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Motion prediction and the velocity effect in children

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In coincidence-timing studies, children have been shown to respond too early to slower stimuli and too late to faster stimuli. To examine this velocity effect, children aged 6, 7.5, 9, 10.5, and adults were tested with two different velocities in a prediction-motion task which consisted of judging, after the occlusion of the final part of its path, the moment of arrival of a moving stimulus towards a specified position. A similar velocity effect, resulting in later responses for the faster velocities than for the slower, was found primarily in the three younger groups of children (for the longer occlusion conditions: 600–1,320 milliseconds). However, this effect was not seen in all children in these groups. Individual analyses showed that this velocity effect, when present, is linked to the use of distance rather than time information, or to the confusion between these in extrapolating the occluded trajectories. The tendency to use one type of information or the other is a good predictor of accuracy and variability in this task and a good indicator of the development stage of the participants. Across development, children tend to initially use distance information with poor accuracy but relative consistency in responses. In a second stage, they use time and distance information alternatively across trials trying to find a better source of information with still poor accuracy and now great variability. In a final stage, they use time information to reach consistency and accuracy in their responses. This chronology follows the stages proposed by Savelesbergh and Van der Kamp (2000) explaining development with an initial stage of 'freezing' non-optimal relationships between information and movement, then a 'freeing' stage during which new solutions are searched for, and finally an 'exploiting' stage with an optimal relationship between information and movement.

The production of adapted motor behaviour depends on the appropriate use of information. In the course of development, children explore the environment in order

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to discover information appropriate to producing and controlling their actions. Savelsbergh and Van der Kamp (2000), following the work of Bernstein (1967) on the learning of complex coordination patterns, argued that perceptuomotor development and learning is composed of stages of *freezing*, *freeing*, and *exploiting* the degrees of freedom between information and movement.

Development starts with the emergence of a spontaneous coupling between information and movement to fit roughly with the requirement of the task (Savelsbergh & Van der Kamp, 2000). This coupling is strengthened by repetition and results in *freezing* out of other couplings. This stage of *freezing* has as its principal goal the economization of limited perceptual resources while permitting development of relatively adaptive behaviours. At the same time, this stage is reflected by behaviours that are stereotyped and weakly adapted to changing environmental conditions. The goal of the stage of *freeing* is to mitigate such limitations by allowing the exploration of new possibilities for coupling between information and movement. In the course of this stage, an increase in the variability of movements is frequently observed that serves to increase the range of possible and adaptive responses to the same task. By the end, the individual discovers the most adaptive couplings permitting him or her to face the diversity of situations that may be encountered. When the *exploiting* stage is reached, information is used efficiently and economically to produce the most adaptive actions (e.g. Broderick & Newell, 1999).

One situation where this conception of development can be tested is that of coincidence-timing (CT) actions, which consist of coordinating a movement, simple or complex, with the motion of an object. A large number of studies have shown that children are less accurate than adults in natural as well as in experimental coincidence timing tasks (e.g. Bard, Fleury, & Gagnon, 1990; Williams, 1985, 1986). Most of the studies show that performance improves mainly between the age of 5 and 11 years (e.g. Haywood, 1983; Stadulis, 1985; Wade, 1980). In addition, it has been frequently observed that young children have the most difficulty in adjusting their responses when the stimulus velocity varies from trial to trial during an experimental session (e.g. Bard, Fleury, Carrière, & Bellec, 1981; Stadulis, 1985; Wrisberg & Mead, 1983). Most of the studies on this subject show that young children respond too early for the slower velocities and too late for the faster velocities (e.g. Gagnon, Bard, & Fleury, 1990; Shea, Krampitz, Northam, & Ashby, 1982; Williams, 1985; see also Dunham & Reid, 1987, for contradictory findings).

To explain this velocity effect, which could correspond to a range effect (Poulton, 1975), the hypothesis of assimilation was proposed by Haywood, Greenwald, and Lewis (1981). This hypothesis suggests that children do not take into account the specific characteristics of each trajectory but assimilate the various velocities to an average velocity that would correspond to the stimulus's velocities on previous trials. This assimilation could lead children to adopt a strategy in which they use a fixed distance cue to produce their responses. In other words, they initiate the motor sequence (which involves a visuomotor delay in the execution of the response) at the moment when the moving stimulus, whatever its velocity, reaches a fixed position before contact. This fixed position would be approximately chosen to obtain errors centered on perfect timing with the perceived average velocity. This strategy, resulting in the velocity effect, would produce (1) for faster velocities, the arrival time of the moving stimulus being shorter than the motor sequence, which would result in late responses; and (2) for slower velocities, the arrival time of the moving stimulus being longer than the motor sequence, which would result in early responses.

In contrast, an efficient strategy should lead older children and adults to use time information to initiate the motor sequence at the moment when the time remaining before contact [what is classically called the time-to-contact (TTC)] reaches a value equal to the motor sequence time.

As coherent as this hypothesis would appear to be, it has never really been tested in a CT task because it is not possible to predict the extent of the estimate's bias. For this, it would be necessary to know the last moment at which information can be picked up for use in producing the response. The prediction motion (PM) task makes it possible to infer the source of information exploited by subjects (Benguigui, Ripoll, & Broderick, 2003).

The PM paradigm

PM tasks are frequently used to test the ability to estimate TTC of a moving object (e.g. Schiff & Oldack, 1990; Tresilian, 1995). These tasks consist of presenting a moving object that is occluded just before reaching the observer or a specified position. The observer is then required to make a simple response (e.g. press a button) that will coincide temporally with the moving object's immediate arrival at the observer's position or another specified position in space. The numerous studies carried out in this field have shown that a linear relationship exists between TTC estimates and actual TTC (e.g. Caird & Hancock, 1994; Schiff & Oldack, 1990). According to Yakimoff, Mateff, Erhenstein, and Hohnsbein (1993), this relationship can be expressed by the equation: $TTC_e = \alpha(TTC_a) + \theta$, where TTC_a is the actual TTC of the moving object, TTC_e is the participant's estimate of TTC, and α and θ are the two parameters characterizing the accuracy in extrapolation. It has been observed in a large number of studies that the slopes (α) are generally much lower than 1 and the intercepts are greater than 0 (e.g. Manser & Hancock, 1996; Schiff & Detwiler, 1979; Schiff & Oldak, 1990). This means that participants underestimate TTC for the longer occlusions and overestimate it for the shorter occlusions. Generally, the transition point between under- and overestimations is at 1 second of occlusion (e.g. Manser & Hancock, 1996; Schiff & Detwiler, 1979). Note that this relationship is true only for occlusions equal to or greater than 200 milliseconds. For occlusions shorter than 200 milliseconds, the accuracy of responses should not be different from the accuracy in CT tasks (in which there is no occlusion). The occlusion time of 200 milliseconds corresponds to the duration of a visuo-motor delay during which information about the time remaining before the arrival of the moving object is not used to coordinate the response (Benguigui, Broderick, & Ripoll, 2004; Yakimoff, Mitrani, & Bocheva, 1981).

Age and PM tasks

Whereas many studies have been conducted with adults, it is surprising to note that occlusion procedures have rarely been used to address the development of TTC estimation. Dorfman (1977) tested six different populations (ages 6–7, 8–9, 10–11, 12–13, 14–15, and 18–19) in a task that required participants to displace a luminous spot with a cursor on an oscilloscope along a rectilinear trajectory in order to intercept another luminous spot moving on a transverse axis. Dorfman observed that occlusion of the final part of the trajectory (610 milliseconds) had less effect on accuracy in the participants aged 14–15 and 18–19 than in younger children.

In a recent study, Benguigui *et al.* (2004) tested children aged 7, 10, and 13 and adults in a PM task with occlusions shorter and longer than 200 milliseconds (0, 50, 100, 200, 400, 600, and 800 milliseconds). No differences appeared between children and adults in short occlusion conditions in which the processes are supposed to be perceptually driven. In contrast, large differences in response variability appeared for longer occlusion durations, which require cognitive extrapolation. However, it appears that the estimates were made using the same extrapolation strategy regardless of participant age: using the linear method of Yakimoff *et al.* (1993), the four age groups showed no differences in the calculated slopes and intercepts. Children as young as 7 years of age are capable of using the same type of strategy as adults to cope with the disappearance of the moving object and to extrapolate in time the occluded trajectory. Consequently, PM tasks could be used to explore perceptual processes in young children and to identify the origin of the velocity effect.

Identifying the origin of the velocity effect with a PM task

In both PM and CT task with various velocities, young children should be affected similarly by the velocity effect with later responses for the faster velocities than for the slower. However, the PM task offers an opportunity to test the assimilation hypothesis, specifically whether the child uses distance instead time information in the estimation of TTC after occlusion. The hypothesis can be tested by plotting the time estimated by the participant against both the time and the distance during which the moving object is occluded. If children use distance information, they should estimate the occluded time as a function of the occluded distance: the longer the occluded distance, the longer their time estimation. Adults, who are able to better take into account the kinematics of the trajectory, should be able to base their estimation on the occluded time rather than on the occluded distance.

The goal of this study was thus to identify the origin of a velocity effect by using a PM task. We expected different errors in children as a function of the two velocities used, that is later responses for the faster velocity than for the slower. Accordingly, calculations were made to determine whether prediction errors were due to the use of an assimilation strategy and of distance information instead of time information. On a more conceptual level, the chronology of development in PM tasks was examined in relation to the developmental stages described by Savelsbergh and Van der Kamp (2000). The three stages (*freezing*, *freeing*, and *exploiting*) were operationalized as follows: during the *freezing* stage, non-optimal information (i.e. distance instead time information) could be used to estimate TTC. During the *freeing* stage, variability in responses should appear with no clear tendency in the use of time, velocity or distance information across trials. Finally, time information should be used systematically by participants who have reached the *exploiting* stage.

Method

Participants

Four groups of 12 children aged 6 [M (in years) = 6.12, SD (in years) = 0.52], 7.5 ($M = 7.58$, $SD = 0.37$), 9 ($M = 9.06$, $SD = 0.46$), and 10.5 ($M = 10.49$, $SD = 0.53$) years participated in this experiment. A fifth group of 12 adults ($M = 22.19$, $SD = 1.15$) also took part. The groups were composed of both males and females. The ratio between boys and girls in an age group was either 5/7 (groups 6, 9, and adults) or 7/5 (groups 7.5 and 10.5).[1] Informed consent was obtained from the participants and from the parents of the children who participated to this experiment. All participants reported normal or corrected-to-normal vision.

Apparatus and task

The experimental situation required the participants to estimate the arrival moment of an apparent motion at a target. The apparent motion was generated on a 4-meter-long simulator by the sequential switching of 200 red LEDs positioned at 2 cm intervals. The illuminated stimulus moved left to right towards a target corresponding to LED 175 situated at 3.48 m from LED 1. The target was represented by two red marks, placed above and below the target LED. The illumination of the LEDs, trial onset, and data acquisition were synchronized using Labview (National Instruments Corporation, Austin, Texas, USA).

The stimulus generator was positioned at 1.20 m height. Participants sat on an adjustable chair allowing their eye level to be at the level of the stimulus generator. They sat 2 m away from the apparatus at a small table (75 cm height), directly in front of and facing the target. They initiated each trial by pressing a button on the table with their preferred hand and were required to press the same button when they estimated that the moving stimulus had reached the target. The time difference between the participant's estimate and the real TTC defined the response accuracy (in milliseconds). Early responses were marked with a negative sign, and late responses were marked with a positive sign. Stimulus motion could be either presented until the arrival at the target or occluded in the preceding instants. The occlusion was the result of the non-illumination of the LEDs situated in the 'occlusion zone'.

Procedure

After having been informed of the purpose of the test, the participants had a training period with stimulus velocities of 1 and 2 m/s and occlusion durations of 0, 80, 160, 320, 640, and 1,280 milliseconds. The combination of the two factors led to 12 different moving stimuli which were presented twice in two separate blocks, from the shorter occlusions to the longer, to ensure that the participants understood the requirements of the task. Immediately after each trial, participants were given knowledge of results (KR) of the spatiotemporal accuracy of their estimation, in the form of the re-illumination of the LED(s) which had been lit (or should have been lit if there was no occlusion) at the moment they pressed the key. Four levels of accuracy were defined and explained to the participants. 'Perfect response' corresponded to a trial in which the participants were able to press the button at the exact instant of the illumination of the target LED. 'Good response' corresponded to a trial in which the participants were able to press the button while one of the three LEDs placed before and after the target LED was illuminated. This zone was marked by blue sticks placed above and below the LEDs. When the participant pressed the button before or after the arrival of the stimulus in this zone, the responses were considered as 'too early' and 'too late', respectively. During the training period, the

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[1] *No hypothesis was made about a possible gender effect. Experiments with PM tasks as well as CT tasks in children provide contradictory findings with very inconclusive interpretations (e.g. Sidaway, Fairweather, Sekiya, & McNitt-Gray, 1996; Haywood* et al., *1981; Wrisberg & Mead, 1983). Note that ANOVAs were run on the data with gender as a between factor and revealed no main gender effect or interaction with this factor.*

experimenter verified that the participants provided responses that ensured that they had understood the goal of the task: for the longer occlusion conditions (i.e. 320, 640, and 1,280 milliseconds), if a participant pressed systematically the response button before or just after the disappearance of the moving stimulus, he/she was considered to be unable to be tested in this experiment. Three children, all 6 years old, were excluded from the experiment according to this criterion.

During the test, 25 occlusion conditions were used with durations of 0–1,320 milliseconds with steps of 20 milliseconds between 0 and 200 milliseconds and with steps of 80 milliseconds between 200 and 1,320 milliseconds. Two stimulus velocities were used (1 and 2 m/s). The combination of the two factors led to 50 different trajectories which were presented in a randomized order. The starting position of the moving stimulus was always LED 1. As a consequence, the viewing time ranged from 0.420 to 3.280 seconds as a function of velocity and occlusion time. A preliminary experiment had shown that the viewing time had no effect on TTC estimations of adults as well as children when it was above 240 milliseconds (Benguigui, 1997; see also Rosenbaum, 1975, for a similar result). The distances for which the stimulus was visible and occluded ranged, respectively from 0.84 to 3.28 m and from 2.64 to 0.20 m, depending on velocity and occlusion time. KR was given to the participants according to the same criteria as during the training period.

Data analysis and results

Errors in TTC estimations

Errors in TTC estimations were calculated for each trial as the difference between the estimated TTC and the actual TTC. Constant error (CE), absolute error (AE), and variable error (VE) were then calculated on the basis of these errors. In order to reduce the variability inherent to this kind of task and to make the data more understandable, we grouped the data into five categories of five trials (i.e. 0–80, 100–180, 200–520, 600–920, and 1,000–1,320). For each participant, a CE value was calculated with the signed errors for the five categories. CE was used to identify a possible bias in the estimations (i.e. under- or overestimations) as a function of age and the stimulus velocity. AE values were calculated with the same procedure but with the unsigned errors. AE was used to provide a measure of the overall accuracy in performance. VE corresponded to the standard error calculated for each category with the five signed errors. VE was used to provide information about the dispersion of the errors. CE, AE, and VE were separately analysed in a 5 × 2 × 5 (age × velocity × occlusion) ANOVA with age (6, 7.5, 9, 10.5, and adults) as a between-subjects factor and velocity (1 and 2 m/s) and occlusion time (0–80, 100–180, 200–520, 600–920, and 1,000–1,320 milliseconds) as within-subjects factors. For all statistical tests, Newmann–Keuls *post hoc* tests were used for comparison of the means and an alpha level of .05 was used to identify significant effects.

The ANOVA on CE indicated significant main effects of age, $F(4, 55) = 3.55, p < .05$, and of occlusion, $F(4, 220) = 3.89, p < .05$.[2] *Post hoc* tests on the age effect showed that the youngest group was different from the adult group (Table 1). *Post hoc* tests on

[2] *An ANOVA with the same condition of age and velocity but with the nine conditions of short occlusion (0, 20, 40, 60, 80, 100, 120, 140, 160, 180 milliseconds) and the condition without occlusion was run once to check whether short occlusions had an effect on responses accuracy in comparison to the condition without occlusion. The analysis revealed no effect of occlusion [*$F(9, 36) < 1$, ns*] and no interaction of this factor with age and velocity.*

the occlusion effect showed that 0–80 and 100–180 conditions were different from the 200–520 and the 600–920 conditions but not from the 1,000–1,320 condition (Table 1). This result is consistent with previous experiments using PM tasks (e.g. Manser & Hancock, 1996; Schiff & Detwiler, 1979). It shows overestimation of TTC for occlusions under 1 second and 'good' estimations around 1 second. Note that these 'good' estimations are in fact a consequence of the processes involved in TTC estimation. The time of 1 second is the period for which the line representing TTC estimations as a function of the occlusion time crosses the hypothetical line that would correspond to perfect estimations (e.g. Yakimoff *et al.*, 1993).

Table 1. Values for the main effect of age and occlusion for CE, AE, and VE

	6	7.5	9	10.5	Adults
Main effect of age					
CE	161	80	112	67	17
AE	282	251	196	183	93
VE	248	256	206	196	97
	0–80	100–180	200–520	600–920	1,000–1,320
Main effect of occlusion					
CE	59	68	121	125	63
AE	138	145	196	242	283
VE	136	148	182	243	293

The ANOVA also revealed a velocity × occlusion interaction, $F(4, 220) = 3.89$, $p < .05$, and an age × velocity × occlusion interaction, $F(4, 220) = 1.76$, $p < .05$. The velocity × occlusion interaction revealed that there was a velocity effect in the two longest occlusion conditions (600–920 and 1,000–1,320 milliseconds). *Post hoc* tests on the age × velocity × occlusion interaction showed that this velocity effect was present only in the 6- and 7.5-year group for the 1,000–1,320 occlusion condition and in the 9-year group for the 600–920 occlusion condition (Figure 1). This result confirms a velocity effect for the youngest children in the longest occlusion conditions. It should be noted that the velocity effect in this task is slightly different from that of CT tasks, in which children respond too early for the slower velocities and too late for the faster (e.g. Gagnon *et al.*, 1990; Shea *et al.*, 1982; Williams, 1985). In this experiment, most of the responses were late (see Figure 1), conforming to results obtained in PM tasks, in which most of the occlusion times have been equal to or less than 1 second (e.g. Manser & Hancock, 1996; Schiff & Detwiler, 1979). However, the velocity effect in children is apparent in the relative difference in the timing of PM responses between the two conditions of velocity. Reponses were given later for the faster velocity than for the slower.

The youngest groups had a general tendency to be late in their responses. This could be due to a motor or a perceptuomotor bias explained by a longer visuomotor delay in the production of responses which would not correctly integrated in the response (Benguigui & Ripoll, 1998). However, this bias does not seem to influence the general pattern of responses in the task and does not prevent interpretations of the effect of the perceptual factors we manipulated (i.e. occlusion time and velocity).

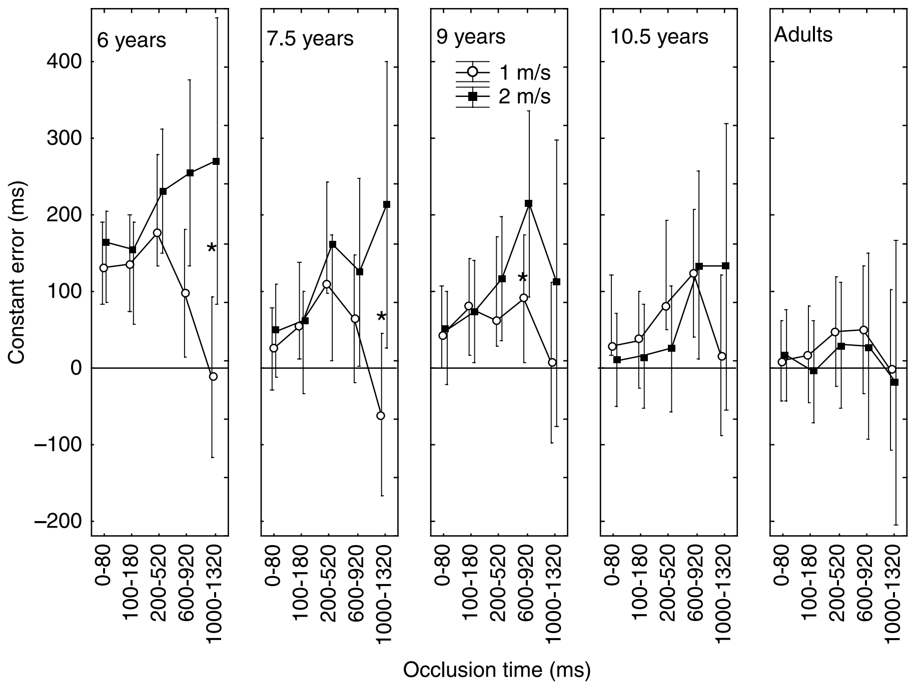

Figure 1. The age × velocity × occlusion interaction for CE showed that there was a velocity effect for the longest occlusion conditions for the three youngest groups. The * indicates the significant differences. The bars indicate the intra-group variability.

The ANOVA on AE showed significant main effects of age, $F(4, 55) = 15.27, p < .05$, of velocity, $F(4, 55) = 6.33$, $p < .05$, and of occlusion, $F(4, 220) = 29.82$, $p < .05$.[3] *Post hoc* tests on the age effect showed that all the age groups were different from each other except the 6 and 7.5 groups and the 9 and 10.5 groups (Table 1). Note that AEs for the child groups were between two and three times larger than for the adult group. The velocity effect led to larger AEs for the faster velocity than for the slower (214 vs. 187 milliseconds). *Post hoc* tests showed that AEs for the 0–80 and 100–180 occlusion conditions did not differ but that AEs significantly increased as a function of increased occlusion time (Table 1).

The ANOVA on VE showed significant main effects of age, $F(4, 55) = 10.96, p < .05$, of velocity, $F(4, 55) = 12.92$, $p < .05$, and of occlusion, $F(4, 220) = 32.87$, $p < .05$. *Post hoc* tests on the age effect showed that all the child groups were different from the adult group (Table 1) with VE for child groups being between two and three times larger than for the adult group. *Post hoc* tests on the velocity effect showed that VE was larger for the faster velocity than for the slower (224 vs. 176 milliseconds). *Post hoc* tests showed that VE for 0–80 and 100–180 occlusion conditions did not differ but that VE significantly increased as a function of increased occlusion time (Table 1). The ANOVA also revealed a velocity × occlusion interaction, $F(4, 220) = 3.42, p < .05$, with larger

[3] *An ANOVA with the same condition of age and velocity but with the nine conditions of short occlusion (0, 20, 40, 60, 80, 100, 120, 140, 160, 180 milliseconds) and the condition without occlusion was run on AE to check whether short occlusions had an effect on responses accuracy in comparison to the condition without occlusion. The analysis revealed neither an effect of occlusion [*$F(9, 36) < 1$, ns*] nor interaction of this factor with age and velocity.*

VE for the faster than for the slower velocity only in the two longer occlusion conditions (600–920 and 1,000–1,320 milliseconds) (Table 2).

Table 2. Values for the velocity × occlusion interaction for AE and VE. AE and VE were significantly higher for the fastest velocity for the two longest occlusion conditions

Occlusion time (ms)	0–80	110–180	200–520	600–920	1,000–1,320
AE					
1 m/s	137	154	200	214	230
				*	*
2 m/s	140	136	192	270	337
VE					
1 m/s	130	145	160	201	245
				*	*
2 m/s	141	152	205	285	341

Significant differences are indicated by *.

TTC estimations

Data were also analysed with the typical PM-task method for calculating two linear regressions for each participant, with 15 occlusions (between 200 and 1,320 milliseconds)[4] as the independent variable and 15 TTC estimates for the slower and faster velocities as the dependent variables. For each participant, these calculations yielded two slopes, two intercepts, and two coefficients of regression, corresponding to the slower velocity and the faster velocity, respectively. These variables were analysed in 5 × 2 (age × velocity) ANOVA with age (6, 7.5, 9, 10.5, and adults) as a between-subjects factor and velocity (1 and 2 m/s) as a within-subjects factor. The regression coefficients were transformed to Fisher *z* scores (Fisher, 1942) for the statistical analysis.

The ANOVA on slopes revealed no effect of age but a significant main effect of velocity, $F(1, 55) = 34.30$, $p < .05$. The slopes were higher for the faster velocity condition (1.07) than for the slower velocity condition (0.83). There was also a significant interaction between age and velocity, $F(4, 55) = 3.46$, $p < .05$. Children aged 6, 7.5, and 9 years had higher slopes for the faster velocity and lower slopes for the slower velocity while no differences were observed in the older groups (Figure 2, Table 3). Differences in slopes in younger children were due to the effect of velocity for the longer occlusion conditions which led children to estimate TTC as longer for the faster velocity than for the slower (Figures 1 and 2; see also above in the analyses of CE).

The ANOVA on intercepts indicated a significant main effect of velocity, $F(1, 55) = 33.58, p < .05$. The intercepts were higher for the slower velocity condition (211 milliseconds) than for the faster velocity condition (51 milliseconds). There was no effect of age or interaction between age and velocity (Table 3).

The ANOVA on R^2 transformed to Fisher *z* scores revealed a significant main effect of age, $F(4, 55) = 21.44$, $p < .05$. *Post hoc* tests indicated that the R^2 values of the two

[4] *Because previous results showed that the linear model of Yakimoff* et al. *(1993) was not applicable to occlusion time inferior to 200 milliseconds (e.g. Benguigui* et al.*, 2004) the occlusion conditions inferior to this value were not used in this analysis.*

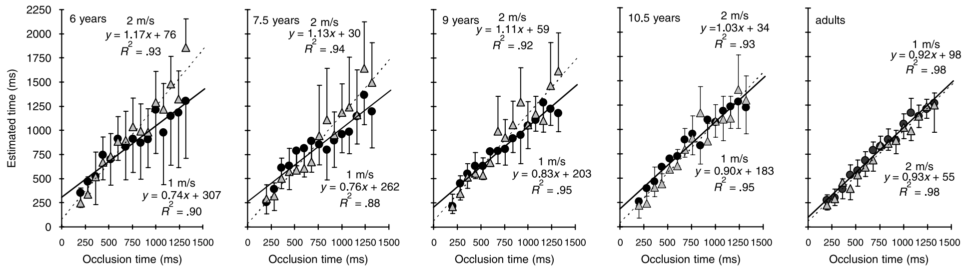

Figure 2. Estimated time after the occlusion as a function of occlusion time for the five age groups. The grey triangles correspond to TTC estimations for the faster velocity. The black circles correspond to TTC estimations for the slower velocity. The velocity effect is apparent in the slopes for the three youngest groups. The bars indicate the intra-group variability.

Table 3. Slopes, intercepts and R^2 as a function of age and velocity. The intra-group variability is in parentheses

	Age groups					
	6	7.5	9	10.5	Adults	Means
Slopes						
1 m/s	0.74 (0.34)	0.76 (0.37)	0.83 (0.24)	0.90 (0.29)	0.92 (0.10)	0.83 (0.27)
2 m/s	1.17 (0.43)	1.13 (0.42)	1.11 (0.25)	1.03 (0.21)	0.93 (0.19)	1.07 (0.30)
Mean	0.95 (0.39)	0.94 (0.40)	0.97 (0.25)	0.96 (0.25)	0.93 (0.14)	0.95 (0.28)
Intercepts						
1 m/s	307 (254)	262 (240)	203 (158)	183 (202)	98 (92)	211 (189)
2 m/s	76 (100)	30 (235)	59 (145)	34 (146)	55 (125)	51 (150)
Mean	191 (177)	146 (237)	131 (152)	108 (174)	77 (108)	131 (170)
R^2						
1 m/s	0.54 (0.21)	0.50 (0.19)	0.67 (0.18)	0.66 (0.21)	0.90 (0.04)	0.65 (0.17)
2 m/s	0.63 (0.17)	0.58 (0.17)	0.68 (0.17)	0.68 (0.17)	0.86 (0.09)	0.68 (0.15)
Mean	0.58 (0.19)	0.54 (0.18)	0.68 (0.17)	0.67 (0.19)	0.88 (0.04)	0.67 (0.16)

younger groups were significantly lower than those of the other groups. The 9- and 10.5-year age groups had R^2 which were also lower than the R^2 of the adult group. There was no effect of velocity or interaction between age and velocity (Figure 1, Table 3).

Using distance information to estimate TTC

The last analysis was run to test whether the velocity effect observed in children could be due to the use of distance information instead of time information. To determine this, we computed two linear regressions from the TTC estimates. For the first, the independent variable was the distance that the stimulus was occluded, and the dependent variable was the TTC estimated for each condition. For the second, the independent variable was the occlusion time, and the dependent variable was the TTC estimated. For this analysis, only the R^2 transformed in Fisher z were analysed to determine whether distance or time was the best predictor of TTC estimates. Comparison of slopes and intercept was not relevant since the independent variables (distance and time) did not have the same units. The z scores were analysed using a

5×2 mixed model ANOVA with Age (6, 7.5, 9, 10.5, and adults) as a between-subjects factor and Information (distance vs. time) as a within-subjects factor.

The analysis revealed a significant main effect of age, $F(4, 55) = 13.72, p < .05$. *Post hoc* tests indicated that the R^2 of all child groups were different from the R^2 of the adult group. The ANOVA also showed a significant main effect of information, $F(1, 55) = 101.27, p < .05$. The R^2 values were higher for time as a predictor than for distance. In addition, the ANOVA revealed an age × information interaction, $F(4, 55) = 13.75, p < .05$. *Post hoc* tests revealed that time was a better predictor than distance for the two older groups. In contrast, no significant differences appeared for the three younger groups (Figure 3).

The evolution of estimations with age can be further understood by calculating a measure we call the 'time–distance tendency'[5] (TDT) of each participant. The TDT was calculated for each participant on the basis of the difference between the R^2 obtained with time as a predictor and the R^2 obtained with distance as a predictor. Participants were grouped into categories as a function of their TDT. A distinction was first made between those who had a distance tendency (with negative scores) and those who had a time tendency (with positive scores). Inside each category, participants were placed into subcategories as a function of their scores. The step between one subcategory to the others was 0.1. With this distinction, it appears that the distribution of participants across the TDT evolves with age from a distance tendency or distance–time tendency (participants who are not clearly differentiated with scores around 0) to a clear time tendency in adults (Table 4). This shows that between the age of 6 and 10.5, and beyond this age for some children, changes can occur in the possible sources of information that are used to extrapolate in time an occluded moving object.

To test the possible relationship between the use of distance information and the velocity effect, regression analyses were performed for each age group with the TDT of each participant as a predictor, and the mean CE difference for each participant across all conditions of occlusion between the faster and the slower velocity conditions as a dependent variable that we called the 'CE velocity differential'. The results showed high correlations between these variables (Figure 4). Participants who demonstrated a distance tendency or no clear tendency were also those who demonstrated a positive CE velocity differential that is responses were given later for the faster velocity than for the slower. Conversely, the regression analyses revealed that participants who clearly based their judgements on time produced responses marked by a negative CE velocity differential. This was the case for adults and also some children in the other age groups.

The TDT variable induces a repartition of participants which is not directly dependent on age (Table 4). However, this repartition can be considered as an indicator of their stage of development in the task. Following this idea and the stages of development proposed by Savelsbergh and Van der Kamp (2000), we formulated the following hypothesis: the participants who are in a freezing stage should have low variability in their estimations while participants who are in a freeing stage should have high variability. Accordingly, we would expect that the transition from freezing to freeing to exploiting could be illustrated by a U-shape pattern in the plot of the R^2 of the time estimate best predictor against TDT.

[5] *We choose to use the term 'tendency' instead of a more affirmative term (such as 'profile') because our analysis does not provide absolute evidence about the use of one type of information instead of another. This term also accounts for the fact that, from one trial to another, some participants could use different sources of information.*

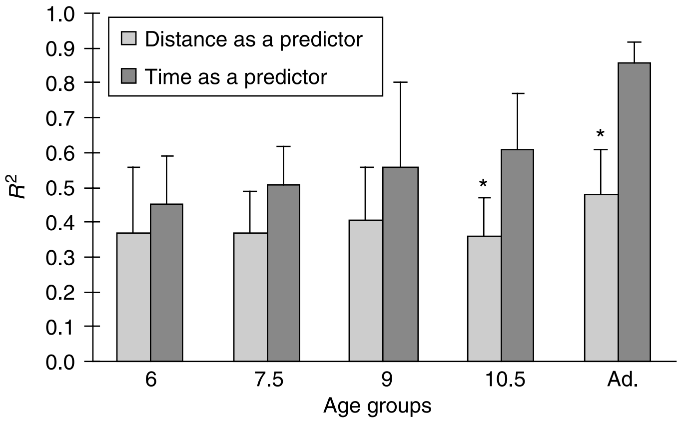

Figure 3. The R^2 for the five age groups with the occluded time and the occluded distance as predictors of their estimations. The bars indicate the intra-group variability. Significant differences are indicated by *.

Table 4. Distribution of the participants (*P*) in each age group as a function of their time–distance-tendency (TDT)

	6 years	7.5 years	9 years	10.5 years	Adults	Number of *P*
Time–distance tendency						
Distance tendency						
TDT < −.1	1	–	1	1	–	3
− .1 < TDT < .0	3	2	1	2	–	8
Time tendency						
.0 < TDT < .1	3	4	4	–	–	11
.1 < TDT < .2	1	1	1	1	–	4
.2 < TDT < .3	4	4	1	2	3	14
.3 < TDT < .4	–	1	3	2	4	10
.4 < TDT < .5	–	–	1	3	4	8
.5 < TDT −	–	–	–	1	1	2

In addition, participants in the freezing stage should produce relatively large errors in spite of being consistent, while participants in the freezing and exploiting stages should be relatively accurate. To test this hypothesis of stage-dependent-variability, we used R^2 from the best predictor of TTC estimations for each participant (distance for participants with negative TDT and time for participants with positive TDT) as an indicator of the response variability (i.e. the smaller the R^2, the smaller the explained variance and the greater the variability in responses). We also used the TDT as an indicator of the development stage where the participants were. We performed second order polynomial fits to the R^2 data with the TDT of each participant as the independent variable. We also performed second order polynomial fits to the R^2 data with the age of each participant as the independent variable to verify that TDT was a better predictor than age.

To test the hypothesis of developmental stage-dependent accuracy, we used the mean AE of each participant from all conditions of occlusion as an indicator of the overall accuracy in the task. We performed a linear regression analysis (the curvilinear function

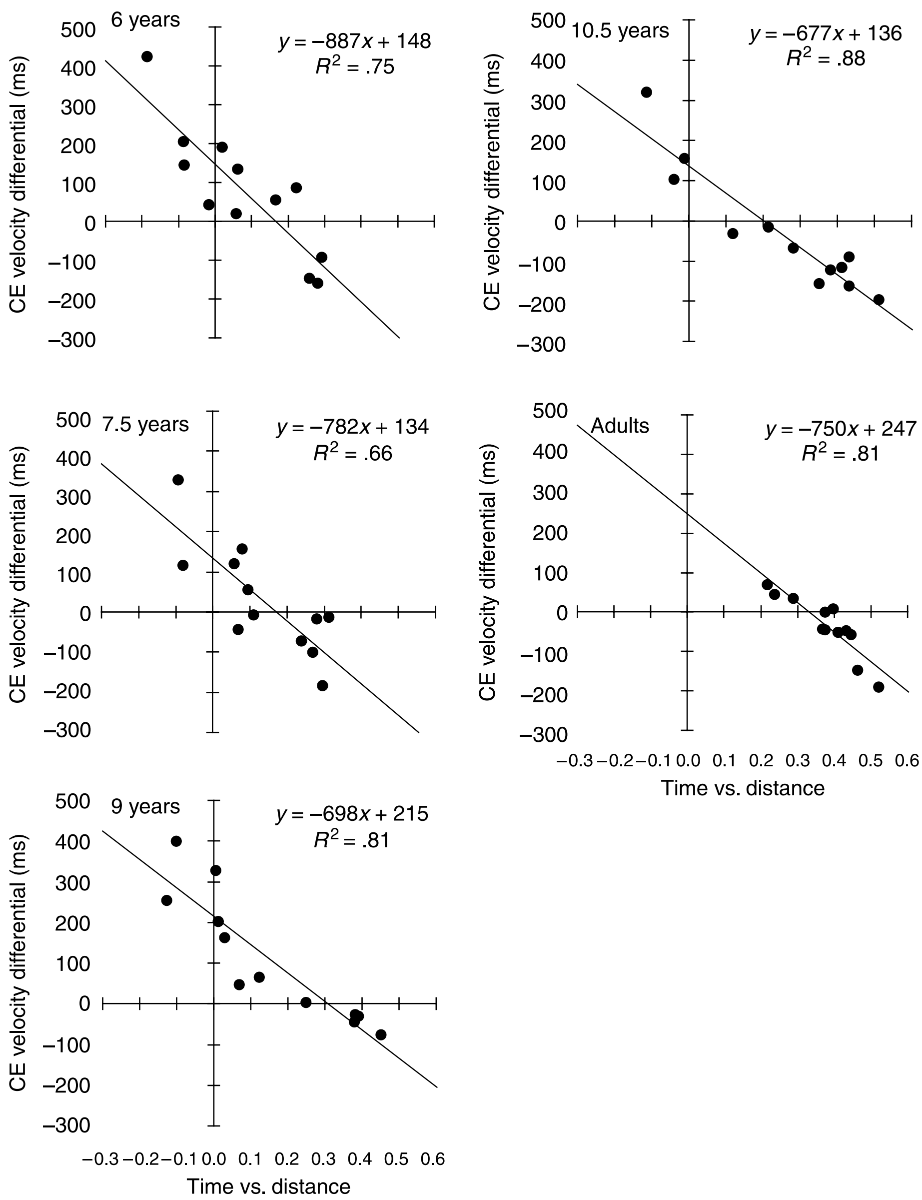

Figure 4. CE velocity differential corresponding to the difference between the mean CE in the faster and slower velocity conditions for all conditions of occlusion for all participants as a function of their TDT. Positive scores for the velocity difference mean that participants respond too late for the faster velocity and too early for the slower velocity and vice versa. The TDT was calculated as the difference between the R^2 obtained with time as a predictor and the R^2 obtained with distance as a predictor. Negative scores indicate a tendency for participants to base their judgments on distance, whereas positive scores indicate a tendency for them to base their judgments on time.

did not give a better prediction) with mean AE as the dependent variable and the TDT of each participant as the independent variable. We also performed a linear regression analysis with mean AE as the dependent variable and the age of each participant as the independent variable to verify that TDT was a better predictor than age.

For variability, the analyses with TDT as a predictor showed that the second order polynomial fit explained 53% of the total variance, whereas the analysis with age as a predictor explained 48% of the total variance (Figure 5a and 5b). In comparison with a linear fit, the second order polynomial fit increased the total variance explained by 11% for TDT as the predictor, compared to a 1% increase in total variance explained with age as the predictor. TDT appears to be a better predictor, particularly when the adult group is removed from the analyses. In this case, the second order polynomial fits explains 55% of the variance with the TDT as a predictor and only 15% of the variance with age as a predictor. In fact, the high R^2 for the all-group analysis with age was due to both the clear difference in AE between the adult group and the children as a group, and the large temporal gap – and thus a large data gap – between oldest age group of children (10.5 years) and the 22-year-old mean of the adult group.

For accuracy, the analysis with TDT as a predictor explained 51% of the total variance whereas the analysis with age explained only 47% (Figure 6a and 6b). Again, TDT appeared to be a better predictor and this is particularly true when the adult group is removed from the analysis, with 40% of the variance explained by TDT as a predictor and only 9% explained by age as a predictor. Again, the high R^2 for the all-group analysis with age was due to the age/data gap between the children and the adults (Figure 6b).

The regression patterns for the time-estimate best predictor and performance accuracy confirm our hypothesis. The participants who had a TDT $< -.01$ could be considered in a freezing stage with a low variability (i.e. high R^2) but with a great inaccuracy. During this stage, consistency and inaccuracy in their time estimations can be explained by their preferential use of distance as information (which is non-optimal information). The participants who had TDT between $-.1$ and $+.1$ could be considered in a freeing stage with high variability (i.e. low R^2) and still great inaccuracy. During this stage, variability and inaccuracy in their time estimations can be explained by the alternative use across trials of distance and time as information. The participants who had TDT $> +.1$ could be considered in a freezing and exploiting stage with low variability (i.e. high R^2) and great accuracy. During this stage, consistency and accuracy in their time estimations can be explained by their use of time as information.

Discussion

The purpose of this study was to identify, by using a PM task, the origin of the velocity effect in children previously reported for CT tasks. Confirming previous studies (Benguigui *et al.*, 2004; Caird & Hancock, 1994; Schiff & Oldack, 1990), the results showed that errors (AE and VE) in estimations increased with the occluded time (when the occlusion is greater than 200 milliseconds) and with diminishing age (Tables 1 and 2). Linear regression analyses between the occluded time and the estimated time were in accordance with the findings of Yakimoff *et al.* (1993): there were no differences between age groups in slopes and intercepts (Table 3), confirming that as young as the age of six, children use a strategy similar to the adults to coherently extrapolate in time occluded trajectories (Benguigui *et al.*, 2004). The slope values for all groups, ranging from 0.86 to 0.95, were consistent with those generally observed in studies using PM tasks (see Caird & Hancock, 1994; Schiff & Oldack, 1990). The age-related differences were found in the coefficients of correlation which reflect the variability in responses. Our results indicate that in the course of development children produce TTC estimates that are progressively more in accordance with the linear model of Yakimoff *et al.* (1993).

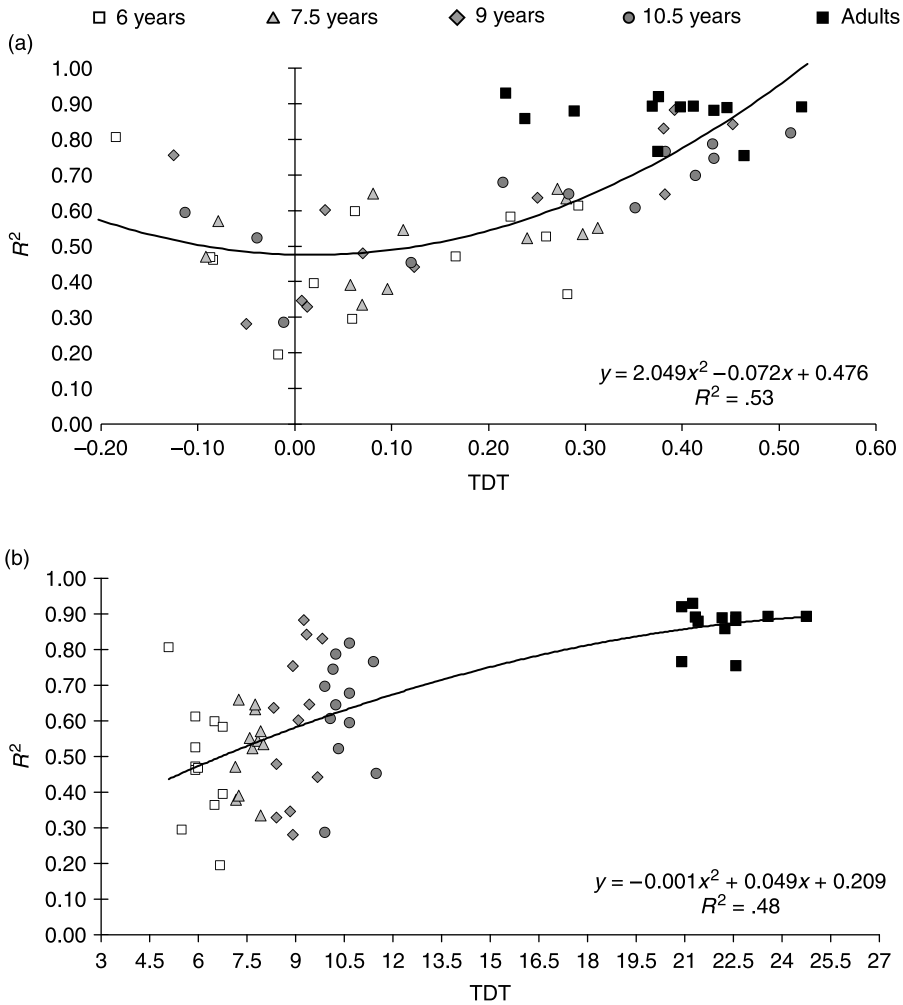

Figure 5. Curvilinear relationships between (a) TDT and R^2 and between (b) age and R^2 for all participants. The R^2 correspond to the regression analyses with time or distance (the best was selected) as a predictor of TTC estimations. R^2 were used as an indicator of variability in responses (the smaller the R^2, the greater the variability). The 6-year-old children are represented in white squares, the 7.5-year-old children in clear grey triangles, the 9-year-old children in medium grey ovals, the 10.5-year-old children in dark grey circles, and the adults in black squares. TDT ($R^2 = .53$) appeared to be a better predictor than age ($R^2 = .48$). This was more obvious when the analysis excluded the adult group, with a slight increase in R^2 for TDT as a predictor ($R^2 = .55$) but a large decrease with age as a predictor ($R^2 = .15$).

Regarding bias in responses (CE), results showed a velocity effect only for the youngest groups (6, 7.5, and 9 years) with later responses for the faster velocity than for the slower velocity in the longer occlusion conditions (Figure 1). This velocity effect was also apparent for those groups in the regression analyses on the estimated TTC as a function of the occlusion time with higher slopes for the faster velocity than for the slower (Figure 2, Table 3).

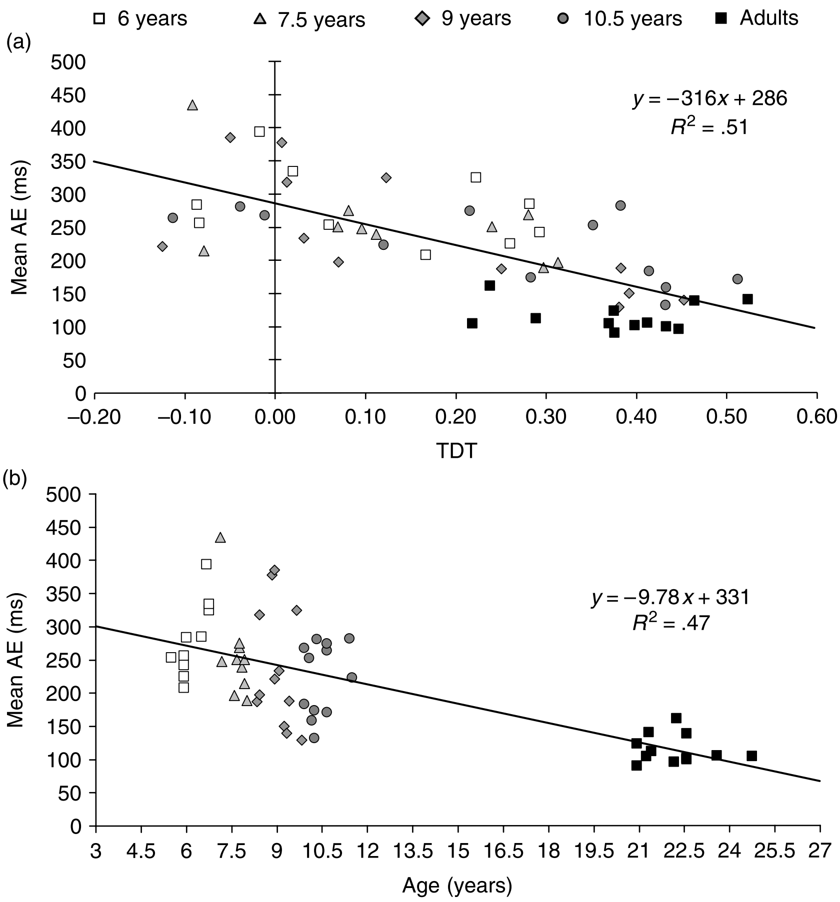

Figure 6. Linear relationships between (a) TDT and mean AE and between (b) age and mean AE for all participants. The mean AE was calculated for each participant with the AE for all conditions of occlusion. Mean AE was used as an indicator of the overall accuracy in the task. The 6-year-old children are represented in white squares, the 7.5-year-old children in clear grey triangles, the 9-year-old children in medium grey ovals, the 10.5-year-old children in dark grey circles, and the adults in black squares. Again, TDT ($R^2 = .51$) appeared to be a better predictor than age ($R^2 = .47$). This was more obvious when the analysis excluded the adult group, with a slight decrease in R^2 for TDT as a predictor ($R^2 = .40$) but a large decrease with age as a predictor ($R^2 = .09$).

To explain these results, we tested the hypothesis that young children use distance instead time information. In agreement with this hypothesis, the results showed that only the two older groups demonstrate a clear use of time information (Figure 3). For the three younger groups, there was no systematic tendency (neither time nor distance) (Figure 3). Analyses of individual participants reveal that the absence of a clear tendency in the younger groups is due to inter-individual differences in each of these groups. Some children, and among them some of the very young, already use time information (Table 4, TDT $> .1$). A minority have a tendency to use distance information instead (Table 4, TDT $< -.1$). Another group of children is somewhere between the two (Table 4, TDT $> -.1$ and $< .1$). These results suggest that the possible sources of information for estimating TTC can vary with age. This also suggests that development of TTC estimation is not solely a function of age or maturation. Other factors such as sport practice can strongly influence this development (e.g. Benguigui & Ripoll, 1998; Ripoll & Benguigui, 1999). These propositions were confirmed by the linear and curvilinear relationship that were found between TDT and accuracy and consistency in TTC estimations (Figures 5 and 6). TDT was a better predictor of accuracy and consistency in TTC estimations than age.

Individual analyses also showed that there was a strong correlation between the TDT and the velocity effect. Young children who demonstrated either a distance tendency or no tendency were also those who demonstrated a positive velocity effect (i.e. responses were given later for the faster velocity than for the slower). The more a child manifests a distance tendency the greater the velocity effect (Figure 4). This result strongly implicates the use of distance instead time information to explain the velocity effect.

In addition, an unexpected result appeared from this analysis. Participants who strongly based their estimations on time information demonstrated a negative velocity effect (i.e. later responses for the slower velocity than for the faster velocity, see Figure 4). We do not have an explanation for this result, but it leads us to speculate about the possible origin of the contrary findings that are found in the literature on the velocity effect (e.g. Dunham & Reid, 1987; Shea *et al.*, 1982). The different information strategies of children might be linked to the different sources of information available in CT actions (e.g. Van der Kamp, Savelsbergh, & Smeets, 1997) and to the developmental stage the participants have reached (Savelsbergh & Van der Kamp, 2000).

It has been shown that diverse sources of information could be used that specify the movement and position of contact (e.g. Michaels, Zeinstra, & Oudejans, 2001). Adults are in general capable of utilizing this diversity to better select the most adaptive information, or to combine information sources to obtain the most precise estimation of TTC [see Tresilian (1994) for a development of the idea]. This capacity corresponds to an *exploiting* stage such as described by Savelsbergh and Van der Kamp (2000) that would permit an actor to use, in our example, the most appropriate temporal information. In this experiment, adults and some children could be considered at this stage with accurate and consistent TTC estimation. A minority of children appeared to be in a *freezing* stage that led them to inappropriately use distance information that happened to be more accessible or more relevant to other situations. Hence these children manifested the velocity effect along with lower accuracy than the other participants. However, it is worth noting that an initial freezing stage in children induced a relative consistency in responses (Figure 5a) which contrasts with the common idea that variability in responses decreases progressively with age. The majority of children between 6 and 9 years were in a *freeing* stage that led them to try different strategies and to switch between time and distance information. These alternations of strategy would explain their larger response variability and the absence of a clear time or distance tendency (Figures 3 and 5, Table 4).

These results could be surprising when compared to studies which showed that for instance babies were sensitive to information about the approach of a moving object (e.g. Ball & Tronick, 1971; Bower, Broughton, & Moore, 1970; von Hofsten, 1980) and particularly to looming information, which is also known to be a potential source of TTC information (Lee, 1976). However, these studies on babies only focused on whether an avoidance or catching behaviour occurs in response to moving objects and did not analyse timing and accuracy. It would not be surprising that accurate timing requires long-term experience and that during development non-optimal sources of information (i.e. distance instead time) could be used even when children are sensitive to optimal sources (e.g. looming or other TTC information).

In summary, this study has identified the informational basis of the velocity effect in children: whereas time information was clearly used by older children (10.5 year olds) and adults to estimate TTC, this was not true for the younger children (6, 7.5, and 9 year-olds), who tend to use distance rather than time information to estimate TTC, or to confuse time and distance information. Results also showed significant inter-individual differences between children of the same age in the source of information used. More research is certainly needed to clarify the developmental processes responsible for these individual differences.

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