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Body-Scaled Ratio as a Control Parameter for Prehension in 5- to 9-Year-Old Children

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ABSTRACT: *The purpose of the experiment was threefold: (a) To find evidence that grasping is body-scaled and thus remains invariant during development; (b) to seek evidence that the body-scaled ratio of cube and hand size serves as a control parameter for the phase transition from one-handed to two-handed grasping by identifying the presence of sudden jump, enhanced variance, multistability, and hysteresis; and (c) to examine whether the stability properties of the observed grasping patterns increase with age. Thirty-three children aged 5, 7, and 9 years old were required to grasp and lift 14 cardboard cubes of different sizes (2.2, 3.2, 4.2, etc. to 16.2 cm diameter). Three conditions were used: (a) an increasing condition with sizes ordered from the smallest size to the largest; (b) a decreasing condition, with the sizes ordered from the largest to the smallest; and (c) twice in a different random order. Video recordings were analyzed and scored for the percentage of one-handed grasps. The results showed that the shift from one-handed to two-handed grasping occurred at the same body-scale ratio between cube size and finger span for all three age groups. Evidence was found for the presence of a sudden jump, enhanced variance, multistability, and hysteresis, indicating that the body-scaled ratio of cube and hand size serves as a control parameter. No change with age for the stability properties of the grasping patterns were observed.* © *1998 John Wiley & Sons, Inc.* Dev Psychobiol 33: 351–361, 1998

Keywords: *prehension; control parameter; body-scaling; children*

INTRODUCTION

Grasping objects is a very important and highly evolved skill in humans. There are many ways to grasp objects. How one does so is determined, in part, by the relative size of the object. That is, small objects are generally grasped with one hand and large objects are taken with two hands. Information concerning whether an object affords grasping with one or two hands is assumed to be directly available to an observer via optical specification of the object (Gibson, 1979). As such, an object is described as an afford-

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ance, which is defined by Warren (1984) as “the functional utility of an object for an animal with certain action capabilities” (p. 683). In these terms, the affordance that an organism detects is related to its own action system, implying the use of a body-scaled and not an absolute metric for both perceiving and acting.

The control of action by optical specification of environmental characteristics has been demonstrated for a variety of tasks and can be expressed by a dimensionless pi-number—the ratio between a metric of an actor and a metric of the action space. For example, in the case of an actor being confronted with the problem of climbing stairs, the “climbability” is specified by a critical or boundary ratio between the actor’s leg length and the tread height (Warren, 1984). Ratios smaller than the critical ratio specify climbability, ratios larger than the critical ratio specify “nonclimbability.” Hence, body-scale ratios can be used as a critical determinant of action choice—a change beyond the critical ratio value demands a new class of action. In adults, critical body-scale ratios have been found for a diversity of action patterns such as gait (Alexander, 1984), the perception of preferred stair tread height (Warren, 1984), sitting height (Mark, 1987), walking through apertures (Warren & Whang, 1987), and reaching (Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989).

Newell, Scully, Tenenbaum, and Hardiman (1989a) demonstrated that grasping patterns of 3- to 5-year-old children are dependent on the ratio of hand size/object size. In this study, children were required to pick up cubes differing in size and to place them into another slightly larger cube. It was found that despite the growth of hand size with age, shifts in grasping patterns were determined by a constant ratio between hand size and cube size. That is, the ratio between hand size and cube size at which (about 0.6) the children shifted from grasping the cube with one hand to both hands remained invariant over age and physical growth, and was similar as that for adults. Similar findings were reported by Newell, Scully, McDonald, and Baillargeon (1989b) and Newell, McDonald, and Baillargeon (1993) for 4- to 8-month-old infants, and Barreiros and Silva (1995) for 2- to 7-year-old children.

Thus, critical ratios, expressed in dimensionless pi-numbers, describe when a shift in behavior occurs. However, they do not provide information about the nature of the shift. Thus, the actor may determine or calculate the ratio at hand, compare this with an internal representation of a critical ratio, and decide on the basis of this comparison which movement pattern is suitable. In contrast, the switching between movement patterns may also emerge from changes in the constraints imposed upon action.

The latter proposition is advanced by proponents of the dynamical systems theory (Kelso, 1995; Kugler, Kelso, & Turvey, 1980; Thelen & Smith, 1994), who argue that movement patterns show signatures from self-organization, rather than being specified by a priori prescriptive devices that “tell the system what to do.” In emphasizing self-organization, dynamical systems theory captures different levels of organization; movement patterns on a macroscopic level spontaneously emerge from nonlinear interactions of various components or elements at a more microscopic level of organization. The order parameter refers to the macroscopic order of the system, which is stable (i.e., it does not change, and is relatively resistant to perturbations) for a range of values of a relevant but unspecific (i.e., it does not specify the movement pattern) control parameter. At critical values of the control parameter, however, the system becomes unstable and a sudden shift to another movement pattern is observed. Such discontinuous change in macroscopic order, induced by the continuous scaling of a control parameter, is called a phase transition.

For example, in his well-known experiments on rhythmical finger movements, Kelso (1984; see also Kelso, 1995) showed that when the movement frequency was intentionally increased, a spontaneous and unintended change from moving the fingers in an anti-phase to an in-phase mode was observed. Thus, by scaling up the control parameter (in this case, movement frequency) an abrupt change in the order parameter (relative phase between the fingers) took place.

Indicative features for discontinuous phase transitions are sudden jumps, hysteresis, enhanced variance, and multistability. A sudden jump is an abrupt change between movement patterns, such as the change from anti-phase to an in-phase pattern in Kelso’s finger experiments. Hysteresis can be detected by scaling the control parameter up and down. A transition that occurs at a higher control parameter value when scaling up than when scaling down can be described as showing hysteresis. For example, in Kelso’s finger experiments a change from anti-phase to in-phase occurred as frequency was increased; when frequency was decreased the reverse phase shift from in-phase to anti-phase was not observed, indicating hysteresis. Also, multistability (i.e., both the anti-phase as well as the in-phase mode may occur for certain values of the control parameter) and enhanced variance (i.e., an increased variability in relative phase during the actual transition) were present in the finger experiments. Together these features indicate that the shift between anti-phase and in-phase is a discontinuous phase transition.

The present study extends previous work of Newell. That is, the grasping patterns of 5-, 7-, and 9-year-olds picking up cubes differing in size will be examined. The objective of this study is to determine whether the switching between one- and two-handed grasping patterns can be understood as a discontinuous phase transition induced by a gradual increase of the body-scale ratio of object size and hand size (Kelso, 1995; Savelsbergh & van der Kamp, 1993, 1994). That is, the present research seeks to show evidence for the presence of self-organizing features such as the sudden jump, hysteresis, multistability, and enhanced variance in the shift from one-handed to two-handed grasping. To this end, the relative occurrence of one-handed grasps for each cube size, which is a continuous measure, will serve as the dependent variable.

Thus, whereas previous investigations primarily focused on identifying the particular fit between properties of the environment and the organism (i.e., object size and hand size) and the boundaries at which shifts in grasping patterns occurred (i.e., the critical boundaries), this study also examines the dynamics of the shift from one to both hands, that is, the “affordance dynamics” (Kelso, 1995). Hence, not only is the search for change or invariance of body-scaling in the development of prehension of interest, but also the question whether the dynamics of this body-scaling changes during development. More specifically, it will be investigated whether the stability properties of the one- and two-handed grasping patterns change with age.

In sum, the main purposes are to (a) find evidence that grasping cubes of different sizes are body-scaled and not influenced by physical growth in childhood; (b) examine the occurrence of sudden jump, hysteresis, multistability, and enhanced variance, and show that the shift from one to both hands is a discontinuous phase transition in which the body-scale ratio of object and hand size serves as the control parameter; and (c) examine whether the stability properties of the shift increase or remain constant during childhood.

METHOD

Subjects

Thirty-three school children (18 boys and 15 girls) aged 5 (mean age = 5 years, 3 months, *n* = 10), 7 (mean age = 7 years, *n* = 14), and 9 (mean age = 9 years, 2 months, *n* = 9) years from the International School of Amsterdam (representing 10 different countries) took part in the experiment. Parental permission forms were obtained for all subjects prior to participation, which was voluntary on the part of the subjects.

Apparatus and Procedure

Subjects were seated on a chair, which could be adjusted in height, at a table and were required to grasp a cube presented by the experimenter seated opposite to the subject. A set of 14 cardboard boxes with a size range from 2.2, 3.2, 4.2, etc. to 13.2, 14.2, and 16.2 cm in width were used. All boxes were easy to lift. The weight of the smallest box was 2 g, while the largest was 100 g. Weight differences were negligible with respect to the task requirements. All trials were taped on video from 3 m distance (VHS Panasonic).

The table (75 cm in height and 1 m in length and width) was marked where the box and hands of the subject were to be situated before the beginning of each trial. The experimenter placed one box at a time in the marked position in front of the subject, during which time the eyes of the subject were closed. After opening their eyes, the subject’s task was to lift and place the box on a spot indicated by a “X.” The distance between the box before lifting and the X was about 30 cm. The instructions for completing the task were given to the subjects at the beginning of the first trial.

The boxes were presented in three conditions: (a) an increasing condition with sizes ordered from the smallest size to the largest, (b) a decreasing condition with the sizes ordered from the largest to the smallest, and (c) two trials with different random order. The random order trials were different for each subject. The order of the three conditions was randomized among subjects.

The following anthropometric measures of hand size were taken: finger span (end of thumb to the end index finger), hand length (wrist joint to end of middle finger), and hand width (edge of the thumb to edge of the little finger) with an accuracy of 1 mm.

For each trial, the recordings were analyzed frame-by-frame by two different observers and scored with respect to the number of hand(s) used (one or both). Subsequently, for each child these scores were converted into one behavioral variable: the percentage of one-handed grasps, which was calculated by dividing the number of one-handed grasps by the total number of grasps (i.e., four) and multiplying it by 100.

RESULTS

Hand Size

Table 1 shows the anthropometric measures. In order to examine whether hand size actually increased with age, a separate one-factor-ANOVA was carried out for each anthropometric measure. The results showed sig-

Table 1. Means and Standard Deviations (in cm) of the Anthropometric Measures for the Three Age Groups

Anthropometric Measure	Age (years) 5	7	9
Finger span	10.5 (1.4)	11.6 (0.9)	12.7 (1.6)
Hand length	12.8 (1.1)	13.7 (0.5)	14.4 (0.9)
Hand width	14.9 (1.7)	15.5 (0.5)	16.2 (1.0)

nificant main effects of age for finger span, $F(2, 30) = 6.97$, $p < .01$, hand length, $F(2, 30) = 8.80$, $p < .001$, but no significant effect for hand width, $F(2, 30) = 2.66$, $p = .08$. Newman-Keuls post-hoc comparisons ($p < .05$) showed that only for finger span all three means differed, whereas for hand length the differences between the 5- and 7-year-olds, and the 5- and 9-year-olds differed.

Shift from One- to Two-Handed Grasping

In Figure 1, the mean percentage of one-handed grasps for the three age groups is depicted. Examination of Figure 1 shows that the older the children the higher the occurrence of one-handed grasps (37, 46, and 55% for the 5-, 7-, and 9-year-olds, respectively). Moreover, the older the children, the larger the cubes that were taken with one hand.

A 3 × 14 (Age × Cube Size) ANOVA with a repeated measures design on the percentage of one-handed grasps revealed significant effects for cube size, $F(13, 390) = 111.67$, $p < .0001$, Cube Size × Age, $F(26, 390) = 1.95$, $p < .01$, and an almost significant effect for age, $F(2, 30) = 3.06$, $p = 06$. Newman-Keuls post hoc comparisons, $p < .05$, indicated that among the 5-year-olds, the 5.2-cm cube was the smallest cube that significantly differed from a 100% occurrence of one-handed grasps. Among the 7-year-olds it was the 6.2-cm cube, whereas among the 9-year-olds the 8.2-cm cube was the smallest cube to differ significantly from a 100% occurrence of unimanual grasps. Moreover, post-hoc comparisons showed that among the 5-year-olds an almost total disappearance of unimanual grasps occurred for the seven largest cubes (i.e., from 9.2 to 16.2 cm), whereas among the 7-year-olds this was the case for the five largest cubes (i.e., from 11.2 cm to 16.2 cm). Among the 9-year-olds, only the four largest cubes (i.e., from 12.2 to 16.2 cm) were found not to differ significantly from the lowest occurrence of one-handed grasps. Thus, the 9-year-olds shifted at larger cubes from one to two hands as compared to 7- and 5-year-old children.

Body-Scaled Information

From the ecological approach, it is hypothesized that the detected differences in grasping behavior between the age groups are due to the increase of hand size with age. That is, the differences in prehension are expected to disappear when hand size is taken into

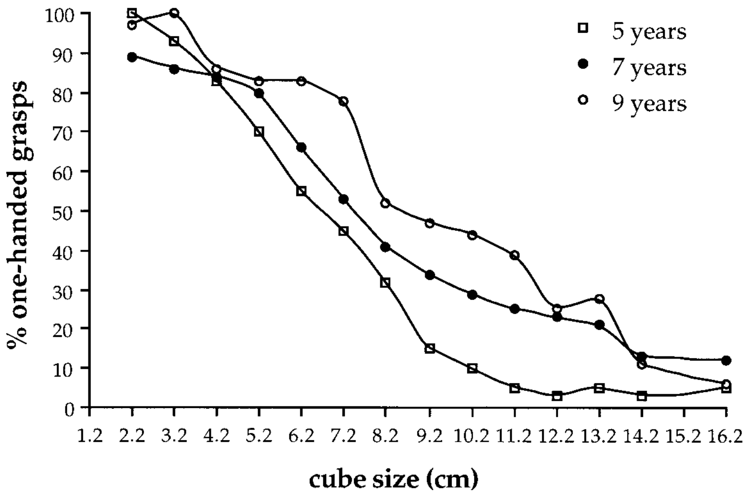

FIGURE 1 Mean (interindividual) percentage of one-handed grasps as function of cube size for the 5-, 7-, and 9-year-olds.

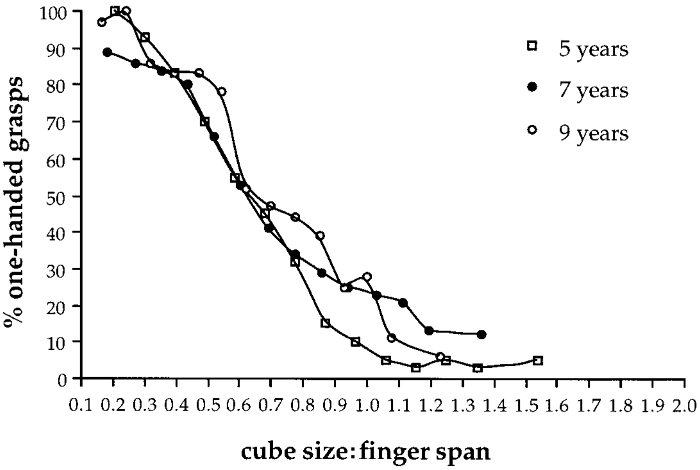

FIGURE 2 Mean (between subject) percentage of one-handed grasps as a function of the cube size:finger span ratio for the 5-, 7-, and 9-year-olds.

account. To examine whether the observed grasping patterns were indeed body-scaled, the data of Figure 1 are replotted on a cube size/finger span ratio axis in Figure 2. The curves for the different age groups are more congruent and more often intersect, which is suggestive for the use of body-scaled information (Newell et al., 1989a; Warren, 1984). To formalize this finding, the mean cube size at which each child changed from unimanual to bimanual grasping was determined: the critical boundary or transition point. This was achieved by determining, first, for each separate trial, the size of the largest cube that was taken with one hand and for which also all smaller cubes were taken with one hand, and second, by determining the size of the smallest cube that was taken with two hands and for which also all larger cubes were taken with two hands. In 66% of the trials these were consecutive cubes. The transition point was defined as the sum of the sizes of the largest cube taken with one hand and the smallest cube taken with two hands divided by two. The resulting transition points were used to provide for each child the mean cube size for calculating the following ratios: absolute cube size, cube size:hand length, cube size:hand width, and cube size:finger span. Table 2 shows the mean transition points for each age group.

A one-factor ANOVA was carried out to determine the effect of age on these four dependent variables for the transition point. Although Table 2 suggests that three ages shifted from one- to two-handed grasps at different cubes, the main effect for for absolute cube size just failed to reach significance, $F(2, 30) = 3.01$, $p = .06$. The body-scaled ratios did not differ significantly between the age groups, cube size:finger span, $F(2, 30) = .47$, $p = .62$, cube size:hand width, $F(2, 30) = 1.84$, $p = .18$, and cube size:hand length, $F(2, 30) = 1.33$, $p = .28$. In sum, when scaling to hand size, differences in prehension between the three age groups disappear. Typically, the ratio between cube size and finger span is used in prehension tasks (e.g., Newell et al., 1989a); therefore, in the remainder of this article body-scaling is used to refer to this ratio.

Sudden Jump

Inspection of Figure 2 does not reveal an abrupt change or sudden jump. In fact, the group data of Newell et al. (1989a) show a similar, more or less, gradual change from one-handed to two-handed grasping. A

Table 2. Means and Standard Deviations (in cm) of the Transition Points for Absolute Cube Size and for Ratio Cube Size:Finger Span, Cube Size:Hand Length, and Cube Size:Hand Width as a Function of Age

	Age (years)		
Transition Point	5	7	9
Cube size	7.1 (1.4)	8.2 (2.8)	9.7 (2.4)
Cube size:finger span	0.68 (0.13)	0.71 (0.25)	0.76 (0.13)
Cube size:hand length	0.55 (0.10)	0.60 (0.20)	0.67 (0.14)
Cube size:hand width	0.48 (0.08)	0.52 (0.11)	0.60 (0.12)

Table 3. **R^2s for the Continuous and the Discontinuous Model, Without Normalization (Based on Figure 2) and Normalized to Transition Point (Based on Figure 3) for the Averages of Each Age Group**

	Without Normalization		Normalized to Transition Point	
Age Group	Continuous	Discontinuous	Continuous	Discontinuous
5 years	.982	.822	.908	.946
7 years	.968	.846	.857	.971
9 years	.966	.744	.866	.965

continuous change can be discriminated from a discontinuous one by fitting the data to two different models: The continuous model is a second-order polynomial with an intercept, a linear term, and a quadratic term, whereas the discontinuous model is a step function consisting of two horizontal lines (one at 100% and one at 0%) with a gap between them (Wimmers, 1996; Wimmers, Beek, Savelsbergh, & Hopkins, 1998). Table 3 gives the R^2 of both models for the averages of each age group. For all three age groups the data is better predicted by the continuous model, confirming the impression of a gradual change from one- to two-handed grasping. However, an abrupt change may be obscured by pooling subjects with slightly different transition points. As mentioned before, in 66% of all trials the change from unimanual to bimanual grasping occurred between consecutive cubes, indicating a discontinuous shift. Therefore, instead of pooling the data with respect to the ratio between cube size and finger span, the individual data are grouped with respect to the transition point or critical boundary. The resulting graphs are depicted in Figure 3.

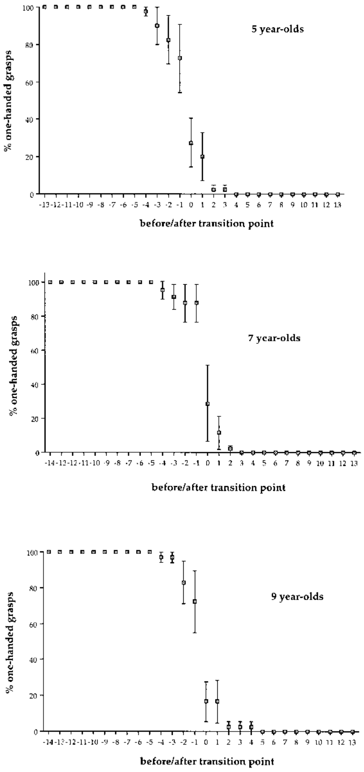

FIGURE 3 Mean and standard error (within subject) of the percentage of unimanual grasps when normalized to the transition point. Note the transition point is at 0 (zero). Upper, middle, and lower panels show the 5-, 7-, and 9- year-olds, respectively.

Table 3 shows the R^2 of the continuous and discontinuous models normalized to transition point for the averages of each age group. After normalizing to the transition point, it is the discontinuous model that best fits the data, albeit for the 5-year-olds the difference between both models is small. It was examined whether the discontinuous model better predicted the normalized *individual* data. R^2 for the 7- and 9- year-olds were significantly higher for the discontinuous model, $t(12) = 3.21$, $p < .01$ (means $= .824$ vs. .925), and $t(8) = 2.78$, $p < .05$ (means $= .800$ vs. .922), respectively, whereas for the 5 year-olds no significant difference between both models was found, $t(9) = 1.26$, $p = .23$ (means $= .838$ vs. .891). In conclusion, a sudden jump is discerned for the 7- and 9-year-olds; for the 5-year-olds a discontinuous change cannot be discriminated from a continuous one.

Hysteresis

A second characteristic for a discontinuous phase transition is the presence of hysteresis. That is, when scaling up the cube size:finger span ratio, the shift from one-handed to two-handed grasping should occur at a larger ratio than when scaling down. To examine the presence of hysteresis, the two trials in which the cubes were sequentially presented (i.e., the increasing and decreasing conditions) were compared. Table 4 shows the occurrence of hysteresis (i.e., the shift oc-

Table 4. Percentage of Occurrence of Hysteresis, Enhanced Contrast, and Critical Boundary for All Three Age Groups

	Age (years)		
Type of Transition	5	7	9
Hysteresis	70	86	89
Enhanced Contrast	0	7	11
Critical Boundary	30	7	0

curring at a higher cube size:finger span ratio for the increasing sequence), critical boundary (i.e., the shift occurring at the same ratio in both sequences), and enhanced contrast (i.e., the shift occurring at a lower cube ratio for the increasing sequence) for all three age groups. Clearly, in most (82%) subjects hysteresis was present. Only the 5-year-old group showed a substantial amount (30%) of critical boundary cases. Figure 4 shows the mean percentage of one-handed grasps for all subjects for the increasing and decreasing presentation order separately. The change from single to both hands in the increasing sequence occurred at a higher ratio as compared to the change from both to one hand in the decreasing sequence.

Using the cube size:finger span ratio at the transition point for the increasing and decreasing trials, a 3 × 2 (Age × Sequence) ANOVA with a repeated measures design was conducted. Only a significant main effect for sequence was found, $F(1, 30) = 35.91$, $p < .0001$. The overall means show that for the increasing sequence the shift from unimanual to bimanual grasping was made at a higher ratio, $x = .98$, $SD = .18$, as compared to the decreasing sequence, $x = .62$, $SD = .29$.

The interaction of Age × Sequence, $F(2, 30) = .49$, was not significant, indicating that hysteresis was present in all three age groups. It also demonstrates that the magnitude of hysteresis is similar for the three age groups. The same is found when only the subjects who showed hysteresis were analyzed (i.e., those subjects showing a critical boundary or enhanced contrast were excluded from analysis). No interaction between Age × Sequence was present, $F(2, 23) = .77$. We interpret this to mean that the relative stability of the two grasping patterns is similar for all three age groups (cf. Hock, Kelso, & Warren, 1984; Schöner, 1993; Kruse, Strüber, & Stadler, 1995).

Enhanced Variance

Figure 5 represents the averages of the within subject standard errors for each age group scaled to the transition cube. Note that these standard errors are similar to those shown in Figure 3. A clear increase in mean standard error can be observed just before or at the cube at which the children changed from a one-handed to a two-handed grasping pattern. This is the more remarkable because it concerns the variability after normalizing to the transition point. In other words, the

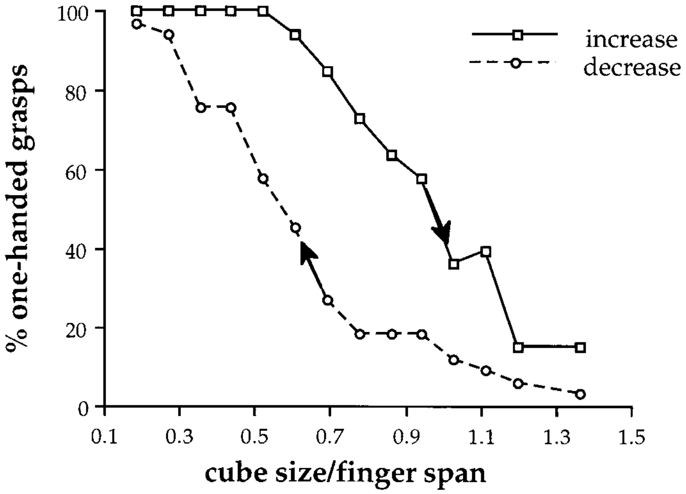

FIGURE 4 Mean percentage of one-handed grasps as a function of the cube size:finger span ratio for the increasing and decreasing order of presentation for all subjects pooled together.

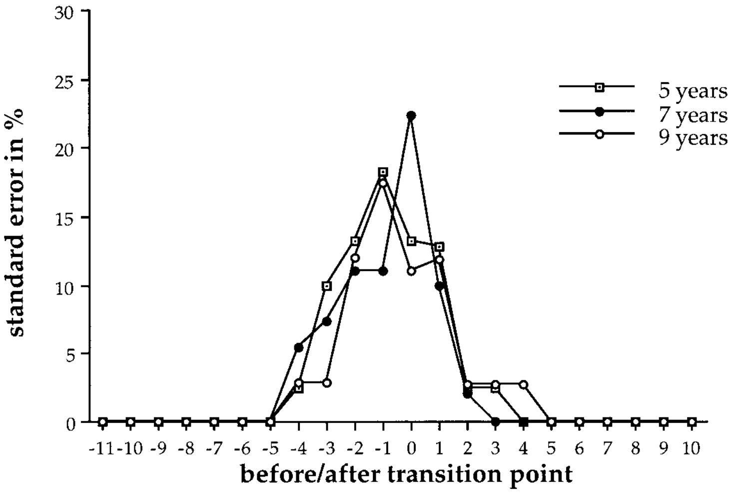

FIGURE 5 The mean within subject standard error in percentage of one-handed grasps as function of transition point for the 5-, 7-, and 9-year-olds.

observed increase in variability is not simply due to the hysteresis effect. This larger, mean within subject standard error in the transition region can be interpreted as reflection of enhanced variance.

DISCUSSION

Warren (1984) argued that what the situation affords the actor is defined by the relationship between properties of the environment and properties of the action system. Hence, perceiving and acting are guided by body-scaled ratios which should be similar over individual differences in body dimensions. Developmentally, changes due to physical growth should not affect the perception of affordances. That is, during development children should remain tuned to similar body scaled ratios without the need for new learning or reorganization of the action system (Pufall & Dunbar, 1992). Consistent with this hypothesis, the present study shows that for prehension a critical ratio between object and hand size defines the shift from one-handed to two-handed grasping, and that this ratio remains invariant during development. In this respect, the present study replicates previous findings of Newell et al. (1989a), which can now be generalized to 5- to 9-year-olds. The average ratio in the present study, about .70, fits well with .60 found by Newell et al. (1989a) and .70 found by Barreiros and Silva (1995). Taking these studies together, it is well established that, despite changes in hand size, grasping smaller objects with one hand and picking up larger objects with two hands is body-scaled—at least from 2–3 years onward. It remains to be settled, however, from exactly what age body-scaling predominates in prehensile action.

Most importantly, the present study demonstrates that the body-scaled ratio of object size and hand size may serve as a control parameter for switches in prehensile action. Evidence for this contention is found in the combined presence of the sudden jump, enhanced variance just before and during the switch, multistability, and hysteresis. These features together indicate that the switch from one-handed to two-handed grasping is a discontinuous phase transition.

The existence of a sudden jump was substantiated by demonstrating that the shift from unimanual to bimanual grasping was better accounted for by a discontinuous model as compared to a continuous model, although for the 5-year-olds the models did not differentiate. The second feature to testify for a discontinuous phase transition was the increase of the average within subject variance just before and during the shift between grasping patterns, even after scaling for transition point. The shift between the two grasping patterns occurred at higher values of cube:hand size ratio when the cubes were presented from the smallest size to the largest as compared to presenting the cubes from the largest to smallest. This not only demonstrates multistability, but also hysteresis. In fact, hysteresis was found in 82% of the subjects.

Hysteresis is a common observation in the classical psychophysical or sensory discrimination literature (cf. Gescheider, 1976; Helson, 1964). In a sensory discrimination procedure investigators seek to identify absolute or just noticeable differences (JND) thresholds in the assumption that such thresholds reflect the difference in neural activity for two distinct sensations. That is, different values of the same physical stimulus (e.g., intensities, durations, magnitude, etc.) are presented repeatedly to an observer, who is asked to report whether or not he/she perceives it (or the difference). The stimulus value for which 50% of the responses are similar is called the 50% threshold. Typically, stimulus values presented in ascending orders yield higher thresholds or JNDs as compared to descending orders.

In classical psychophysics, hysteresis or "time-order" effects are merely experimental error which should be corrected (e.g., Gescheider, 1976; for an alternative view see Helson, 1964). From a dynamical systems point of view, however, hysteresis is regarded important in its own right. Hysteresis, in combination with other features such as sudden jumps, enhanced variance, etc., should be interpreted as a manifestation of the dynamics of the perception action coupling and should not be eradicated. Hysteresis shows that the system only changes when the old state becomes unstable (cf. Wimmers, 1996; Wimmers et al., 1998). The fit between actor and environment exhibits self-organizing properties, which cannot uniquely be attributed to neural activity, as is done in classical psychophysics, or other prescriptive devices. In sum, the change from an one-handed to a two-handed grasp or vice versa is a discontinuous phase transition induced by scaling up or down the control parameter, that is, the ratio between object and hand size. First the previous stable state (e.g., unimanual grasping) becomes unstable, and eventually an abrupt change to another stable state (e.g., bimanual grasping) is observed.

The present study suggests that the stability of the examined prehensile actions does not increase with age. For instance, there is no discernible difference in enhanced variance between the age groups. For all age groups, the variance increases a few cubes before the transition cube, and drops quickly thereafter. Hock et al. (1993) and Kruse et al. (1995) have argued that the magnitude of hysteresis is correlated to the stability of the system: A greater magnitude indicates that intrinsic fluctuations that result in spontaneous changes are reduced, and hence, the system is more stable. However, no difference in magnitude of hysteresis was found between the age groups, indicating that the stability of the grasping patterns remains constant during childhood. However, the finding that the change between uni- and bimanual grasping for the 5-year-olds was as well accounted for by the gradual as well as by the discontinuous model might suggest that these children are somewhat more sensitive to fluctuations (The slightly lower occurrence of hysteresis points in the same direction.) A more-extensive analysis, however, is needed to confirm these impressions. By using perturbation studies, for instance, insight can be acquired in the role of kinetics variables such as object mass, but also variables such as object shape, surface area, surface texture, volume, distance to the object, and postural orientation in the development of prehension.

Considering body-scaled metrics as control parameters contrasts with ecological psychology (e.g., Gibson, 1979; Warren, 1984), where information is regarded as directly specifying the affordance and guiding the action. In other words, there is no further need for processing the information. The concept of critical ratios within ecological psychology presupposes a strict one-to-one mapping between information (body-scaled) and action. But if body-scaled information serves as a control parameter, dynamic self-organizing features are involved in the coupling between perception and action. For example, the hysteresis effect suggests that previous performance influences the body-scaled ratio (i.e., the value of the control parameter) at which the change between uni- and bimanual grasping occurs: The same body-scale ratio is accompanied by different grasping patterns on a more macroscopic level. Such self-organizing characteristics are also observed in speech perception (Tuller, Case, Ding, & Kelso, 1994), the perception of ambiguous figures (Ditzinger & Haken, 1989; Kanizsa & Luccio, 1995), and the perception of apparent motion (Hock et al., 1993; Schöner & Hock, 1995). These studies show that what observers detect in the perceptual field depends upon the (immediately) preceding perceptual experiences. On basis of these findings, Hock et al. (1993, p. 78) argued that "hysteresis and temporal stability are properties of the percept, not the stimulus." Paraphrasing these authors, a more-flexible understanding of the coupling between perception and action is proposed in which action is not uniquely determined by information, but is dependent upon the dynamics of the fit between actor and environment.

The presence of hysteresis implies that in studying body-scaled metrics, it is the designation of the area of instability or transition area rather than the search for the critical ratio that is of utmost importance. The limits of such a transition area can be discovered by using ascending and descending orders of presentation. Thus, instead of neglecting and averaging out hysteresis effects, researchers should attend to them. In this context, it might be more accurate to use the concept of action scaling (cf. Konczak, Meeuwsen, &

Cress, 1992; Savelsbergh, Douwes-Dekker, Vermeer, & Hopkins, 1998; Ulrich, Thelen, & Niles, 1990). Action scaling is used to emphasize that the perception of affordances is not exclusively determined by a geometrical mapping of body dimensions to dimensions of the environment. Also action capabilities such as leg strength, hip joint flexibility, and walking experience influence the perception of affordances. It is the whole complex and dynamical interplay between organismic and environmental constraints that determines the fit between actor and environment for a particular task. As such, the nonsignificant tendency for the cube size:hand size ratios to increase with age is of minor importance: It is the area of instability and the dynamics of change that really matter.

In conclusion, the findings of the present experiment and previous reports (Newell et al.,1993; Newell et al., 1989b; Newell et al., 1989a) provide evidence for robust body-scaling in the development of prehension. Furthermore, the presence of self-organizing signatures such as sudden jump, hysteresis, enhanced variance, and multistability demonstrate that the body-scaled ratio between cube and hand size serves as a control parameter in the transition from one-handed to two-handed grasping. The stability properties of the prehensile action seem to remain constant from 5 to 9 years of age.

NOTES

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