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DEVELOPMENT OF INFORMATION-MOVEMENT COUPLINGS IN A RHYTHMICAL BALL-BOUNCING TASK: FROM SPACE- TO TIME-RELATED INFORMATION

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Abstract

We studied the development of information-movement couplings in a ball-bouncing task with a special interest in how space- and time-related information is used by people of different ages. Participants from four age groups (children aged 7 to 8, 9 to 10 and 11 to 12 years, and adults) performed a virtual ball-bouncing task in which space- and time-related information were independently manipulated. Task performance and information-movement couplings were analysed. Our results confirm a clear use of time-related information in adults, whilst children demonstrated a predominant relationship between space-related information and the period of movement. In the course of development, however, the children become progressively more capable of using time-related information in order to control the rhythmic ball-bouncing task. A second and weaker coupling, between ball height information and racket velocity at impact, also appears in the course of development. The data seem to show that the development of children follows the freezing-freeing-exploiting sequence proposed by Savelsbergh and Van der Kamp (2000), with a significant change in how information is used to control movement related to age.

Keywords: development; information-movement coupling; space/time related information; ball bouncing.

1. Introduction

The improvement of people's adaptive capability to control rhythmic motor coordination (e.g., walking, clapping, juggling) on the basis of perceptual information provided by the environment is a fundamental challenge of development (Volman and Geuze 2000). The development of such adaptive behavior implies that, with age, it becomes possible to tune motor coordination to a multiplicity of information provided by the environment. Goal-oriented and efficient behaviors relate to a perception-action cycle, which is defined as a circular relationship that enables the continuous and interactive control of information gathering and movement (Newell 1986). Thus, a perception-action cycle provides the basis for stability and adaptability in goal-oriented behaviors (Warren 2006). In this regard, van der Kamp et al. (2003) noted that identifying information involved in the regulation of adaptive behaviour is a crucial point in understanding the processes that underlie the development of such behaviour during infancy and childhood. For instance, assessing the selection of different information coupled to movement or the changes in the way they become coupled is a central point of development dynamics. The relations between task-specific informational variables and action variables are often referred to as "information-movement couplings" (Davids et al. 2001; Le Runigo et al. 2010).

Little is known about the development of rhythmic perceptual-motor skills. Volman and Geuze (2000) investigated age-related differences in two basic rhythmic perception-action coordination patterns, namely finger tapping synchronization and syncopation. Children aged 7, 9 and 11 years were asked to synchronize finger tapping to the beat of an auditory metronome either "on the beat" (synchronization), or "off the beat" (syncopation). The relative phase between the tap-events and auditory stimuli was an indicator of performance. For both conditions, results showed a significant decrease in relative phase variability with age. The number of unsuccessful trials was also analyzed. It was higher in trials that involved syncopation rather than synchronization, especially for the 7-year-old children. Some of them were even unable to produce a single syncopation trial. These results indicate that the stability of rhythmic perception-action coordination patterns increases with age. In

a more recent study, Bazile et al. (2013) investigated the development of a ball-bouncing task. Children between the ages of 5 and 12 years were asked to rhythmically bounce a virtual ball on a virtual racket, both of which were visible on a large screen. They did so by manipulating a physical table tennis racket. Bazile et al. (2013) observed major changes in both performance and behaviour at the age of 7 years. Those aged less than 7 years exhibited restricted perceptual-motor coordination characterized by a high frequency of racket oscillation and poor performance. After 7 years of age, children's ability to accurately adjust racket motion increased progressively with age, because of the development of a cycle-to-cycle regulation that is based on the visual information provided by the ball's trajectory. The performance of children aged 11 to 12 years remained below that of adults, revealing that the ability to master this complex task requires long-term development.

The age-related improvements in performance observed in ball bouncing after 7 years of age could result from of a developmental change in the use of perceptual information. Indeed, recent studies related to the ball-bouncing task have shown that racket motion is continuously regulated using visual information (Warren 2006). Siegler et al. (2010; 2013) have identified how racket timing and error correction are visually controlled in adults. To control the timing of oscillation, racket period T_r is modulated by the ball's upward half-period t_{up} , while to perform error correction, the change in racket velocity from the previous impact Δv_r is regulated by ball peak height h_p (or bounce error ϵ). However, ball peak height (h_p) is also informative about the time taken for the ball to return to its previous impact height. It could also be used to modulate racket period. Yet, Siegler et al. (2013) observed that adults are better attuned to time-related information (t_{up}) than to space-related (h_p) information. Time-related information t_{up} can be considered as more useful and appropriate than space-related information h_p for controlling a movement timing variable such as racket period; this is because t_{up} and racket period are in the same unit and interceptive actions are known to be regulated on the basis of temporal information (Lee et al. 1999). Furthermore, the use of t_{up} does not require specific knowledge of gravity acceleration (Siegler et al. 2010). In this context, one can wonder whether children are as effective as adults when picking up visual information to perform the task. This issue was addressed by Benguigui et al. (2008b) in a motion prediction task

that consisted of estimating the arrival time of a moving object on a target after the occlusion of the final part of the trajectory. Benguigui et al. (2008b) showed that children aged between 6 and 9 years old tend to use distance rather than time-related information to estimate time to contact (TTC), whereas older children (aged 10.5 years) use time-related information, like adults.

Consequently, the lack of accuracy observed among children in the ball-bouncing task could result from the fact that children do not pick up the most appropriate informational variable for the task. Time-related information (t_{up}) is maybe more difficult for children to pick up than space-related information (h_p). The use of space-related information could be a way to simplify control of the task and address other complex components of the ball-bouncing task such as the use of a racket, the gravitational acceleration of the ball or the need for a fine control of the racket velocity at impact in order for the ball to reach a particular ball height. This simplification of task control could enable children to partially achieve the task, but with more variability and less efficiency than adults. Development would enable children to discover a more effective coupling based on the use of time-related information.

Many studies have reported a higher variability in children's motor performance than in that of adults. That said, variability is no longer considered to reflect sensory and motor noise only (Deutsch and Newell 2005). In a recent review paper, Vereijken (2010) presented childhood development studies that also revealed how variability can be functional and reflect task exploration. From her point of view, "developmental progress is not aimed toward reducing variability, but toward learning to control and exploit variability". In a previous ball-bouncing experiment relating to child development, we observed that children's motor variability in a steady-state ball-bouncing task remained higher than that of adults; indeed, it was different in nature until at least 12 years of age (Bazile et al 2013). In the present experiment, we will explore the mean performance and performance variability of children and adults when perturbations are introduced into a ball's trajectory. Furthermore, we will discuss how performance variability may relate to the development of information-movement couplings.

In sum, the present study aims to characterize performance and information-movement couplings in a ball-bouncing task for

children aged between 7 and 12 years. We wanted to determine the respective use of time-related (t_{up}) and space-related (h_p) variables according to age. To this end, we used a virtual environment to dissociate these two informational variables and to determine their respective roles in the regulation of racket period and racket velocity. The virtual environment allowed perturbation of t_{up} while h_p was maintained constant (*Time session*), and reciprocally, perturbation of h_p while t_{up} was constant (*Space session*). Children were shown to use distance rather than time-related information in arrival time estimation (Benguigui et al. 2008b); thus, we predicted that children would rely more on space-related information (h_p) than on time-related information (t_{up}) to control racket movement than would adults. Based on this expectation, we also wanted to identify the age at which the transition between the use of space- and time-related information takes place.

2. Material and methods

2.1. Participants

Forty-five participants were divided into four age groups, with 12 participants per age group: 7 to 8 year olds (7.3 ± 0.5 yrs; 6 males, 5 females); 9 to 10 year olds (10.1 ± 0.6 yrs; 7 males, 5 females); 11 to 12 year olds (11.1 ± 0.1 yrs; 6 males, 6 females); and adults (25.8 ± 6 yrs; 5 males, 5 females). None of the participants reported specific experience in interception sports. After being informed about the experimental procedure, the children's parents as well as the adults provided written informed consent. Furthermore, the children were invited to explicitly express their agreement about their participation prior to testing. The whole procedure was previously approved by the local ethics board (Comité éthique UPRES UA 4532) in accordance with ethical standards laid down in the 1964 Declaration of Helsinki.

2.2 Task, virtual reality apparatus and data collection

Participants stood in front of a screen (1.70 m x 1.70 m) at a distance of 1.5 m. They held a table tennis racket, referred to as the "physical racket", which could be manipulated in the three spatial dimensions. The position of the physical racket was measured using an electromagnetic sensor (Flock of Bird, Model 6DFOB, Ascension technologies) with a sampling rate of 120 Hz. The sensor was fixed on the rear of the physical racket

while the transmission base of this device (which served as a space reference) was fixed to a stand so that they directly faced each other. The signal was sent to custom software installed on the host computer. From the in-line position of the physical racket, the software computed the position of a “virtual racket”, which was represented as a horizontal bar (20 cm wide × 2.5 cm high) and displayed on the screen using a video projector. The software also computed the position of a “virtual ball” (diameter = 0.04 m) and its interactions at impact with the racket trajectory. The end-to-end visual latency between the physical and the virtual racket motion was 29.78 ± 1.07 ms (see Morice et al. 2007, 2008 for more technical details on the experimental set-up and illustrations). Participants were asked to keep the physical racket horizontal and to perform an elbow motion to move the physical racket in the vertical dimension only in order to “virtually” hit the ball. A sound was made to indicate the impact of ball on racket.

2.3. Protocol

Participants were first shown a short demonstration of the ball-bouncing task. They were then asked to hold the racket with their preferred hand and keep it still for 5 s, with an elbow flexion of about 90° . Racket position was recorded and used as the racket's zero position. Participants were instructed to rhythmically bounce the virtual ball with the racket for the duration of one trial so that, at its peak, the ball would rise as close as possible to a virtual target presented on the screen as a horizontal line. The target was positioned at a height $H = 0.65$ m above the racket's zero position.

Participants undertook a familiarization session, which consisted of six 40 second-long “steady-state” trials in which no specific perturbation in ball motion was applied (Figure 1 A). Then, participants performed two experimental sessions, referred to as the “*Time session*” and the “*Space session*”, in which time-related information and space-related information were perturbed, respectively (see the next section for more details). The order of the two sessions was counterbalanced among the participants in each group. In each session, participants performed 10 trials, each of which was 40 s in length, during which the ball kinematics were perturbed on every 10th impact. A short midsession break was programmed and participants were free to ask for additional breaks. The experiment lasted approximately 25 min.

Insert Figure 1 about here

2.4. Perturbations in ball motion

Two types of perturbation in ball motion were applied in this experiment, as per the adult study by Siegler et al. (2013).

In the *Time session*, the perturbation consisted of modifying the duration of the upward ball trajectory (t_{up}) while the ball peak height (h_p) was maintained the same, as if no perturbation had occurred (Figure 1 B). To do so, a simultaneous change in ball launch velocity v_b and gravity g was produced. The size of the perturbed ball launch velocity was randomly determined within a [-25; +25%] range. The gravitational force applied during the upward ball motion was changed in order for the ball amplitude H (and h_p) to remain unchanged despite the perturbation in v_b . The duration of upward ball motion t_{up} was therefore also perturbed within a range of [- 20%; + 33%]. The gravitational value was reset to the reference value of 9.81 during the downward ball motion. Therefore, the duration of downward ball motion remained the same, as if no perturbation had occurred.

In the *Space session*, the perturbation consisted of changing h_p while t_{up} was maintained unperturbed (Figure 1 C). Taking the same approach as in the *Time session*, the value of the ball launch was changed to a randomly chosen new value within a [- 25%; + 25%] range. A new gravitational value was chosen so that the duration of ball motion (t_{up} and t_{down}) remained unchanged. As a consequence, ball amplitude H (and h_p) were perturbed in the range of [-25 ; +25 %].

2.5. Data reduction and statistical analyses

Raw racket position data were filtered using a second-order Butterworth filter with a cut-off frequency of 12 Hz. A cycle “C” is defined as the racket motion that occurs between two successive maximum racket positions. The cycle “C₀” corresponds to the racket cycle during which a perturbation of v_b and g started at ball impact. C₁ is the following racket cycle, where regulation was expected to occur. T_r refers to the period of the cycle following a perturbation (C₁). Δv_r refers to the change in racket velocity from the previous impact ($v_{r1} - v_{r0}$). Task performance was investigated by computing mean ball peak

heights for each cycle number (occurrences of C_0 , of C_1 , ..., and of C_9). Ball peak in C_0 occurred before the perturbation started (at impact within this cycle) and ball peak in C_1 corresponded to the perturbed ball trajectory. Performance after large negative perturbations (range of perturbation in v_b [-25.0%;-16.5%]) and large positive perturbations (range of perturbation in v_b [16.5%; 25%]) was analyzed. Performance values resulting from negative and positive perturbations were analyzed separately in order to avoid cancelling out perturbation effects. Performance variability was investigated by computing the standard deviation of ball peak heights for each of the 10 consecutive cycles. Responses after positive and negative perturbations were pooled together for this analysis.

In order to investigate how strongly racket movement is coupled to ball informational variables, the correlations of T_r with t_{up} (*Time session*) and with h_p (*Space session*) were computed for each participant from all the C_1 cycle data. The strength of the two linear relationships, measured by the correlation coefficients, was used to quantitatively assess the two different information-movement couplings between visual information and racket period. It was assumed that the higher the correlation, the stronger the information-movement coupling. For a better understanding of how racket velocity is visually controlled in order to correct for bounce errors, the strength of the information-movement coupling between ball height and racket velocity was also assessed by computing the coefficient of correlation between h_p and Δv_r (Siegler et al. 2013). In accordance with Benguigui et al. (2008a), perturbations such that $t_{up} < 0.200$ s were discarded from this analysis because of the 0.200 s visuomotor delay limit. In the same way, when h_p exceeded the edge of the screen ($h_p > 1.05$ m), the perturbation was discarded because it would be impossible for participants to use the visual information h_p . Individual values of the correlation coefficients were converted into Z values using Fisher's Z transformation for statistical purposes. The significance level was set at $p=.05$. The size effect (Cohen's d) was computed for all the post-hoc mean comparisons reported in the information-movement results section. It was successfully compared with the .80 threshold, which is considered to show a large size effect (Cohen 1988). Statistical analyses were

performed using Statistica Statsoft 7.1 software.

Insert Figure 2 about here

3. Results

3.1. Performance

For each of the two experimental sessions, the ball peak heights occurring before (C_0) and after (C_1 - C_9) large positive and negative perturbations were analyzed with a three-way mixed ANOVA with two within factors (2 perturbation categories \times 10 racket cycles) and one between factor (four age groups). For the *Time Session*, a significant interaction between the three factors was observed ($F(27, 360) = 1.84$; $p < 0.05$, $\eta^2 = .12$). In order to get an insight into the group-dependent behaviors, a two-way repeated-measures ANOVA (2 perturbation categories \times 10 racket cycles) was carried out for each of the four groups (Figure 2). Only the group of 7- to 8-year-old children exhibited a significant interaction between perturbation and cycle effects ($F(9, 90) = 3.04$; $p < 0.05$, $\eta^2 = .23$). The youngest children had more difficulty recovering baseline performance following perturbations that required them to slow down (when t_{up} was increased and while ball peak height remained unchanged). Indeed, in this perturbation category, mean ball peak height in cycle C_3 was significantly different from mean ball peak height in cycles C_6, C_7, C_8, C_9 (Figure 2D).

For the *Space Session*, although the three-way mixed ANOVA (perturbation categories \times cycles \times groups) yielded no significant interaction between the three factors, we decided to perform ANOVAs (2 perturbation categories \times 10 racket cycles) separately for each of the four groups in order to further investigate the response patterns following large perturbations. All four groups exhibited a significant interaction between perturbation categories and cycle effects (Figure 2, E-H). This interaction came from the fact that ball height was either increased or decreased in cycle C_1 due to the experimental perturbation, followed by an undershoot or overshoot in cycle C_2 . This pattern was observed in the four groups, although not significantly in the youngest age group. In sum, in the *Time Session* where perturbations were maybe less directly salient to children (because ball height was not perturbed), the youngest children had more difficulty recovering from perturbations than other age groups. In the *Space Session*, where ball peak height was perturbed but ball duration was not, children and adults shared

common response patterns.

Insert Figure 3 about here

3.2. Performance variability

In order to investigate performance variability, standard deviation of ball peak height was analyzed with a mixed ANOVA (10 cycles x 4 groups) for each of the two experimental sessions. In the *Time Session*, ANOVA yielded only a significant main effect for age group ($F(3, 40) = 9.14$; $p < 0.0001$, $\eta^2 = .41$) (Figure 3A). Post-hoc Tukey's HSD tests showed that all children's groups exhibited higher variability than the group of adults. The three children's groups were not significantly different from one another. In the *Space Session*, ANOVA yielded a significant main effect for age group ($F(3, 40) = 13.8$; $p < 0.0001$, $\eta^2 = .51$) and for cycle ($F(9, 360) = 3.07$; $p = 0.001$, $\eta^2 = .07$) (Figure 3B). Post-hoc Tukey's HSD tests showed that all children's groups exhibited a higher variability than the group of adults, and that there was also a significant difference between the 7 to 8 year olds and the 11 to 12 year olds. With regard to the effect of cycle, there was higher variability in the cycle where ball peak height was perturbed (C_1) and in the following cycle (C_2) than in later cycles (C_7, C_9).

Insert Figure 4 about here

3.3. Correlations of racket period T_r with Time- and Space-related visual informational variables (t_{up} , h_p)

Before analyzing information-movement couplings, the perturbations that were either too short or sent the ball higher than screen height were discarded from the analyses (see methods). In the *Time Session*, 38.6%, 23.1%, 21.0% and 0.34% of the perturbations cycles were discarded for the 7 to 8 year olds, 9 to 10 year olds, 11 to 12 year olds and the adult group, respectively. In the *Space Session*, the corresponding values were a bit smaller for the children's groups (31.9%, 20.6%, 17.4%, 1.5%). Increased variability in the children's performance induced more out-of-screen or very small ball bounces (see Bazile et al. 2013 for a detailed description of children's performance in steady-state trials).

Figure 4 illustrates the correlation coefficients of racket period with t_{up} and h_p across age groups, thus characterizing the two couplings involved in the timing of ball impact. A two-way ANOVA (4 age groups x 2 couplings) was performed

on the transformed correlation coefficients Z to test the influence of age on couplings. This ANOVA yielded a significant main effect of age [$F(3, 44) = 5.58$, $p < 0.05$, $\eta^2 = .32$], a significant main effect of coupling [$F(1, 44) = 27.29$, $p < 0.001$, $\eta^2 = .42$], and a significant interaction [$F(3, 44) = 16.62$; $p < 0.001$, $\eta^2 = .55$]. Post-hoc Tukey's HSD tests yielded a significantly higher value of Z when racket period was correlated with h_p than t_{up} in all children's groups and vice-versa in the adults group. Cohen's d values of the differences between the Z values for the 7 to 8 year olds, 9 to 10 year olds, 11 to 12 year olds and the adults were 1.02, 1.89, 1.61 and 1.11, respectively. Hence, racket period is mainly coupled to h_p during childhood, while in adulthood it is mainly coupled to t_{up} . In other words, during childhood, the preferred information used in task regulation is spatial (h_p); however, for adults, it is temporal (t_{up}). Post-hoc Tukey's HSD tests also showed that racket period was significantly better correlated with t_{up} for the 11 to 12 year olds than for the 7 to 8 year olds ($d = 0.86$); thus, the coupling between racket period and timing information (t_{up}) increases during childhood (Figure 4).

Individual analyses showed that all the children in the two youngest age groups exhibited a higher correlation of racket period with h_p than with t_{up} , showing a dominant and systematic use of space-related information. This was not the case for four children in the 11 to 12-year-old group, showing that these children had already made a transition from space-related information to time-related information. With regard to racket period, all the adults exhibited higher correlation coefficient values with t_{up} rather than with h_p .

Insert Figure 5 about here

3.4. Correlations between the change in racket velocity Δv_r and the space-related informational variable (h_p)

Figure 5 illustrates the coefficient values for the correlation between the change in racket velocity Δv_r and h_p across age groups, thus characterizing the coupling involved in the control of ball height. The correlation coefficients are negative, because a target overshoot (h_p too large) should be compensated by a decrease in racket velocity for the next impact ($\Delta v_r < 0$), and an increase in racket velocity after undershoots. A one-way ANOVA (four age groups) was performed on the transformed correlation coefficients Z to test the influence of age on this coupling. This

ANOVA yielded a significant main effect of age [$F(1,3)=7.74$, $p<0.001$, $\eta^2(= .35)$]. Post-hoc Tukey's HSD tests showed that the difference between the 7 to 8 year olds, 9 to 10 year olds and the adults was significant; however, the difference between the 11 to 12 year olds and the adults was only marginally significant ($p=0.07$). Using Cohen's d estimate of effect size, these differences in Z values were also shown to be large. Indeed, the d values for the difference between the adults and the 7 to 8 year olds, the 9 to 10 year olds and the 11 to 12 year olds were 3.24, 1.75 and 0.89, respectively. Correlations between Δv_r and t_{up} were also tested; however, they are not described here, because the correlation coefficients remained below 0.2 for all groups, indicating that this coupling is marginal.

Insert Figure 6 about here

4. Discussion

In this experiment, the perceptual-motor behaviors of children and adults were investigated using a rhythmic ball-bouncing task. In order to carry out a good and stable performance in this task (i.e. with the ball reaching a target height on each cycle), participants needed to meet two simultaneous requirements: (1) to be able to control impact timing by regulating racket period so that the ball could be hit during the racket upswing, (2) to be able to control racket velocity at impact to compensate for previous bounce error. These two task constraints require distinct information-movement couplings (Siegler et al. 2013). As was found by Bazile et al. (2013), the children's performance appeared to be significantly more variable than that of the adults. This increased variability for children could be related to the use of a space-related informational variable to control racket period, which is less efficient in the control of ball bouncing than a time-related one (Siegler et al. 2010, 2013). As expected, our results show a difference between children and adults in terms of the visual information that is involved in the control of racket period. Our analysis of the correlation coefficients between informational variables and movement variables showed that adults rely more on time-related information (t_{up}) to regulate the racket period than on space-related information. This time-related coupling can be considered as the reference for the control of racket period in adults (Siegler et al. 2010, 2013). Conversely, children exhibited a stronger coupling

to ball peak height (h_p) than to the duration of the ball ascending phase (t_{up}). Our results on ball peak heights also showed that children aged 7 to 8 years had much more difficulty recovering their baseline performance after a perturbation in t_{up} than adults. The difference in performance between children and adults was less pronounced when the space-related informational variable (h_p) was perturbed. This predominantly space-related control strategy in children is consistent with previous results for a motion prediction task presented by Benguigui et al. (2008b). Our results showed a similar evolution in the use of space- and time-related information for children who were initially attuned to space-related information.

However, in the study by Benguigui et al., the transition between a space and time control strategy was achieved by children aged 10.5 years. In our study, the group of 11 to 12 year olds was still predominantly relying on space-related information. Indeed, the shift to time-related information was not completed before the age of 11 to 12 years, with only four children from that group of twelve showing a dominant use of time-related information. This difference in the transition age for the use of space- and time-related information may be explained by task difficulty. The constraints of the task are possibly higher in our experiment than in the study by Benguigui et al. (2008), because we used a virtual racket. Alternatively, the need to accurately control the contact in order to reach the ball height may have increased the level of difficulty. From a dynamic systems perspective, research by Thelen and colleagues has led to the belief that developmental change emerges from context-dependent dynamic interactions of multiple factors (Thelen and Smith 1994). Whether a child of a given age is able or not to pick up the most relevant information to perform a ball-bouncing task may be limited by the fact that the ball-bouncing task involves simultaneously different task requirements and therefore different subsystems. At first, children may learn to coordinate perception and action on a coarse-grained level. As children grow, they may move on to a more fine-grained level (Chihak et al. 2014). It could also be the case that, over time, children progressively learn to inhibit the use of spatial-related information in favor of the time-related informational variable. This hypothesis is in line with current developmental research, which accounts not only for a general and incremental development of coordination-activation skills

through ages and stages, but also a general process of selection-inhibition of competing strategies (Houdé and Borst 2014).

The second information-movement coupling investigated was between ball peak height (h_p) and the change in racket velocity (ΔV_r) involved in the correction of bounce errors. In adults, this coupling was weaker than the one involved in the control of racket period and impact timing, as shown by the respective absolute values of correlation coefficients ($|R| \approx 0.5$ vs. $|R| > 0.8$). This was observed and discussed in a previous study (Siegler et al. 2013). Here, this strength discrepancy between the two couplings is even more pronounced in children than in adults. In children, the bounce error correction coupling is much weaker, with a correlation coefficient of approximately 0.3 for the 9 to 10 and 11 to 12 year olds, and less than 0.2 for the youngest children. This means that a bounce error (e.g., ball overshoot) will be less systematically compensated for by a change in racket velocity when the next impact occurs (i.e. $\Delta V_r < 0$) in children than in adults. Children might need several consecutive overshoots (or undershoots) before changing racket velocity and reaching the visual target height more precisely.

These different results for different age groups related to the information-movement couplings involved in the regulation of ball-bouncing fit with the freezing-freeing-exploiting learning sequence proposed by Savelsbergh and Van der Kamp (2000). According to these authors, learning to expand the repertoire of information-movement couplings can be viewed as analogous to the sequence of freezing, freeing and exploiting the (mechanical) degrees of freedom (DoF) of bodily components described by Vereijken et al. (1992). Such an opinion is based upon the DoF problem (Bernstein 1967; see also the handbook by Edwards 2010). The authors proposed that when multiple sources of perceptual information are available for controlling a motor task (i.e. many perceptual DoF), the learning process starts with the emergence and strengthening of a particular coupling between information and movement, which fits the task requirements (e.g., the “freezing” phase). In the current experiment an initial information-movement coupling was observed between the racket period and space-related information (h_p) for children, specifically those aged between 7 and 8 years. Children seem to pick up one informational variable (h_p) from among the numerous available. In other words,

children exploit one perceptual DoF from among the many possible informational variables. The youngest children also seem to control only the racket period and not the change in racket velocity at impact that is involved in the cycle-by-cycle correction of bounce errors. This is analogous to the “freezing of mechanical DoF” observed when novice participants begin to learn a complex motor task that involves many DoF. Novices tend to couple or block some joint movements in order to reduce the number of mechanical DoF to be controlled; in this way, they make it easier to perform motor control (Vereijken et al. 1992). Savelsbergh and Van der Kamp (2000) also stated that, during this early phase of learning, an alternative information-movement coupling may not be available or may be too weak to contribute to a successful performance of the task.

With development or practice, alternative information-movement couplings can arise, which correspond to the freeing phase of the model. Our results show a continuous increase in the contribution of time-related information with age (see Figure 4 which shows an increase of t_{up}). Moreover, for the older group of children, four of the 12 children demonstrated a dominant use of time-related information. However, it remains unclear how the change from using space-related information to time-related information occurs. One explanation could be that children can operate a combination of information in a process that remains to be identified. Another explanation could be that, across trials, children tried to use different sources of information and progressively chose to use the most adapted one. Indeed, Eleanor Gibson emphasized the role of exploratory activities in the education of attention in babies and children and in their capacity to pick up the most relevant informational variable for a given motor task (Gibson 1988). The findings on task exploration fit with the observation of an increase in performance variability, and with age-related improvements in mean performance accuracy. Recently, the importance of action exploration in motor learning has been recognized (Herzfeld and Shadmehr 2014; Wu et al. 2014). In particular, Wu et al. (2014) observed that high levels of task-relevant motor variability can predict faster learning both across individuals and across tasks.

In the last stage of the developmental process, namely the “exploiting phase”, skilled performance is characterized by the ability to exploit different information-movement couplings

to meet different task constraints. In ball bouncing, adults are able to simultaneously control impact timing and correct for bounce errors. In our study, bounce error correction was much less effective in children than in adults. Even the group of 11 to 12 year olds had not reached the exploiting phase of ball bouncing. Adults also exhibit the capability to exploit the most relevant information for a given task, for example, the time-related information (t_{up}) for racket period regulation. In sum, Savelsbergh and van der Kamp's model offers a good support for explaining the general principals of the development of perceptuo-motor behavior, which can be applied to the control of rhythmic ball bouncing (Figure 6). First, in their search for effectiveness, children are guided towards finding a short-term solution. Then, children improve their sensorimotor behavior and find the most appropriate solution that yields a high level of adaptive capability, performance and a reduction in variability.

The observed age-related access to temporal information can also be connected to studies on the development of the visual system as well as other developmental perceptual systems. Drake et al. (2000) investigated the development dynamics of acoustical tempo-discrimination capability associated with people of different ages (children aged 4, 6, 8 and 10 years, and adults) using a motor tapping and tempo discrimination task. Interestingly, the authors showed that increasing age brings an increase in tempo-discrimination capability as well as an increase in people's ability after the age of 10 to synchronize motor tapping with a rhythmic acoustical pace (see also Droit-Volet and Zélanti 2013). In a real ball-bouncing task, haptic feedback during ball-racket impacts may help children in the control of ball-racket coordination. Indeed, in adults, Sternad et al. (2001) have found that haptic information may play a role in the control mechanisms and performance stability found in ball bouncing. Recently, Ankarali et al (2014) were more specific when describing how haptic information helps performance stability. Using ball stability analyses, the authors concluded that haptic information can give the person performing the task an indication about the moment of impact that is more precise than that offered by visual information. In turn, this increased "knowledge" about impact timing reduces the influence of noise and perturbations on motor performance. In our experiment, we chose to use a virtual-reality set-up in order to

simplify the task requirements by limiting ball and racket movements to the vertical direction and to be able to introduce controlled perturbations in ball motion. However, the absence of haptic feedback may have had a more detrimental effect on children's performance than on that of adults. This would be particularly the case for the youngest children. Indeed, a series of studies on perceptuo-motor coordination reported that children under 8 years of age rely more on kinesthetic feedback than visual feedback (Manyam 1986; Hay et al. 1991; Redon et al. 1994; Lantero and Ringenbach 2007).

5. Conclusion

Our study provides significant data on the development of information-movement couplings involved in the control of movement using rhythmic visual-motor skills. The results show a predominant relationship between space-related visual information and the movement period for children. Furthermore, with advancing age, children become progressively more capable of using time-related visual information in order to control motion period, in the same way as adults. With regard to the control of racket velocity and ball height, a weaker information-movement coupling is evident; this coupling is strengthened during the course of a child's development. From this perspective, it seems that the development path of children follows the freezing-freeing-exploiting sequence proposed by Savelsbergh and Van der Kamp (2000). With advancing age, a significant change in the use of information for controlling movement is apparent. Yet to be understood, however, is the nature of this change, together with all the possible combinations of information and the alternative use of different sources of information across trials with a progressive preference for the most-adapted information.

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FIGURE CAPTIONS

Fig1 a. Definition of variables for racket motion (solid line) and ball trajectory (dotted line). b. Time session: t_{up} is perturbed while h_p is unchanged. c. Space session: h_p is perturbed while t_{up} is unchanged

Fig2 Mean ball peak height (group mean \pm standard error) as a function of racket cycle (before and after two categories of large perturbations in cycle C_1) in *Time Session* (a-d) and *Space Session* (e-h) for the four age groups. The position of the visual target is indicated as a blue line. The results of the ANOVAs on interaction effects (perturbation category \times cycle) are inserted in the panels. Asterisks (*) indicate the significant differences exhibited by post-hoc Tukey’s HSD tests.

Fig3 The standard deviation of ball peak height (group mean \pm standard error) as a function of racket cycle (before and after large perturbations in cycle C_1) in *Time Session* (a) and *Space Session* (b).

Fig4 Correlation coefficients between racket period Tr and visual informational variables (t_{up} , h_p) (mean + std) for the four age groups, characterizing the perception-action couplings to control racket motion for impact timing.

Fig5 Correlation coefficients between changes in racket velocity Δv_r and h_p (mean + std) for the four age groups, characterizing the perception-action couplings to maintain control of ball height.

Fig6 Model of the development of perception-action couplings in ball bouncing in children, based on the model of Savelsbergh and van der Kamp (2000). Children aged 7 to 8 years pick up ball height information to control racket period and regulate impact timing. This coupling strengthens in those aged 9 to 12 years, who also become progressively more capable of using t_{up} , but to a lesser extent than h_p . The control of racket velocity emerges between 9 and 12 years old and strengthens between 12 years old and adulthood. The thickness of the lines between informational variables and movement variables represents the strength of the coupling.

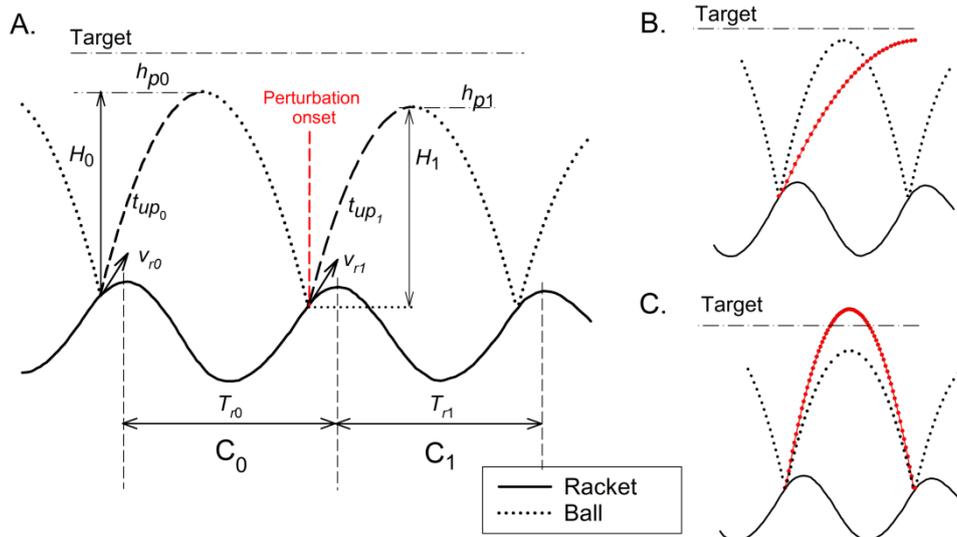


Figure 1

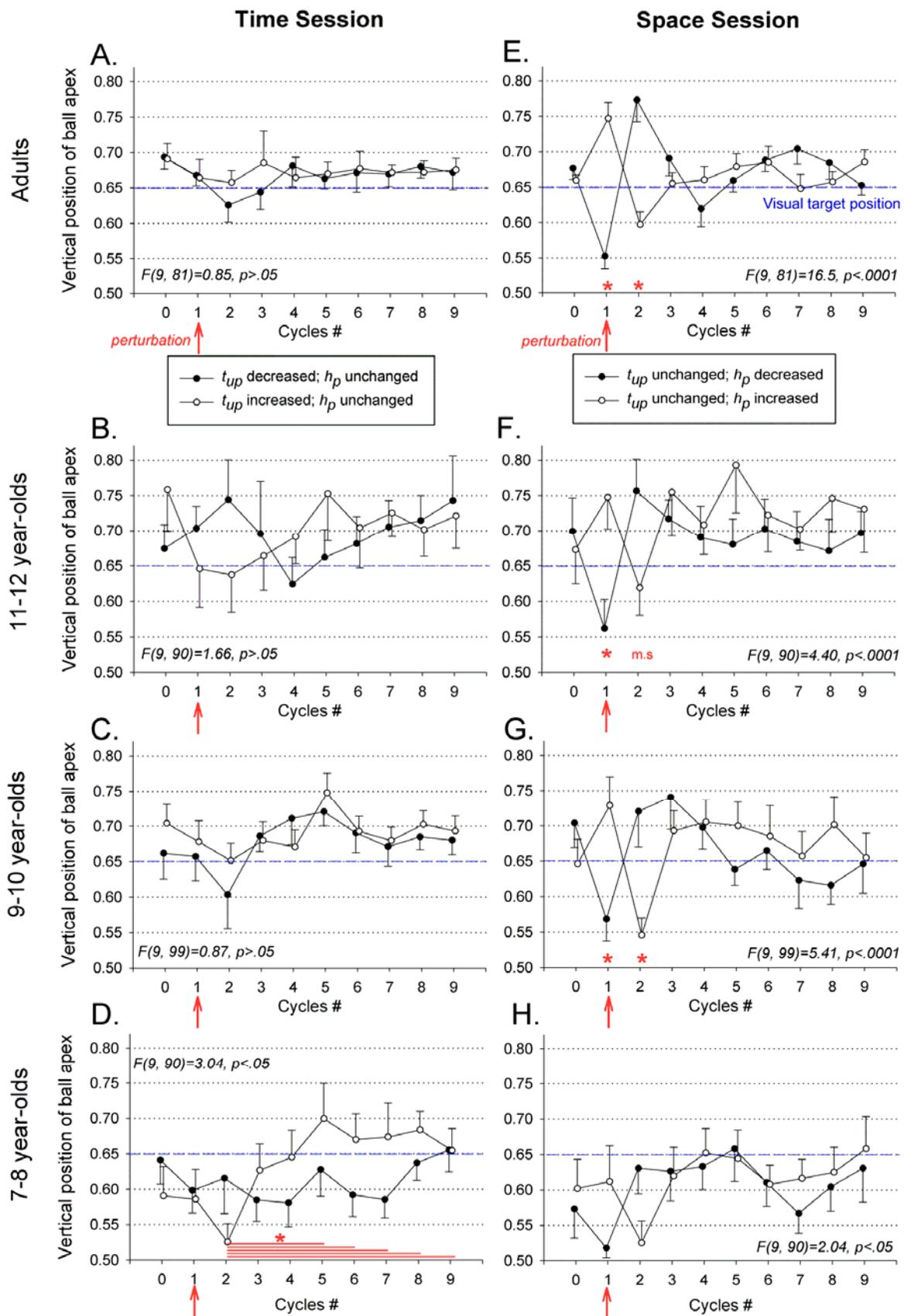


Figure 2

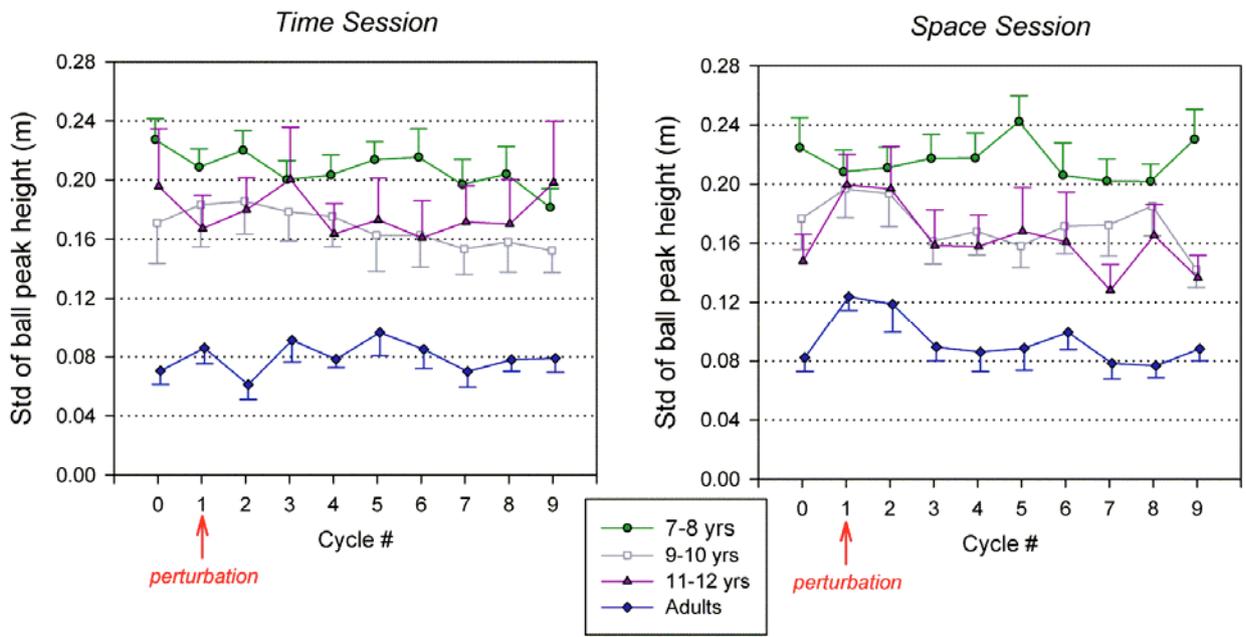


Figure 3

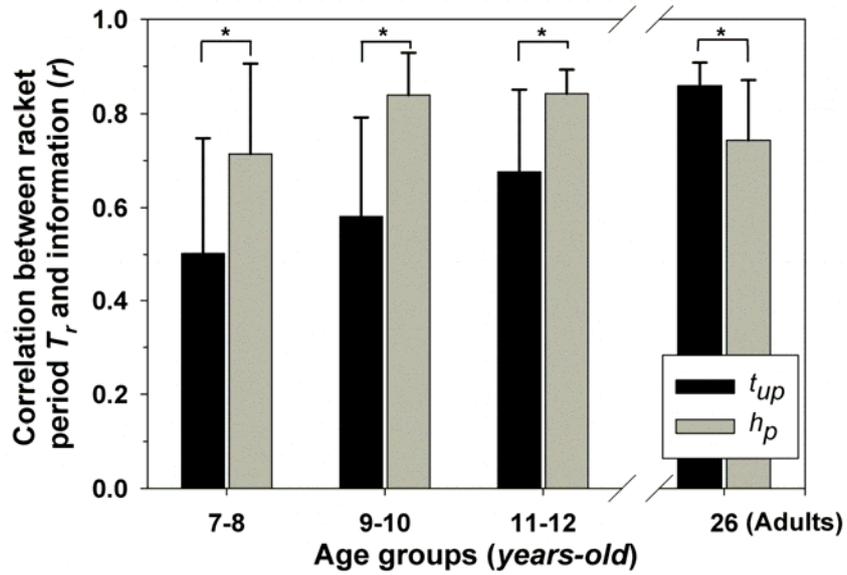


Figure 4

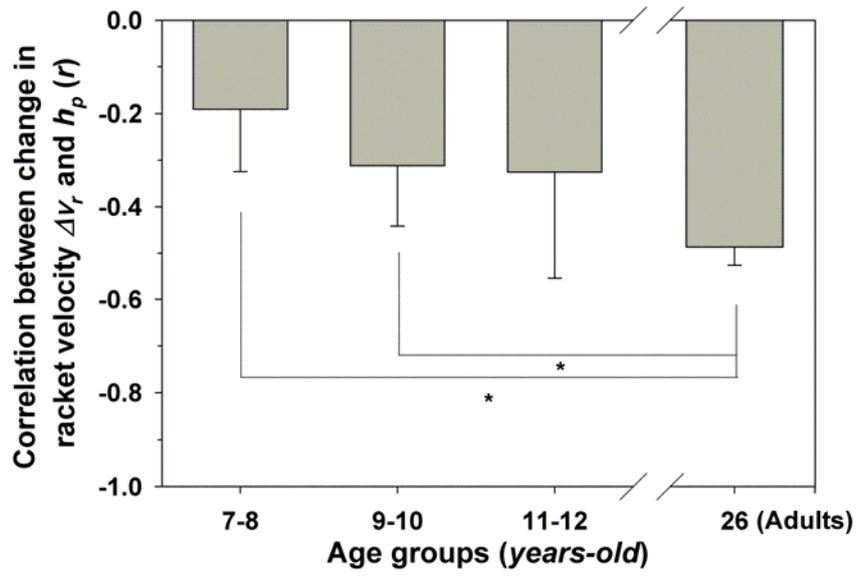


Figure 5

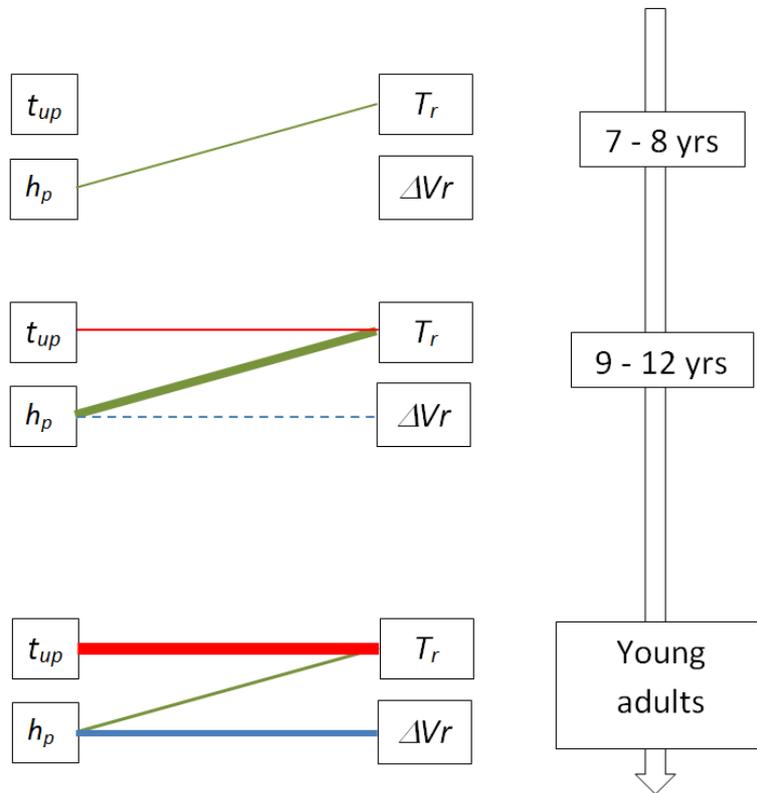


Figure 6