Anim Cogn (2007) 10:89–103
DOI 10.1007/s10071-006-0040-9

ORIGINAL ARTICLE

Stacking of blocks by chimpanzees: developmental processes and physical understanding

Misato Hayashi

Received: 25 April 2005 / Revised: 12 July 2006 / Accepted: 13 July 2006 / Published online: 15 August 2006

Abstract The stacking-block task has been used to assess cognitive development in both humans and chimpanzees. The present study reports three aspects of stacking behavior in chimpanzees: spontaneous development, acquisition process following training, and physical understanding assessed through a cylindrical-block task. Over 3 years of longitudinal observation of block manipulation, one of three infant chimpanzees spontaneously started to stack up cubic blocks at the age of 2 years and 7 months. The other two infants began stacking up blocks at 3 years and 1 month, although only after the introduction of training by a human tester who rewarded stacking behavior. Cylindrical blocks were then introduced to assess physical understanding in object–object combinations in three infant (aged 3–4) and three adult chimpanzees. The flat surfaces of cylinders are suitable for stacking, while the rounded surface is not. Block manipulation was described using sequential codes and analyzed focusing on failure, cause, and solution in the task. Three of the six subjects (one infant and two adults) stacked up cylindrical blocks efficiently: frequently changing the cylinders' orientation without contacting the round side to other blocks. Rich experience in stacking cubes may facilitate subjects' stacking of novel, cylindrical shapes from the beginning. The other three subjects were less efficient in stacking cylinders and used variable strategies to achieve the goal. Nevertheless, they began to learn the effective way of stacking over the course of testing, after about 15 sessions (75 trials).

M. Hayashi (✉)
JSPS Research Fellow, Section of Language and Intelligence,
Primate Research Institute, Kyoto University,
41 Kanrin, Inuyama, Aichi 484-8506, Japan
e-mail: misato@pri.kyoto-u.ac.jp
Tel.: +81-568-630550
Fax: +81-568-622428

Keywords Stacking blocks · Cognitive development · Chimpanzees · Physical understanding · Object–object combination

Introduction

Cognitive development in human infants and children has been investigated by researchers using a range of experimental methods and described through various unitary scales (Bayley 1969; Case 1985; Gibson 1969; Greenfield 1991; Uzgiris and Hunt 1975). These methods and scales have also been applied to assess cognitive ability in nonhuman primates (Gómez 2004; Parker and McKinney 1999). Cognition in the physical domain has received considerable attention from researchers because it can be tested even in the absence of verbal responses. Understanding the physical properties of objects may be essential in daily activity of nonhuman primates. Based on Piagetian theory of development in the physical domain (object concept, causality, space, and time), comparative data have been accumulated for nonhuman primates (Mathieu et al. 1980; Parker and Gibson 1977; Parker and McKinney 1999; Vauclair and Bard 1983). Ape infants show developmental patterns similar to those in humans in terms of the sequential course of development in the physical domain. However, differences exist in terms of developmental speed and the absence of some advanced stages. For example, both humans and nonhuman primates progress through increasingly advanced developmental stages in the same order; however, the age at which particular stages emerge may differ among the species.

Previous works have also addressed physical causal understanding as a basis of physical cognition. Köhler (1957) investigated tool-using ability in an insightful manner based on subjects' understanding of tool function. He provided chimpanzees with situations where tools needed to be used to achieve a goal. He showed that the chimpanzees were capable of using tools in solving a problem, although he also noticed peculiar errors and mistakes during testing. For example, in piling up boxes to reach for a banana suspended from the ceiling, the chimpanzees seemed to ignore whether the stacked boxes were correctly balanced (see Karmiloff-Smith and Inhelder 1975 for human development in a block balancing task). In another episode, a chimpanzee held a box as high as her head and pressed it against the wall, while at the same time trying to climb on top of it.

There have been various experimental settings designed to study physical causal understanding in nonhuman primates. One example of such experimental paradigms addresses the functionality of tools, as it entails an understanding of objects and relations between them by employing a simple tool-choice task. This aims to assess subjects' understanding of the functionality of tools to retrieve food rewards (Fujita et al. 2003; Hauser 1997; Povinelli 2000; Santos et al. 2003, 2005). In a typical setup, there would be two alternative tools in different spatial configurations or with different tool properties (shape, size, and texture). If the subjects understand the physical causality involved in tool use, they should be able to choose the functional configurations and properties of tools which allow effective use of these objects for the retrieval of food. Another line of studies uses a transparent tube containing a food item. For example, Visalberghi et al. (1995) provided subjects with tools that required modification (by disassembling) before they could be used to push the food out of the tube. The subjects had to change the physical properties of the objects provided – such as unwrapping a bundle of sticks to obtain a single stick – before these could be inserted into the tube. The ability to modify the shape of the tool has also been studied in different settings (Povinelli 2000, Weir et al. 2002). One variant of the tube task is called the "trap tube problem" (Limongelli et al. 1995; Visalberghi and Limongelli 1994), where a hole is created in the middle of the transparent tube, which traps any food that passes over it. The individual now has to push the reward out from a particular end of the tube so as to avoid the trap.

Povinelli and Dunphy-Lelii (2001) invented a unique test to examine physical cognition in chimpanzees. The subjects were required to make an oblong block stand on a platform. In a crucial probe trial, one of the blocks (referred to as the "sham" block) could not be made to stand, as its shape was beveled or its weight unbalanced. This task can be categorized as a test of understanding physical causality of object properties in relation to the supporting substrate and gravity. The researchers measured whether the subjects explored the object in search of the cause of failure on the task. For this purpose, they focused on behaviors such as examining the block visually or tactilely and compared the performance of chimpanzees to that of human children. The chimpanzees tried as hard as humans to get the sham block to stand, and both species detected their failure in the task. In contrast, however, chimpanzees showed fewer behaviors examining the cause of the failure, particularly when no apparent differences existed between the normal and sham blocks. It is important to note that the sham-block task was, in fact, impossible to solve: the subjects could not change the outcome by examining the block. How can we provide subjects with an opportunity to solve such problems following examination? The answer may be provided by the stacking-block task.

The stacking of blocks has been used to assess cognitive development in humans and chimpanzees (Forman 1982; Hayes 1951; Tanaka and Tanaka 1982; Takeshita 2001). Human infants first begin to stack up blocks at around 1 year of age, and they succeed in stacking up eight blocks at around 2 years (Ikuzawa 2000). Thereafter, humans proceed to construct a variety of structures from blocks (Reifel and Greenfield 1982), and to copy structures built by a tester using blocks (Tanaka and Tanaka 1984). Researchers have also examined stacking-block behavior in chimpanzees. Both juvenile and adult chimpanzees possess the ability to stack up blocks, although differences between chimpanzees and humans in block manipulation have also been suggested (Hayashi and Matsuzawa 2003; Matsuzawa 1987; Potì 2005; Potì and Langer 2001).

The stacking of blocks requires the ability to combine multiple detached objects.[1] Subjects have to place a block on top of an existing tower without toppling the structure. They also have to adjust the placement of blocks to ensure a well-balanced tower. They are required to finely control their manual movement to accurately position the block on the tower and to then release their grip on the block. There have been reports of the successful stacking of blocks by great apes, however no such results have been obtained from monkeys. Since monkeys also possess the skills necessary for fine, dexterous manipulation of objects, the lack of stacking may imply that high levels of cognition or physical causal understanding among objects are also involved in the behavior. The first part of the current study presents a developmental perspective on the stacking of blocks in infant chimpanzees. I provided three mother-reared chimpanzees with opportunities of free block

[1] Combinatory manipulation has been of interest to researchers as a prominent feature of object manipulation potentially shedding light on cognitive capability. Several terms have been used by different authors to describe the behavior of relating a detached object to another object or substrate: combinatory manipulation (Fragaszy and Adams-Curtis 1991), combinatorial manipulation (Westergaard 1993; Westergaard and Suomi 1994), secondary manipulation (Torigoe 1985), and orienting manipulation (Takeshita and Walraven 1996). The term "object–object combination" was used by Hayashi and Matsuzawa (2003) to refer to the behavior of combining multiple detached objects. Hayashi et al. (2006) reviewed the terms of object manipulation including combinatory manipulation.

manipulation for 3 years after birth in order to document the spontaneous development of stacking behavior. Thereafter, I began to encourage the same three infants to stack up blocks, so as to explore their cognitive capacity for making vertical stacks.

To manipulate experimentally the complexity of physical causal understanding required to solve a task, the present study also introduces a new stacking task: utilizing blocks of different shapes, such as a mixture of cubes and cylinders. The shape of a cube facilitates stacking because a block at the base can support a block on top as long as the surfaces of the two blocks overlap sufficiently. Unlike cubic blocks, cylinders can be positioned in two different orientations relative to the support surface. In the "upright" position, where the cylinder touches the block underneath with one of its flat surfaces, is suitable for stacking and will also support the next block on top. In the other, "sideways" position, the cylinder is placed on another block with its rounded surface touching. This orientation neither produces stable stacking nor will support the next block. Thus, the subject has to choose correctly between the two types of placement to successfully stack up cylindrical blocks. The stacking of cylindrical blocks therefore requires an understanding of the physical properties of the individual objects and also their function as support structures in the stacking task.

The task used in the present study was a simple one: subjects were required to stack up four blocks, including two cylinders. The goal of stacking up all four blocks was rewarded by the human tester with food. Even when they failed to stack up the four blocks and gave up stacking, the subjects got food reward. In this way, the subject remained motivated to solve the task and continued to participate in the testing sessions. There were many possible ways to achieve the goal of the task. However, some ways were more effective than others. It is possible to assess the subjects' physical understanding by examining their manipulative behavior of cylindrical blocks shown in the course of achieving the goal. If the subject understands the physical properties of the cylindrical blocks, he will choose the flat side of the cylinder for stacking and may actively change the orientation of the cylinder whilst doing so. In contrast, a subject, who does not possess this physical understanding, may show many errors or ineffective manipulations of the cylinder. The subjects have to interpret the shape of cylinders and adjust their orientation in order to stack up all four blocks efficiently.

Taken together, the stacking of blocks – particularly using different shapes – may represent a useful diagnostic task for testing physical understanding in the context of object–object combination. Multiple detached objects need to be combined into a tower structure counteracting gravity. The rounded side of a cylindrical block is not suitable as a surface upon which the next block can be stacked. In this sense, not only the physical constraints inherent in an object but also the relationships among objects must be taken into account to solve the task.

Following on from the points discussed earlier, the present study aimed to address three questions concerning stacking-block behavior in chimpanzees. First, when in the course of chimpanzee development does spontaneous stacking first appear? Second, how far can stacking skills be extended through training? Third, what kind of failures, causal cognition, and solutions for the problem can be found in the cylindrical-block task?

Methods

Subjects

Three infant and three adult chimpanzees (*Pan troglodytes*) participated in the experiment (Table 1). All six subjects were members of a social group of 15 chimpanzees, living in an enriched environment at the Primate Research Institute, Kyoto University (Matsuzawa 2006). The three infants were being raised by their own biological mothers in the group, and participated in various cognitive tasks together with their mothers, including a face-to-face task with human testers (Hayashi and Matsuzawa 2003; Matsuzawa 2003). First, free block manipulation by the three infants was observed without any training during their first 3 years of life, in order to examine spontaneous developmental patterns in

Table 1 Details of the chimpanzee subjects who participated in the present study

Subject (sex)	Date of birth	Stacking experience	Test period of cylindrical-block task
Ayumu (male)	April 24, 2000	Trained from 3 years 1 month	3 years 6 months to 4 years 1 month
Cleo (female)	June 19, 2000	Trained from 3 years 1 month	3 years 7 months to 4 years 2 months
Pal (female)	August 9, 2000	Spontaneous stack at 2 years 7 months	3 years 2 months to 3 years 10 months
Ai (female)	October 1976	Trained from childhood	At 27 years
Pan (female)	December 7, 1983	Trained from childhood	At 19 years
Akira (male)	April 1976	Trained from just before the test	At 28 years

chimpanzee infants. Then, the three infants were trained to stack up blocks in a face-to-face setting to elucidate cognitive capability involved in stacking blocks through training. After the mastery of cubic-block stacking, the present task using cylindrical blocks was introduced to the infant subjects.

The three adult chimpanzees were also tested in the same cylindrical-block task. Two subjects (Ai and Pan) were adult females with extensive prior experience of participating in several different kinds of cognitive tasks, including the stacking of cubic blocks (see Matsuzawa 2003 for a review). The third was an adult male (Akira), who had more limited experience in object-manipulation tasks. He was first given training (five sessions) in stacking up cubic blocks 2 months ahead of the cylindrical-block task, after a long hiatus in participating in face-to-face tasks. All six subjects in the present study participated in the face-to-face tasks voluntarily and collaborated with human testers.

Materials

Two kinds of cubic blocks were used during the first 3 years of observation of the infants' development. Smaller cubic blocks measured 2.5 cm × 2.5 cm × 2.5 cm and were painted red or green. Larger cubic blocks were 5 cm × 5 cm × 5 cm, painted white, red, blue, or yellow. Two cubic blocks (5 cm × 5 cm × 5 cm) and two cylindrical blocks (diameter 5 cm, height 5 cm) were used as materials for the subsequent cylindrical-block task, and they were unpainted and unvarnished. All types of blocks were made from wood.

Procedures

Developmental processes of stacking behavior

Different sets of procedures were used in the three phases of the present study. The first phase focused on the developmental processes of stacking behavior in chimpanzee infants. Spontaneous manipulation of blocks by the infants was observed without any training or prompting by human testers during the infants' first 3 years of life. Smaller cubic blocks were given to all three infants once a week for about 5 min over the course of 3 years (see Hayashi and Matsuzawa 2003 for a report of the development during the first 2 years). The infants were allowed to freely manipulate 8–16 blocks while their mothers engaged in the stacking-block task in a face-to-face situation with a human tester. Larger cubic blocks were given to Ayumu and Pal for about 10–15 min per day, on average 5 days a week, during their second and third year. They were given four or more blocks during the observation of free manipulation while the mothers performed stacking tasks using colored blocks. Thus, in this first phase, the stacking behavior of the mothers was the only possible source for the infants to be motivated for stacking blocks.

Training of stacking behavior

The second phase focused on infant chimpanzees' ability to stack up blocks when they were trained to do so. The human tester began to provide training and food reward for stacking up cubic blocks to all three infants at the age of 3 years and 1 month. The tester gave a block to an infant while holding another block placed on the floor and tapping or pointing to its top. If the infant oriented the block to the one on the floor, the human tester verbally encouraged the infant to continue. If the infant successfully stacked up the block, the human tester provided social praise and gave the infant a piece of fruit (such as a small slice of orange). One of the infants (Cleo) showed no orienting response toward the appropriate block and instead attempted to give her block back to the tester during the first training session. To facilitate stacking behavior, two or three blocks were glued together to emphasize the height of a tower of blocks. The tester placed his hand near to the top of the glued tower to elicit an orienting response from the infant toward his hand (and, through spatial proximity, also toward the top of the glued tower). If the infant (Cleo) oriented to or contacted the block in her hand with the glued tower, a piece of apple was delivered as a food reward. Using this procedure, the infant gradually learned to stack up a block on top of another. After the infants learned to stack one block on another, the human tester presented additional blocks (more than 10 blocks were available) in succession to construct taller towers. To continue to encourage the subjects, food reward was given after several blocks were stacked and/or at the time the tower eventually collapsed. The training lasted around 5 min and was conducted once a day, several times a week. One adult (Akira) was also trained to stack up cubic blocks through procedures identical to those used for the infants, with training lasting about 5 min a day, on average once a week.

Introduction of cylindrical blocks

The third phase consisted of the introduction of the cylindrical-block task to the chimpanzees who had already acquired the skill of stacking up cubic blocks. Two different methods were used for presenting the four wooden blocks (two cubes and two cylinders) used in the task: simultaneous presentation and successive presentation. Simultaneous presentation meant that all four blocks were provided to the subject at the same time. One of the two cylindrical blocks was presented in the upright position (touching the ground with its flat side), while the other cylinder was presented sideways (touching the ground with its rounded side). Successive presentation meant that the four blocks were provided one at a time in a random order. The base block was either a cubic block or a cylindrical block in the upright position, held to the ground by the human tester's hand. Simultaneous presentation was used in most cases for both infants and adults. Successive presentation was applied in sessions 1–21 for Cleo and sessions 26–50 for Pal. Successive presentation made the goal of the task clearer to the infant subjects, i.e., to stack up the blocks presented into a tower, and it was also helpful in maintaining their motivation to participate in the face-to-face stacking task. However, under both presentation conditions, two cubes and two cylinders (one upright and one sideways), were given to the subjects in the first place. Thus, both types of presentation were sufficient to illuminate the effectiveness of manipulative patterns of the cylindrical blocks.

The human tester faced the chimpanzee subjects inside an experimental booth in the context of a controlled test situation. A piece of fruit was given to the subjects as food reward at the end of each trial, regardless of the effectiveness of manipulative patterns. Thus, no specific type of manipulation was rewarded other than stacking up all four blocks presented to the subjects. To maintain the subjects' motivation to participate in the task, if subjects stopped manipulating blocks after a long sequence of errors and gave the blocks back to the tester, they were nevertheless given food reward. The quality of the food reward was generally higher than that used in computer-controlled tasks (where it often consist of a very small piece of apple delivered after each correct trial), incorporating fruits that were desirable but not frequently provided in large pieces (such as slices of pineapple, pear, or plum).

One session consisted of five trials, with each session lasting about 5 min. Each subject received only one session per day. The stacking-block task was performed as part of a daily series of cognitive tests (lasting about 15 min in total) in a face-to-face situation. Block manipulation by the subjects was video recorded using SONY digital video cameras from outside of the experimental booth through transparent acrylic panels.

Analysis

During the first and second phase of the present study, the maximum number of blocks that were stacked into a tower was recorded each day. During the third phase (cylindrical-block task), I transcribed the subjects' manipulation of the blocks in the form of sequential codes. This notation system was first applied in a previous study to describe whole sequences of nesting-cup manipulation by chimpanzees and humans (see details in Hayashi 2006). Each segment of object manipulation was denoted as a code consisting of two numbers and one alphabetical code referring to "object," "location," and "action," respectively. The first number referred to the "object," i.e., *what* was manipulated by the subject. The alphabetical code referred to the "action" involved in the manipulation, i.e., *how* the object was manipulated. The second number referred to "location" in an object–object combination, i.e., *where* the manipulated object was related to. Each segment consisting of object–action–location information was separated from those before and after it by slashes. In this manner, the entire flow of manipulation could be described in the form of sequential codes.

I differentiated between the shape (cube or cylinder) and the orientation (in the case of cylinders) of blocks in "object" and "location": cubic block (0), cylindrical block in the upright position (1), cylindrical block in an oblique position at the time of contact with another block (2), cylindrical block in the sideways position (3), or any combination of these within a tower (e.g., 301 referred to a cylindrical block resting in the sideways position on top of a cubic block, which, in turn, was positioned on top of a cylindrical block in the upright position). I distinguished among 18 different manipulation patterns in the "action" code (see details in Table 2). For example, Ayumu's manipulation of the blocks in the first trial of session 15 can be described by the codes 1P0/0P10/3VM/1P010//, meaning that he first placed a cylindrical block in the upright position on top of a cubic block, then placed a cubic block on top of both (the cylindrical block in the upright position and the cubic block), adjusted the orientation of the cylindrical block from sideways to upright position using his mouth and hand, and finally placed the second cylindrical block in the upright position on top of this tower of three blocks. The Appendix shows all manipulation of blocks by two infant chimpanzees (Ayumu and Pal) during the first test session.

The manipulation of cylindrical blocks by each infant and adult chimpanzee during the first test session was plotted on a two-dimensional plane. This aimed to visualize and compare the manipulative patterns performed by each subject in terms of two measures that described effectiveness in stacking up the cylinder. The plane was defined by the percentage of contacts made with cylinders in the sideways position and the percentage of changes in cylinder orientation. Such plots can be informative regarding individuals' knowledge about the physical properties of cylindrical blocks and the frequency with which subjects changed the orientation of cylindrical blocks in order to facilitate stacking.

I then focused on three measures to explore changes over the course of testing in the manipulative behavior of the three infants. The first measure, "failure," was the number of falls that occurred from a tower of stacked blocks. The second measure, "cause," corresponded to the number of contacts made with cylinders in the sideways position. The

Table 2 List of action codes

Code	Action	Description
U	Put	Contact a block to another block(s) and retrieve it without releasing
P	Pile	Pile a block onto another block(s)
H	Hit	Hit a block with the hand or with another block
D	Disassemble	Remove a block from a tower of blocks
CD	Change direction by dropping	Change the orientation of a block by dropping it on the floor
CS	Change direction with single hand	Change the orientation of a block while holding it in one hand
CC	Change direction while in contact	Change the orientation of a block while keeping it in contact with another block or the floor
CM	Change direction with mouth	Change the orientation of a block using mouth and hand(s)
CB	Change direction with both hands	Change the orientation of a block using both hands
L	Fall	Fall of single held object or fall from a tower of blocks*
T	Touch	Touch a block or a tower without changing its position
R	Replace	Take a block and change its position on the floor without contacting it to another block
F	Floor	Put a block on the floor
S	Support	Keep holding the top block on a tower
B	Hand back	Hand back block(s) to the human experimenter
A	Adjust	Adjust the position of the top block on a tower
M	Miscellaneous	Other forms of behavior, such as mouthing or throwing

*Falls from a tower are prefixed with a minus sign and the number of blocks that fell, e.g., /-3L/.

third measure, "solution," was the number of changes in the orientation of cylindrical blocks from sideways to upright. I differentiated among five patterns: change in orientation resulting from dropping a block, change in orientation while in contact with another block or the floor, change in orientation using one hand, change in orientation using the mouth, and change in orientation using both hands. All three measures were calculated as percentages of the total number of segments in the sequential codes recorded during a session and designed to show the relative proportion of each behavioral measure to the total manipulation length (as length of manipulation varied among trials and individuals).

Other types of manipulative behavior also recorded during the course of testing are listed in Table 3. Fifteen categories of behavior were used to examine the manipulative patterns of the subjects in detail. These categories were devised in order to illuminate typical error patterns as well as the strategies to solve the problem. The presence/absence of each behavioral category within a session was recorded for each subject. Categories 1–4 focused on the stacking of cylinders in the sideways position and the resulting fall of the block(s). Categories 5–8 focused on the adjustment of behavior in the course of cylindrical-block manipulation. Category 9 corresponded to the subject taking advantage of an accidental change in the cylinder's orientation. Categories 10 and 11 recorded instances of subjects stacking a sideways cylinder as the fourth and final block of a tower. In categories 12 and 13, subjects tried to maintain contact with cylindrical blocks by holding them. Categories 14 and 15 denoted subjects constructing two separate towers, either as a transitional state in the process of building a full tower or as the final stable constructions.

Results

Development of the stacking of blocks in chimpanzee infants

The manipulation of cubic blocks was observed during the first 3 years of life in three infant chimpanzees without any training or prompting by humans. One of the infants (Pal) spontaneously started to stack up blocks when she was 2 years and 7 months old. The other two infants (Ayumu and Cleo) did not show any stacking behavior or attempts at stacking during the first 3 years of observation. Figure 1 shows the developmental process of stacking behavior in the three infant chimpanzees. The maximum height of stacked tower of blocks on each testing day was plotted against the subjects' age at testing. The plot for each infant starts when the individual first stacked up a block on top of another block. One infant (Pal) started to stack up blocks without any food or social reward and soon was able to build a tower consisting of seven blocks. She sometimes showed excitement after she successfully stacked up blocks, by jumping around the tower. She also showed distress by pouting her lips or scratching her body when the tower shook as she stacked a new block or when blocks fell from the tower. However, she ceased to stack up blocks about 4 months after the first stacking event, possibly as a result of loss of motivation in the absence of any reinforcement other than

Table 3 List of infrequent behaviors shown during the cylindrical-block task

	Ayumu										Cleo										Pal										Akira	Ai	Pan
Behavioral category	1–5	6–10	11–15	16–20	21–25	26–30	31–35	36–40	41–45	46–50	1–5	6–10	11–15	16–20	21–25	26–20	31–35	36–40	41–45	46–50	1–5	6–10	11–15	16–20	21–25	26–30	31–35	36–40	41–45	46–50	1	1	1
(1) Stack a sideways cylinder on another block(s) resulting in the immediate fall of the cylinder	5	5	5	5	1	1	2	2	1	2	5	4	5	3				1						1	1	1					+		
(2) Repeatedly stack a sideways cylinder on another block(s) resulting in falls of the cylinder	2	4	2								3	1	4	1																	+		
(3) Put a block on top of a sideways cylinder resulting in the immediate fall of the cylinder from the stacked tower	4	3	2		1		1		1		3	3	5	1	1																		
(4) Stack a block on a sideways cylinder resulting in the immediate fall of the block	3	4						1				2	3	1				2	1	1						1							
(5) Place a block on a sideways cylinder and retrieve it without actually releasing it from hand (no fall)	4		1		1		1	2	2	1	2		1	1	1	3	2		1	1		4	2	2	1	1					+		
(6) Place a sideways cylinder on a block and retrieve it without actually releasing it from hand (no fall)	4	2	4	1	5	2	1	1		1	1	1	2	2	1	1		3	1		2			1	2		1		1		+		
(7) Disassemble the top sideways cylinder from the stacked tower	5	4	4	2	2	3	1	2	2	2	1	1	2	2	2	1	1	1			1		3				1				+		
(8) Put a cylinder in oblique position on top of another block(s), change the orientation in motion, and pile up in upright position	4	5	4	5	5	5	5	5	5	4	3	4	5	5	5	4	4	4	4	4	5	4	4	5	4	3	4	3	2	2	+	+	
(9) Stack a cylinder after change of orientation from sideways to upright due to fall (accidental)	5	3	3		1						1	3	2															1	1	1	+		
(10) Stack a sideways cylinder on top of the final tower without fall	3	2									2*	1*	3*																				
(11) Stack a sideways cylinder on top of the final tower after fall	4	3	1								2	2	5																		+		
(12) Combine two blocks together before piling them up on another block(s)	2	2	1	1						2																							
(13) Keep supporting a block on top of a sideways cylinder	2	1		1																													
(14) Make two towers, disassemble the first tower immediately, and unite the two into one tower	2	2	1	1		2		1			1		1																		+		
(15) Make two separate towers by stacking the third block on the remaining block on the floor	1																																

Numbers in the table correspond to the number of sessions (1–50) out of five in which each behavior was observed. The behaviors listed were not observed in one of the subjects (Pan).

*The blocks were presented sequentially by the human tester.

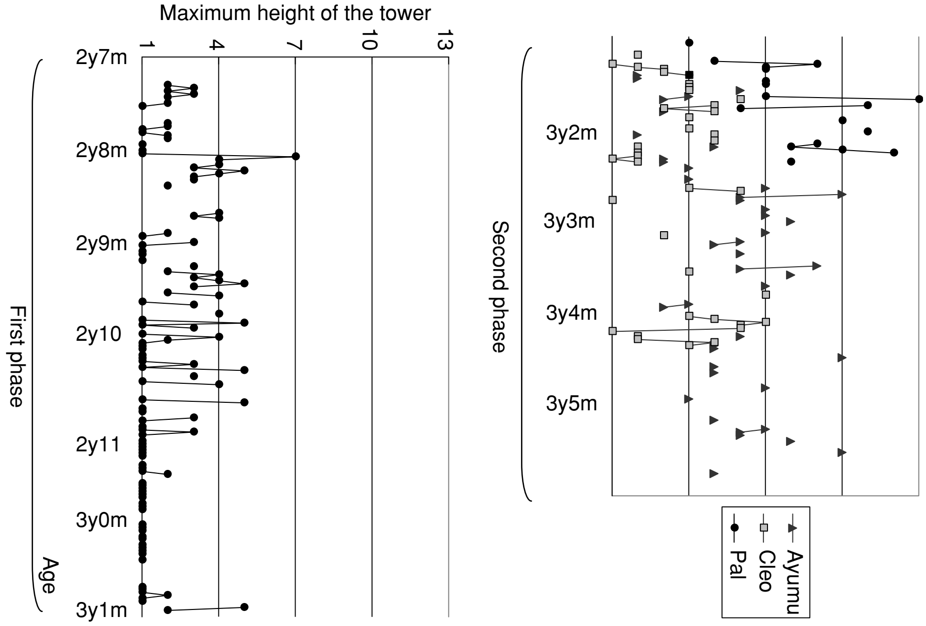

Fig. 1 Developmental changes in the stacking of cubic blocks by three infant chimpanzees. The plots show, starting for each infant at the first appearance of stacking behavior, the maximum number of blocks stacked up into a tower on each testing day

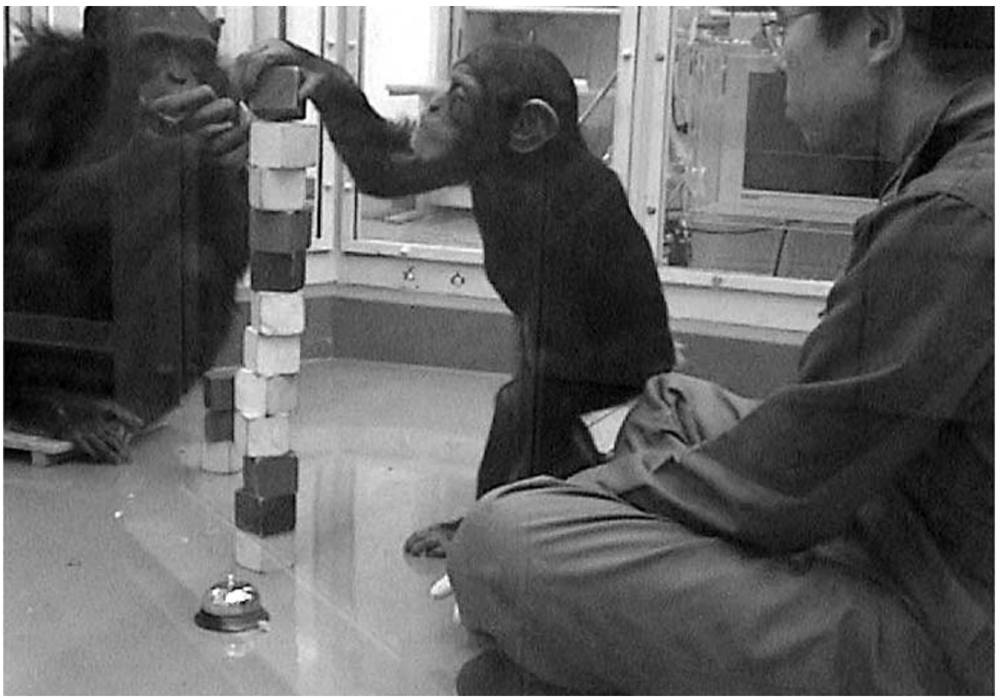

Fig. 2 An infant chimpanzee (Pal) stacking cubic blocks into a high tower

stimulation from the activity alone. Different from human mothers, the chimpanzee mothers did not show any social encouragement related to the stacking behavior of their own infants.

Training of stacking

Human testers began training infants to stack up blocks at the age of 3 years and 1 month. Pal started to stack up blocks again when rewards for stacking were introduced. She successfully stacked up 13 blocks into a high tower (see Fig. 2). The other two infants also showed rapid improvement in stacking cubic blocks into high towers when they were given training and rewards.

One naïve adult (Akira) was also given training and rewards for stacking cubic blocks before the cylindrical-block task began. He succeeded in stacking up two blocks during the first session, although he then had initial difficulties stacking up all blocks presented. He stacked up two blocks, disassembled the top block from the tower, and stacked it on

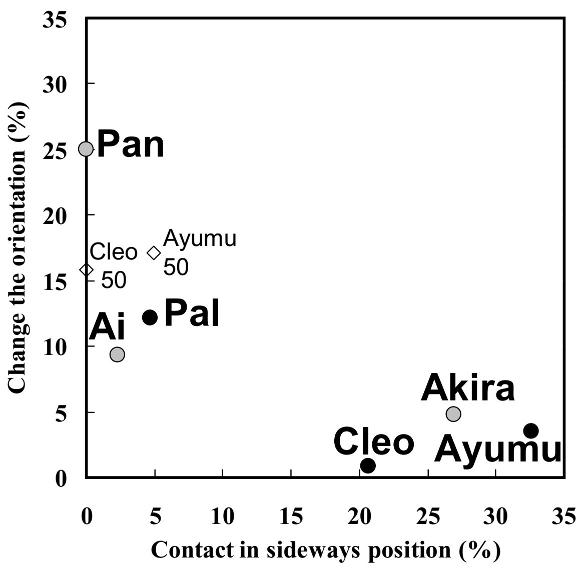

Fig. 3 Characteristics of the manipulation of cylindrical blocks during the first test session by infant and adult chimpanzees. The *horizontal axis* shows the percentage of contacts in the sideways position, while the *vertical axis* shows the percentage of changes in the orientation of cylindrical blocks. The three *black dots* indicate the three infants, the three *gray dots* correspond to the three adults. *Open diamonds* show manipulation during the final, 50th session in two of the infants

another base block on the floor. During the first half of the second session (the first time when three blocks were provided), he repeatedly constructed two-block towers without stacking the third block as well. This behavior may correspond to "pairing" in the nesting cup task (Greenfield et al. 1972; Johnson-Pynn and Fragaszy 2001) where only two cups are combined. Nevertheless, Akira eventually stacked up a maximum of four, eight, four, and seven blocks in the second to fifth sessions, respectively.

Manipulation of cylindrical blocks during the first session

The results of cylindrical-block manipulation during the first test session are shown in Fig. 3. I plotted the characteristics of the block manipulation by infant and adult chimpanzees in a two-dimensional plane defined by the percentage of contacts in the sideways position and the percentage of changes in orientation. The manipulative patterns of the six subjects appear in two different regions of the two-dimensional graph. One infant chimpanzee (Pal) and two adult females (Ai and Pan) are plotted in the top left of the plane, indicating efficient stacking of cylindrical blocks. They rarely made contacts with the rounded side of the cylinder and changed its orientation in advance of stacking. The infant (Pal) was the only subject who spontaneously started stacking up cubic blocks in the course of development. The two adult chimpanzees

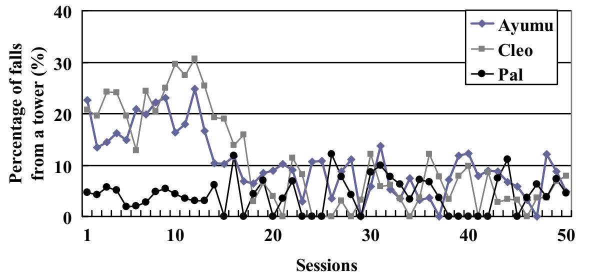

Fig. 4 Percentage of falls from towers of stacked blocks in sessions with infant chimpanzees

(Ai and Pan), who appear in the same top left region of the plane, had had rich experience stacking cubic blocks, although they had no previous encounters with cylinder stacking.

Two of the three infant chimpanzees (Ayumu and Cleo) are plotted in the bottom right of the plane, indicating their failure to stack up cylindrical blocks as effectively as Pal, Ai, and Pan. They frequently made contacts between the rounded side of the cylinder and rarely changed its orientation. Manipulation by one adult chimpanzee (Akira), who had limited experience in the stacking task, also appears in the same region of the graph. Finally, the characteristics of manipulation by two infant chimpanzees (Ayumu and Cleo) in their 50th session fall into the top-left region of the graph, showing the infants' improvement in the cylindrical-block task.

Changes in manipulation of cylindrical blocks by infant chimpanzees

Figure 4 shows the percentage of falls from a tower of stacked blocks in the three infants. In the case of two infants (Ayumu and Cleo), falls from a tower occurred frequently during the first 15 sessions (75 trials). Thereafter, the frequency of falls decreased significantly (Mann–Whitney U-test comparing the frequency of falls during sessions 1–15 and 15–50: $z = 5.18$, $p < 0.01$ for Ayumu, $z = 5.51$, $p < 0.01$ for Cleo). In the remaining infant (Pal), falls occurred only rarely from the first session onward (Mann–Whitney U-test for sessions 1–15 vs. 15–50: $z = -0.57$, $p > 0.05$). Note that Pal was also the infant who spontaneously began to stack up blocks at the age of 2 years and 7 months.

Figure 5 shows the percentage of contacts made with cylindrical blocks in the sideways position. This measure shows how frequently subjects made contact between the rounded side of a cylinder and another block. Two of the infants made such contacts often during the first 15 sessions (75 trials), after which the frequency of sideways contacts decreased significantly (Mann–Whitney U-test comparing the frequency of contacts in the sideways position during sessions 1–15 and 15–50: $z = 5.47$, $p < 0.01$ for Ayumu,

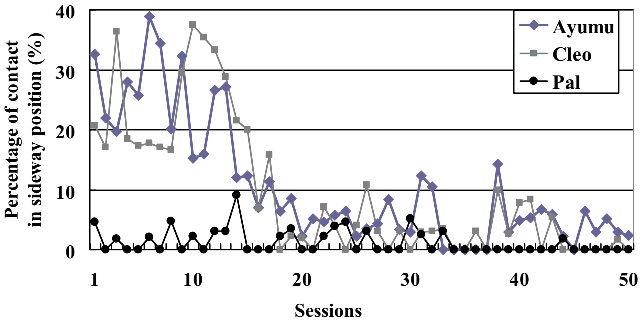

Fig. 5 Percentage of contacts made with cylindrical blocks in the sideways position in sessions with infant chimpanzees

$z = 5.56$, $p < 0.01$ for Cleo). In the case of Pal, sideways contacts occurred only rarely throughout all sessions (Mann–Whitney U-test for sessions 1–15 vs. 15–50: $z = 1.40$, $p > 0.05$), indicating that she had understood, from the beginning, that the rounded side of the cylinder was not suitable for stacking. I analyzed the order of blocks in the final tower of four blocks in one of the infants (Ayumu) who completed all 50 sessions with simultaneous presentation. Cylindrical blocks in the sideways position appeared on top of the final stack in 44% of the trials during sessions 1–10 (see Fig. 6). During sessions 10–15, this figure dropped to 8% and finally to 0% during sessions 15–50. A Mann–Whitney U-test, comparing sessions 1–15 and 15–50, showed that this difference was significant ($z = 3.33$, $p < 0.01$).

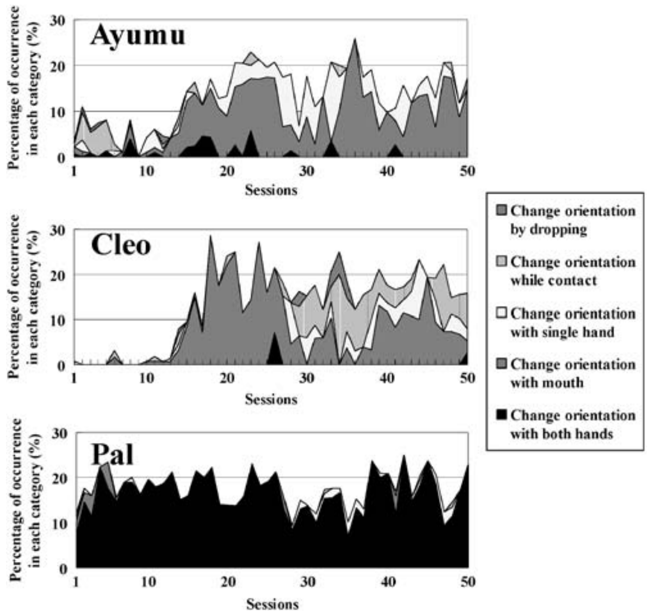

Fig. 7 Percentage occurrence of each strategy relating to changes in the orientation of cylindrical blocks in infant chimpanzees

Figure 7 shows frequencies of the different methods through which the infants changed the orientation of cylindrical blocks from sideways to upright. Initially, Ayumu only sporadically changed the orientation of cylinders, and mainly while these were in contact with another block or with the floor. After about 15 sessions, changes in orientation became

Fig. 6 An infant chimpanzee (Ayumu) stacking a cylinder in the sideways position on top of a tower of three blocks

significantly more frequent, and Ayumu began to employ his mouth and hand in the process (Mann–Whitney *U*-test comparing frequencies of changing cylindrical block direction during sessions 1–15 and 15–50: $z = -5.13, p < 0.01$). Cleo also began to change the orientation of cylindrical blocks significantly more often after about 15 sessions, using mainly her mouth and hand (Mann–Whitney *U*-test for sessions 1–15 vs. 15–50: $z = -5.54, p<0.01$). After about 30 sessions, Cleo altered her strategy again, as she began to change the orientation of cylinders while these were in contact with another block or with the floor, and not always using her mouth. Pal frequently changed the orientation of cylinders using both hands from the first session onwards, and continued in the same manner until the end of testing (Mann–Whitney *U*-test for sessions 1–15 vs. 15–50: $z = -1.39$, $p > 0.05$).

Table 3 lists 15 additional patterns of manipulation observed in each individual. Two infant subjects (Ayumu and Cleo) showed many patterns of block manipulation during the early sessions. Falls of different types (categories 1–4) frequently occurred in the first 13 sessions in Ayumu and 17 sessions in Cleo. They showed behavioral adjustment in manipulating cylinders (categories 5–8) throughout the test phase. They stacked cylindrical blocks whose orientation changed accidentally from the sideways to the upright position, and also tended to stack sideways cylinders as the uppermost block of the final stack (category 9–11). However, these behaviors ceased after about 15 sessions. One infant (Pal) also exhibited some of these behaviors but with frequencies well below those shown by the other two infants. Ayumu occasionally tried to press two blocks together in the air using both hands and also kept contact of a block with cylinders by holding them on a tower (categories 12 and 13). Ayumu and Cleo sometimes made two towers by placing the third block on top of the remaining block on the floor (categories 14 and 15). However, they then immediately disassembled the first tower and united the four blocks into one tower. There was only one case in which Ayumu stopped manipulation after having constructed the two separate towers. One adult (Akira) stacked sideways cylinders on cubic blocks resulting in falls, but he did not choose sideways cylinders as support surfaces during the first session. He also showed behavioral adjustments in manipulating cylinders. Although one adult (Ai) showed one adjustment behavior, the other adult (Pan) showed none of these behavioral categories during the first testing session.

In sum, individual differences were observed in the cylindrical-block task. Among the six subjects of the present study, two adults (Ai and Pan) and one infant (Pal) effectively stacked up the novel, cylinder-shaped blocks from the start of the testing phase. The two adults had had rich previous experience in manipulating cubic blocks, while the infant was the only subject who began to stack up blocks spontaneously during the 3 years of observation of free block manipulation. The other three subjects initially showed many errors in stacking up cylindrical blocks. However, these subjects employed a variety of strategies to solve the task, such that even the two infant subjects (aged 3–4 years) learned the effective way of stacking cylinders after 15 sessions.

Discussion

Development of stacking behavior in chimpanzee infants

One of the three chimpanzee infants spontaneously started to stack up blocks during the 3-year period when free block manipulation was observed. The relationship between the development of stacking and "inserting" behavior in chimpanzees was in clear contrast to data from humans. Human infants start to insert a rod into a hole in a box and to stack up blocks at almost the same age, at around 1 year and 1 month (Ikuzawa 2000). Chimpanzee infants (the same three subjects as those of the present study) started to insert a rod into a hole at an age comparable to humans (Hayashi and Matsuzawa 2003). In contrast, they did not stack up blocks until the success by one infant at the age of 2 years and 7 months as reported in the present study. The infants had been given opportunities to observe both inserting and stacking behavior performed by their mothers as demonstrators and had experiences of manipulating objects on their own. During this period, the human testers never rewarded inserting and stacking behavior by the infant subjects in order to observe "natural" development in mother-reared chimpanzees. From the early stages of development, a clear difference was observed between inserting and stacking behavior in chimpanzees, even though both behaviors can be categorized as combinatory manipulation.

Chimpanzees in the wild may be confronted with various problem-solving situations important for survival. Many instances of chimpanzees' use of inserting tools have been reported from most of the study sites throughout Africa (Whiten et al. 1999; Yamakoshi 2004). However, very few reports describe tool use in the wild which resembles stacking action. One such exception is nut-cracking behavior reported from a few sites in West Africa (Biro et al. 2003). Individuals in nut-cracking communities have to place a nut on top of an anvil stone before hitting the nut with a hammer stone. When using tools in their natural habitat, chimpanzees may have a tendency to insert objects into a hole but not to stack up objects. Both types of combination require underlying cognitive machinery and fine manual control for combining tools and targets appropriately. However, the potential ecological significance of the two behaviors may differ greatly in the wild: inserting-type tool use is likely to be more meaningful in gaining rewards than the stacking up of objects.

In captivity, chimpanzees are known to make more variable types of constructions including insertion, stacking, and alignment (Potì and Langer 2001). However, chimpanzees show different levels of complexity in functional spatial construction (insertion and stacking) from nonfunctional spatial construction (alignment). It may prove interesting to compare development in humans and chimpanzees in terms of the patterns or dimensions of their construction to reveal species differences in perceiving and interpreting the outer world.

Potential ability of stacking blocks revealed through training

The present study has shown that chimpanzee infants possess the cognitive capabilities required for stacking up blocks. When human testers began to train the infants to stack up blocks at the age of 3 years and 1 month, they immediately started to do so. The infants quickly learned how to stack up blocks and to thus build high towers. This suggests that they had the cognitive basis for combining multiple objects as well as the manual skill to finely adjust the placement of blocks. They may have lacked an intrinsic motivation for stacking up blocks and yet had the cognitive and manual bases to develop this behavior. In human infants' development, parents or caretakers often give positive feedback to the infants' stacking activity or its attempts. This may lead infants to engage in stack construction from an early stage of development. In contrast, the chimpanzee mothers did not show any social praise in response to their infants' stacking behavior. Once the infants were given positive reinforcement for stacking up blocks, they understood the goal of the task and were able to construct high towers by carefully adding and balancing successive blocks. Based on the chimpanzees' ability to stack up cubic blocks, the present task of stacking cylinders was conducted with the aim that it would provide a comparative scale that can be applied to apes and humans to assess their understanding of the physical properties of objects.

Cylindrical-block task: a test for physical understanding

The six subjects of the present study fall into two distinct groups based on the manipulative patterns they exhibited during the cylindrical-block task. Three of the six chimpanzees could be categorized as "efficient," as they seemed to have understood the physical properties of cylindrical blocks and their function in a stacking situation from the outset. Two adults in this group (Ai and Pan) had had rich previous experience of manipulating cubic blocks. The third individual (Pal) was the only infant who spontaneously started to stack up cubes in the first phase of the present study. In contrast, the other three subjects (one adult and two infants) did not seem to pay attention to the orientation of the cylinders, which they rarely adjusted during the early stages of testing. Rich experience in stacking up cubic blocks may therefore facilitate learning about the physical properties of blocks and the physical causality involved in stacking up blocks against the force of gravity. The difference between the appropriate and inappropriate orientation of cylinders was clear from the objects' appearance. This may provide a link to an affordance perspective of object manipulation (Lockman 2000). It is possible that experienced individuals were sensitive to the affordance in cylindrical blocks and used this for guidance in the familiar stacking situation.

Changes across the 50 sessions of the cylindrical-block task performed by the infant chimpanzees suggested that a critical shift in the pattern of manipulation occurred around the 15th session (75 trials). Stacking behavior in two of the infants frequently resulted in falls from towers of stacked blocks during the first 15 sessions. Thereafter, contacts in the sideways position became less common, and changes in the orientation of cylinders more frequent, leading to fewer falls. Through interaction with the cylinders over 15 sessions, even 3–4-year-old infant subjects were able to learn effective ways of handling the novel shaped blocks. A block falling off the top of a tower of stacked blocks is a visible "failure" in a trial. The goal of each trial was to stack up all four blocks presented to the subject, thus if block(s) at the top of a tower fell, this could be easily perceived as a setback. The notion that "a cylindrical block in the sideways position is much more likely to fall from a tower" might be perceived as the invisible "cause" behind the failure. The subject was not prompted by the tester to attend to the orientation in which cylinders were positioned. However, such considerations are necessary if falls from a tower are to be avoided. The chimpanzees were required to understand this invisible cause and to change the orientation of cylinders into the upright position before actually stacking them as a "solution" to the failure in order to efficiently solve the problem. Thus, using the cylindrical-block task, it is possible to measure the subjects' physical understanding by seeing whether they can detect the failure, infer its cause, and find the solution involving the change in orientation. The subjects of the present study learned the invisible "cause" through repetitive "failure" and changed their stacking behavior as a "solution" to the task.

The two infant chimpanzees who were less successful during the first phase showed other interesting behaviors. Ayumu used both hands to press together a cylinder and another block in the air or on a tower as if he was attempting to stick them together. This may resemble an episode reported by Köhler (1957) where a chimpanzee pressed a box against a vertical wall, off the ground. Cleo frequently placed sideways cylinders on top of a tower, which led to many falls. However, she repeated this sequence ceaselessly, seemingly waiting for the cylinder to fall in such a way that it landed upright. Less efficient subjects initially used a variety of different strategies to stack up all four blocks, while in the later stages of testing, they showed less variability in achieving the goal. This observation may provide a link to the overlapping waves model in the development of human children (discussed in Siegler and Chen 2002) in which strategies are at first variable, but with experience become more consistent and channeled to suit the task at hand.

The present study assessed physical understanding in the context of manipulating multiple objects. Single objects have their own physical properties. However, they also have a function in relation to the other blocks in the stacking task. For example, a subject can place a cylinder in the sideways position on top of another block even though this will often result in a fall from the tower. However, subjects can not proceed to stack another block on top of a cylinder that is lying on its side. Thus, a cylinder in the sideways position can be an "actor" in a stacking situation but not a "receiver," In fact, one adult, who was inefficient in the first test session, piled up sideways cylinder on another block but did not choose the sideways cylinder as a supporting surface, "receiver." Two infant subjects (Ayumu and Cleo) initially often placed a cylinder in the sideways position as the uppermost block of a four-block tower. In some trials of this type, the placement was not preceded by any previous falls, such that, it is conceivable that the subject planned in advance the order in which the blocks were to be stacked, and decided to use the sideways cylinder as the "terminator" in a trial. In other cases, however, the trial did involve falls and the construction may therefore have been the result of trial and error.

One important future perspective will deal with the question whether physical understanding of cylindrical blocks gained through the stacking task can be generalized to other novel shapes. I will also test human infants using the same set of objects to compare directly the development of stacking in humans and chimpanzees. Taken together, the present study has shown that the paradigm of stacking blocks is a useful tool in examining physical understanding of objects as well as relationships among them. Results, so far, suggest that 3–4-year-old chimpanzees possess the cognitive abilities necessary for stacking upright cylindrical blocks and that these abilities interact with previous experience in object manipulation.

Acknowledgements The present study was supported by grants from the Ministry of Education, Science, and Culture in Japan (#12002009 and #16002001), from the biodiversity research of the 21COE (A14), and from JSPS core-to-core program, HOPE. Preparation of the manuscript was supported by Research Fellowship 16-1059 from the Japan Society for the Promotion of Science for Young Scientists. Special thanks are due to Tetsuro Matsuzawa (who conducted the face-to-face tests with the subjects Ai and Akira, and sessions 1–10 with Ayumu) for supervision in the course of conducting experiments and manuscript preparation. I would also like to thank Masaki Tomonaga (who conducted sessions 1–7 with Cleo), Masayuki Tanaka (who tested Pan and conducted sessions 1–7 with Pal), Hideko Takeshita, and Masako Myowa-Yamakoshi for their support and helpful comments. I am grateful to Dora Biro for support given in the course of revising the manuscript. The daily running of experiments was supported by Sana Inoue, Etsuko Nogami, Laura Martinez, Yuu Mizuno, Tomoko Takashima, Tomoko Imura, Toyomi Matsuno, Shinya Yamamoto, and Tomomi Ochiai. Thanks are also due to Kiyonori Kumazaki, Norihiko Maeda, Shino Yamauchi, Juri Suzuki, and Akino Kato for the daily care of the chimpanzees. The present experiment complied with the laws of Japan, and housing and feeding conditions were in accordance with the *Guide for the Care and Use of Laboratory Primates* produced by the Primate Research Institute, Kyoto University (2nd ed., 2002).

Appendix

Ayumu: first session

0P1/3P01/0U301/301T/-2L/0M/3P0/-1L/3CM/2U0/1P0/1K/0P10/-2L/0U3/0F/3U3/3P0/
-1L/0,3,3M/1P0/-1L/3P0/3D30/3CD/0P1/-1L/0U1/0P0/2U00/1P00/3P100/-1L/1P100//
3P1/0U0/0U31/-1L/0F/3P0/1P0/3D30/3P10/-1L/3F/0P10/3P010/-1L/3P010//
0P0/3P00/-1L/1P00/3P100/3A/-1L/3P100/-1L/3P100/-1L/3CM/2U100/3P100/-1L/3P10
0/-3L/3P1/0U31/-1L/0U2/3F/0L/3P0/1P0/3D30/3P10/0P310/-2L/0P10/-1L/3P10/-1L/0
U10/0M/0P10/3P010//
1U0/0,0,1M/0P3/0K/0U03/-1L/0P0/-1L/3P0/-1L/1P0/0P10/-2L/3M/3P0/-1L/3M/0P0/3
P00/3U300/-2L/3P0/3U30/-1L/3P0/-1L/0U3/0P0/1U00/-1L/1P0/3P10/0U310/-2L/0U3/
0,0,3M/3U1/0P0/3P00/2U300/3A/-1L/3CB/2U00/1P00/3P100//
0P0/1P00/3U100/-1L/2U00/1P00/3P100/-1L/3U100/3CC/1P100//

Pal: first session

3M/0B/2H0/2M/0P1/0P01/3T/0A/3T/0A/-2L/0U0/0U1/0F/1L/0P0/3T/0A/3CD/0D00/0
P1/0P01/3T/0A/001T/-2L/1R/0P1/0P01/001T/-2L/1R/1H/0P1/0P01/001T/-2L/1M/3U0/
3F/0P0/0D00/0F/3T/0P0/3T/0D00/0P0/0A/3H/3R/3U00/3CC/1P00/1A/3CB/3CM/1P10
0//
0P0/1P00/3U100/3M/1A/3CB/1P100//
1M/1CM/2U0/1P0/0P10/3U010/3CM/3CB/1P010/1A//
3T/0P1/3T/0D01/0P0/1P00/3CB/1P100/1A/1D1100/1M/3CB/2U100/1P100/1A//
1P0/3U10/3CB/1P10/0U110/0M/0CB/0P110/0A/-3L/0,3M/0P0/3CB/1P00/3M/3CB/1P
100/

References

Bayley N (1969) Bayley scales of infant development. The psychological Corporation, New York

Biro D, Inoue-Nakamura N, Tonooka R, Yamakoshi G, Sousa C, Matsuzawa T (2003) Cultural innovation and transmission of tool use in wild chimpanzees: evidence from field experiments. Anim Cogn 6:213–223

Case R (1985) Intellectual development: birth to adulthood. Academic Press, Orlando

Forman GE (1982) A search for the origins of equivalence concepts through a microanalysis of block play. In: Forman GE (ed) Action and thought: from sensorimotor schemes to symbolic operations. Academic Press, New York, pp 97–135

Fragaszy DM, Adams-Curtis LE (1991) Generative aspect of manipulation in tufted capuchin monkeys (*Cebus apella*). J Comp Psychol 105:387–397

Fujita K, Kuroshima H, Asai S (2003) How do tufted capuchin monkeys (*Cebus apella*) understand causality involved in tool use? J Exp Psychol Anim Behav Proces 29:233–242

Gibson EJ (1969) Principles of perceptual learning and development. Appleton Century Crofts, New York

Gómez JC (2004) Apes, monkeys, children, and the growth of mind. Harvard University Press, Cambridge, pp 83–93

Greenfield PM (1991) Language, tools, and brain: the ontogeny and phylogeny of hierarchically organized sequential behavior. Behav Brain Sci 14:531–595

Greenfield PM, Nelson K, Saltzman E (1972) The development of rulebound strategies for manipulating seriated cups: a parallel between action and grammar. Cogn Psychol 3:291–310

Hauser MD (1997) Artifactual kinds and functional design features: what a primate understands without language. Cognition 64:285–308

Hayashi M (2006) A new notation system of object manipulation in the nesting-cup task for chimpanzees and humans. Cortex (in print)

Hayashi M, Matsuzawa T (2003) Cognitive development in object manipulation by infant chimpanzees. Anim Cogn 6:225–233

Hayashi M, Takeshita H, Matsuzawa T (2006) Cognitive development in apes and humans assessed by object manipulation. In: Matsuzawa T, Tomonaga M, Tanaka M (eds) Cognitive development in chimpanzees. Springer-Verlag, Tokyo, pp 395–410

Hayes C (1951) The ape in our house. Harper, New York

Ikuzawa M (2000) Developmental diagnostic tests for children, 2nd edn. (in Japanese). Nakanishiya, Kyoto

Johnson-Pynn J, Fragaszy DM (2001) Do apes and monkeys rely upon conceptual reversibility? A review of studies using seriated nesting cups in children and nonhuman primates. Anim Cogn 4:315–324

Karmiloff-Smith A, Inhelder B (1975) If you want to get ahead, get a theory. Cognition 3:195–212

Köhler W (1957) The mentality of apes (translated from the second edition by Ella Winter). Penguin Books, Harmondsworth

Limongelli L, Boysen ST, Visalberghi E (1995) Comprehension of cause–effect relations in a tool-using task by chimpanzees (*Pan troglodytes*). J Comp Psychol 109:18–26

Lockman JJ (2000) A perception–action perspectives on tool use development. Chil Dev 71:137–144

Mathieu M, Daudelin N, Dagenais Y, Décarie TG (1980) Piagetian causality in two house-reared chimpanzees (*Pan troglodytes*). Can J Psychol 34:179–186

Matsuzawa T (1987) Stacking blocks in chimpanzees (in Japanese with English summary). Primate Res 3:91–102

Matsuzawa T (2003) The Ai project: historical and ecological contexts. Anim Cogn 6:199–211

Matsuzawa T (2006) Sociocognitive development in chimpanzees: a synthesis of laboratory work and fieldwork. In: Matsuzawa T, Tomonaga M, Tanaka M (eds) Cognitive development in chimpanzees. Springer-Verlag, Tokyo, pp 3–33

Parker ST, Gibson KR (1977) Object manipulation, tool use and sensorimotor intelligence as feeding adaptations in cebus monkeys and great apes. J Hun Evol 6:623–641

Parker ST, McKinney ML (1999) Origins of intelligence: the evolution of cognitive development in monkeys, apes, and humans. The Johns Hopkins University Press, Baltimore and London, pp 23–79

Potì P (2005) Chimpanzees' constructional praxis (*Pan paniscus, P. troglodytes*). Primates 46:103–113

Potì P, Langer J (2001) Spontaneous spatial construction by chimpanzees (*Pan troglodytes, Pan paniscus*). Dev Sci 4:474–484

Povinelli DJ (2000) Folk physics for apes: the chimpanzee's theory of how the world works. Oxford University Press, Oxford

Povinelli DJ, Dunphy-Lelii S (2001) Do chimpanzees seek explanations? Preliminary comparative investigations. Can J Exp Psychol 55:187–195

Reifel S, Greenfield PM (1982) Structural development in a symbolic medium: the representational use of block constructions. In: Forman GE (ed) Action and thought: from sensorimotor schemes to symbolic operations. Academic Press, New York, pp 203–233

Santos LR, Miller CT, Hauser MD (2003) Representing tools: how two non-human primate species distinguish between the functionally relevant and irrelevant features of a tool. Anim Cogn 6:269–281

Santos LR, Rosati A, Sproul C, Spaulding B, Hauser MD (2005) Means–means–end tool choice in cotton-top tamarins (*Saguinus oedipus*): finding the limits on primates' knowledge of tools. Anim Cogn 8:236–246

Siegler RS, Chen Z (2002) Development of rules and strategies: balancing the old and the new. J Exp Psychol 81:446–457

Takeshita H (2001) Development of combinatory manipulation in chimpanzee infants (*Pan troglodytes*). Anim Cogn 4:335–345

Takeshita H, Walraven V (1996) A comparative study of the variety and complexity of object manipulation in captive chimpanzees (*Pan troglodytes*) and bonobos (*Pan paniscus*). Primates 37:423–441

Tanaka M, Tanaka S (1982) Developmental diagnosis of human infants: from 7 to 18 months (in Japanese). Ootsuki, Tokyo

Tanaka M, Tanaka S (1984) Developmental diagnosis of human infants: from 18 to 36 months (in Japanese). Ootsuki, Tokyo

Torigoe T (1985) Comparison of object manipulation among 74 species of non-human primates. Primates 26:182–194

Uzgiris IC, Hunt JM (1975) Assessment in infancy: ordinal scales of psychological development. University of Illinois Press, Urbana

Vauclair J, Bard KA (1983) Development of manipulations with objects in ape and human infants. J Hum Evol 12:631–645

Visalberghi E, Fragaszy DM, Savage-Rumbaugh S (1995) Performance in a tool-using task by common chimpanzees (*Pan troglodytes*), bonobos (*Pan paniscus*), an orangutan (*Pongo pygmaeus*), and capuchin monkeys (*Cebus apella*). J Comp Psychol 109:52–60

Visalberghi E, Limongelli L (1994) Lack of comprehension of cause–effect relations in tool-using capuchin monkeys (*Cebus apella*). J Comp Psychol 108:15–22

Weir AAS, Chappell J, Kacelnik A (2002) Shaping of hooks in New Caledonian crows. Science 297: 981

Westergaard GC (1993) Development of combinatorial manipulation in infant baboons (*Papio cynocephalus anubis*). J Comp Psychol 107:34–38

Westergaard GC, Suomi SJ (1994) Hierarchical complexity of combinatorial manipulation in capuchin monkeys (*Cebus apella*). Am J Primatol 32:171–176

Whiten A, Goodall J, McGrew WC, Nishida T, Reynolds V, Sugiyama Y, Tutin CEG, Wrangham RW, Boesch C (1999) Cultures in chimpanzees. Nature 399:682–685

Yamakoshi G (2004) Evolution of complex feeding techniques in primates: is this the origin of great ape intelligence? In: Russon AE, Begun DR (ed) The evolution of thought: evolutional origins of great ape intelligence. Cambridge University Press, Cambridge, pp 140–171