1007/s10648-021-09608-7>.
- Zuur, A. F., Ieno, E. N., Walker, N. J., Saveliev, A. A., & Smith, G. M. (2009). *Mixed effects models and extensions in ecology with R*. Springer.