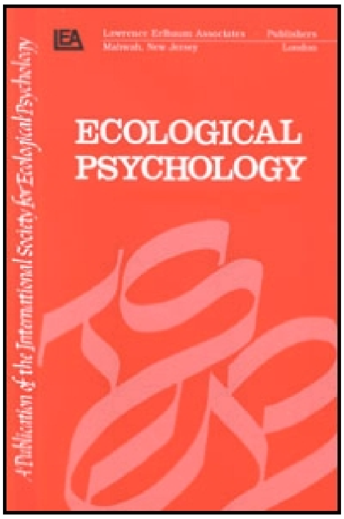

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Age-Correlated Incremental Consideration of Velocity Information in Relative Time-to-Arrival Judgments

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One hundred fifty-one children and 43 adults judged which of 2 cartoon birds would be the first to arrive at a common finish line. Objects moved unidirectionally along parallel trajectories, either at the same or different speeds, and disappeared at different distances from the goal. Overall, 9–10-year-old children performed as well as adults, but 4–5- and 6–8-year-olds erred significantly more often. On trials for which distance to goal at disappearance was a valid cue, 4–5-year-olds scored 80% correct, and no differences were seen between 6–10-year-olds and adults. On the opposite type of trials, where the trailing bird would win the race, only adults retained their level of performance, and all age groups differed markedly. Findings suggest a gradual developmental transition from a distance-based to a time-based understanding of the task.

Understanding velocity, or speed, in terms of distance divided by time, is a fairly recent achievement of human thought (Wallis, 1671). It is certainly not

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part of an inborn "core knowledge" in the sense of Spelke and Kinzler (2007). The definitional implication, that the ratio of a given distance to instantaneous velocity gives the time remaining till arrival (t_A), introduces a further level of complexity. Despite this, pigeons perform perfectly on such tasks (at least if these animals are approached by an object head-on; Frost & Sun, 2004), and adult humans do well also (Regan & Gray, 2004). Comparatively little is known about the development of this ability (cf. Benguigui, Broderick, Baurès, & Amorim, 2008, for a recent review).

In the wake of Piaget (1946a, 1946b), many researchers investigated children's conceptual understanding of space and time by engaging them in Platonic dialogues (originally called "méthode clinique" [clinical interview] by Piaget) about relative distances, durations, and speeds related to a multiple binary choice task (or variations thereof; e.g., Matsuda, 1996; Siegler & Richards, 1979). Results suggested several stages of development, with *time* being the most difficult concept, not usually mastered at age 4. This body of research has been criticized by proponents of information integration theory (e.g., Wilkening, 1981) for distracting attention from potentially relevant information and for imposing undue memory load. More important, the Piagetian choice task does not seem to reveal anything about understanding the relations between concepts. Findings from a prediction task suggested an earlier command of concepts than hitherto assumed (cf. Zhou, Peverly, Boehm, & Chongde, 2000, pp. 218–220, for balance). In contrast to the aforementioned approaches, ecological psychology (E. J. Gibson & Pick, 2000) focuses on the use of *perceptual* information for action coordination. No estimates of physical parameters are obtained; participants simply have to respond to critical spatial or temporal margins (cf. Lee, Young, & McLaughlin, 1984, for an example).

Perception of t_A (also called time-to-collision or time-to-contact; Lee, 1974; Schiff & Oldak, 1990) has been investigated utilizing different paradigms. In a prediction-motion task, observers have to respond to the spatio-temporal coincidence of a moving object (which is occluded en route) and a goal position (J. J. Gibson, 1947; Gottsdanker, 1952; Schiff, 1986). In a relative-judgment task, observers have to indicate which of two or more objects will arrive earliest at a designated goal—or did arrive, if the answer is delayed beyond stimulus offset (DeLucia & Novak, 1997; Todd, 1981). According to our experience (Benguigui et al., 2008; Benguigui, Broderick, & Ripoll, 2004; also cf. Dorfman, 1977), ordinal judgment is easier than coincidence responding and therefore was chosen for the present study, which would include child participants (cf. Tresilian, 1995, for a thoroughgoing comparison of both tasks—between them and to interceptive action).

Law et al. (1993) were among the first to study relative judgment of t_A in the frontoparallel plane. With student participants, they observed a "distance bias": of two objects, the one already closer to its goal was most often chosen to be the one presumptively to arrive first. Such bias is often seen in young children. For example, Hoffmann (1994), in multifactor analysis of variance, observed an interaction between distance and velocity for 7- to 8-year-old children but a main effect of velocity only for 9- to 10-year-olds—which the author interprets to indicate increasing use of velocity information with age. Benguigui et al. (2008), by means of linear regression, found that distance was a better predictor of t_A judgments than was occlusion time, for a number of children age 6 and beyond, suggesting that a critical developmental stage transition is likely to occur at around this age or earlier.

Although the two last mentioned studies had posed a prediction-motion task, we decided to emulate part of Law et al.'s (1993) Experiment 1 and customize it for use with children. We reasoned that selecting these authors' simplest and empirically easiest stimulus configuration—parallel trajectories with objects moving in the same direction—and a relative judgment task should allow us to more convincingly trace a developmental sequence from distance-based to more appropriate time-based Δt_A judgments.

METHOD

Participants

One hundred ninety-four persons (children and adults) participated. Table 1 shows distribution by age and gender. Adults were psychology undergraduates.

Apparatus

Stimuli were presented on a notebook computer (screen size 28.5 × 21.5 cm, resolution 1,024 × 768 pixels, refresh rate 60 Hz). Participants' viewing distance could not be controlled precisely but most of the time ranged around 45 cm. For programming, Vizard 3 (WorldViz LLC, Santa Barbara, CA) had been used.

TABLE 1
Number of Participants by Age and Gender

Age	*4–5*	*6–8*	*9–10*	*Adult*
Male	25	31	20	7
Female	19	26	30	36
Total	44	57	50	43

Stimuli and Response Measure

Two nonanimated cartoon drawings of identical but differently colored birds, one turquoise (RGB 88, 199, 225) and one orange (RGB 228, 146, 80), were presented against a dark blue background (RGB 0, 0, 256). The birds moved horizontally from left to right straight toward their nests, which were placed on the tips of two identical branches of a tree. Trajectories were spaced 4 cm apart. Individual birds' overall size was 3 × 1.7 cm (head and trunk 2 × 0.7 cm), nests were 1.7 × 0.7 cm, and tree branches extended 6.2 cm into the field of view. The orange bird served as standard, always starting 19.32 cm clear of its goal and traveling at a constant velocity of 2.91 cm s^{-1} ($\cong$ 4° s^{-1}). The turquoise (test) bird either traveled at the same or at one of two slower speeds (1.94 cm s^{-1} [($\cong$ 2.5° s^{-1}] or 1.46 cm s^{-1} [($\cong$ 2° s^{-1}]). This created three different velocity ratios ($v_{\text{Standard}}/v_{\text{Test}}$) of 1:1, 1:0.75, and 1:0.5. The distance of the test bird's starting point to its goal varied between 8.21 and 22.23 cm.

The scenario as described was explained to participants as a race in which there would be no ties. When the prospective winner had covered two thirds of its traveling distance, both birds were gracefully faded out simultaneously within 250 ms. Subjects had to extrapolate the birds' movement and press a color-coded key to identify the winner. Times of nonvisibility (measured from end of fade-out) varied between 2,213 and 2,880 ms for the standard and between 1,880 and 3,123 ms for the test. Arrival time differences (Δt_{A}) were 500, 750, and 1,000 ms. Calibrations (adopted from Law et al., 1993, and kept for comparability) implied that for imbalanced velocity ratios the test bird at fade-out was always closer to its goal than was the standard. Position of trajectory (upper vs. lower) and odds of winning, however, were counterbalanced between standard and test.

Design and Procedure

Complete factorial crossing of variables yielded a 3 (velocity ratios) × 3 (arrival times) × 2 (upper vs. lower trajectory) × 2 (standard vs. test being winner) within-subjects design. Age group and gender were added as between-subject variables. Data were collected at several kindergartens and preliminary schools. Participants did 8 practice trials, randomly chosen from the 36 experimental ones, which subsequently were run in two blocks of 18 each. Feedback was provided immediately after each trial. After finishing the experiment, participants had to fill in a short questionnaire (or answer questions verbally, according to age) about favorite colors, computer game proficiency, and the like. None of this information proved predictive and therefore will not be referred to in the remainder.

RESULTS

Responses were converted into percentage accuracy scores, averaging per level of selected within-subject variables (Table 2). Discarding a minor effect of location of trajectory, $M_{\text{upper}} = 83.79\%$, $SD_{\text{upper}} = 14.49$, $M_{\text{lower}} = 81.76\%$, $SD_{\text{lower}} = 13.22$, $t(193) = 2.40$, $p = .017$, $d = 0.172$, and whether standard or test was winner, $M_{\text{Standard}} = 76.32\%$, $SD_{\text{Standard}} = 17.63$, $M_{\text{Test}} = 89.23\%$, $SD_{\text{Test}} = 12.14$, $t(193) = -10.64$, $p = .001$, $d = 0.764$ (this effect will be dealt with in the next paragraph), we aggregated data with respect to Δt_{A} and velocity ratio. A repeated-measures analysis of variance, incorporating these variables plus age group and gender as between-subject factors, revealed significant main effects of age, $F(3, 186) = 67.54$, $p = .001$, $\eta_p^2 = .521$, Δt_{A}, $F(2, 372) = 58.44$, $p = .001$, $\eta_p^2 = .239$, and velocity ratio, $F(2, 372) = 77.53$, $p = .001$, $\eta_p^2 = .294$, as well as a weak interaction between Δt_{A} and velocity ratio, $F(4, 744) = 3.11$, $p = .015$, $\eta_p^2 = .016$. Performance improved with age and increasing Δt_{A} and was better the more balanced the velocity ratio was. However, as shown by Tukey post hoc tests, 9–10-year-old children already performed as well as adults. A second analysis, excluding trials with velocity ratio 1:1, was carried out to look at possible effects of the partial confounding of stimuli and distance to goal at fade-out in the imbalanced velocity-ratio trials (cf. the Method section and Law et al., 1993, pp. 1186–1187). A new variable, Faster/Closer, was calculated, averaging accuracy scores across trials in which either the standard (faster but farther from the goal) or the test bird (slower and closer to the goal) had won the race. A significant main effect of this variable emerged, $F(1, 186) = 114.94$, $p = .001$, $\eta_p^2 = .382$, as well as main effects

TABLE 2
Percentage Correct (Means and Standard Deviations) According to Experimental Conditions and Age

	Age			
	4–5 Years Old	6–8 Years Old	9–10 Years Old	Adult
All trials	67.49 (9.33)	81.34 (11.11)	89.50 (6.88)	92.51 (4.09)
$\Delta t_{\text{A}} = 500$ ms	59.66 (11.91)	76.17 (13.95)	83.67 (9.67)	87.98 (6.63)
$\Delta t_{\text{A}} = 750$ ms	69.13 (11.45)	81.14 (13.96)	89.83 (10.42)	93.41 (6.94)
$\Delta t_{\text{A}} = 1{,}000$ ms	73.67 (14.92)	86.70 (12.29)	95.00 (7.72)	96.12 (6.64)
Velocity ratio 1:1	73.67 (15.35)	87.72 (12.21)	95.50 (7.93)	97.29 (5.05)
Velocity ratio 1:0.75	69.51 (13.91)	84.06 (13.30)	92.33 (8.56)	94.38 (6.49)
Velocity ratio 1:0.5	59.28 (10.20)	72.22 (15.85)	80.67 (13.72)	85.85 (9.88)
Faster = winner	48.86 (15.93)	65.64 (21.42)	79.17 (16.94)	87.21 (11.41)
Closer = winner	79.92 (16.50)	90.64 (11.36)	93.83 (6.69)	93.02 (7.48)

of age, $F(3,186) = 55.95$, $p = .001$, $\eta_p^2 = .474$, Δt_{A}, $F(2,372) = 52.18$, $p = .001$, $\eta_p^2 = .219$, and velocity ratio, $F(1,186) = 69.45$, $p = .001$, $\eta_p^2 = .272$, all of which corresponded to the ones seen in the overall analysis. In the new analysis, significant two-way interactions were found between age and gender and age and Faster/Closer as well as between all within-subject variables except Δt_{A} and velocity ratio. Finally, a weak three-way interaction between Δt_{A}, velocity ratio, and Faster/Closer was observed, $F(2,372) = 5.59$, $p = .004$, $\eta_p^2 = .029$.

The interaction between age and gender, $F(3,186) = 2.88$, $p = .037$, $\eta_p^2 = .044$, came about because, unlike age-matched boys, 6–8-year-old girls already performed as well as their 9–10-year-old gender mates. The most interesting finding was the interaction between age and the Faster/Closer variable, $F(3,186) = 8.55$, $p = .001$, $\eta_p^2 = .121$ (Figure 1): when the faster traveling bird was about to win the race, only adults attained the highest level of performance; but all age groups, except 4–5-year-old children, reached the maximum when the slower traveling bird (being closer to its goal at the time of stimulus fade-out) won. As mentioned, effects of Δt_{A} and velocity ratio were also compromised by interactions with the Faster/Closer variable (Figure 2): only in the Faster condition there was a linear decrease of accuracy with diminishing Δt_{A}, $F(2,372) = 16.70$, $p = .001$, $\eta_p^2 = .082$, and a clear effect of velocity

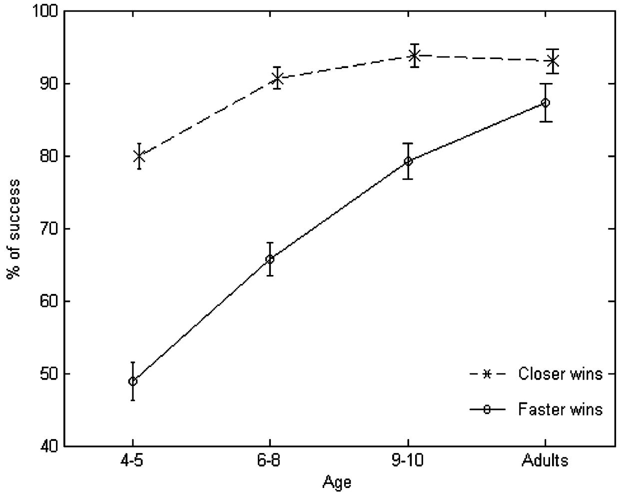

FIGURE 1 Average accuracy scores of relative t_{A} judgments, plotted separately for trials on which, at the time of stimulus fade-out, either the object closer to its goal or the one moving faster actually won the race, as a function of age (imbalanced velocity-ratio trials only). Error bars indicate standard errors of the mean.

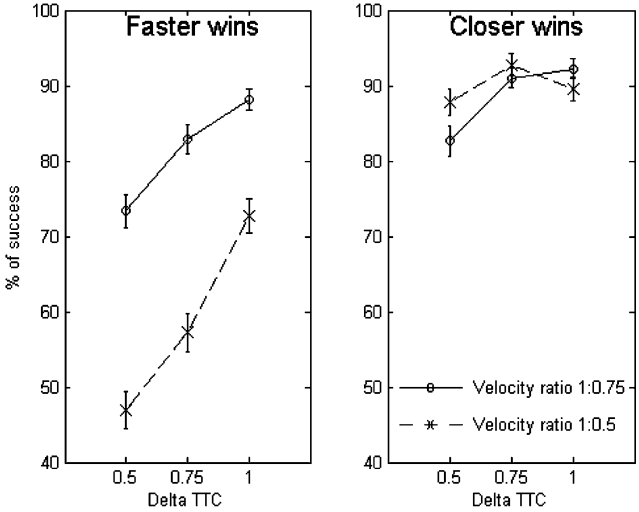

FIGURE 2 Average accuracy scores of relative t_A judgments, plotted by Δt_A and velocity ratio, separately for the Faster/Closer conditions (error bars indicate standard errors of the mean).

ratio, $F(1, 186) = 88.82$, $p = .001$, $\eta_p^2 = .323$—the larger the differences in objects' speeds, the worse participants' performance.

DISCUSSION

As expected, correctness of relative t_A judgments improved with age. That this most probably was due to a transition from a distance-based understanding of the task to a more adequate, distance-by-velocity, or time-based reading, is suggested by the divergence of "growth curves" between conditions for which a distance heuristic either promised success or implied failure (Figure 1): whenever the bird closer to its goal won the race, children as young as 6 years of age performed as well as adults; if, however, the faster moving bird overtook the slower one during the disappearance interval, only adults maintained a level of achievement close to ceiling. Indeed, as far as a distance heuristic was involved, our 6–10-year-old participants may have gotten many of their answers right for the wrong reason. On the other hand, the 4–5-year-olds cannot have applied a distance rule consistently because their scores did not exceed 80% correct on Closer trials, nor did scores drop to zero on Faster trials. We suggest that near the age of 4, children begin to take velocity information into account, although individual variation is large. Inspection of the raw data revealed that 15 of the 4–5-year-olds already performed above chance on Faster trials. At the same time, only 3 failed to score well on Closer trials (cf. Benguigui et al., 2008). We take this as evidence that the great majority even of our youngest participants did understand the task and that few if any of them reverted to a pure velocity heuristic.

In retrospect, a 1:1 velocity ratio appears to constitute a trivial Δd task—if two objects start differently clear of a common finish line but move at the same speed, the leader will always be the first to arrive—yet, Δt_A judgments of our participants were often incorrect (Table 2; cf. Law et al., 1993). It thus seems that equality (and constancy) of velocities was not always seen—even by adults (cf. Runeson, 1974). Still, it is not clear why children, the younger they are, should be less able to cope with t_A events. Hoffmann (1994), on the basis of his data, estimated discrimination thresholds for visually perceived angular velocity to amount to 0.04 rad s^{-1} ($\cong 2° s^{-1}$) for 5–8-year-old children. Assuming these calculations to be valid, our younger participants had to operate near threshold and hence may not always have noticed when our stimulus objects moved at the same or different speeds.

Although misperception of speed can explain errors, even correct identification of velocities would not suffice for correct Δt_A judgments. To this end, integration of distance and velocity information is required. Our study had not been conceived to decide whether observers conceptually combine information according to some algebraic rule (as suggested by information integration theory; Anderson, 1974; Wilkening, 1981) or whether they respond—more directly, as it were—to inherent relations between visual angles and their first derivatives (cf. Smeets, Brenner, Trébuchet, & Mestre, 1996, vs. Gray & Regan, 1999, for attempts to answer this question). As noted by J. J. Gibson (1966, 1979/1986, pp. 253–254, 258, 260–261), the dichotomy as construed may be misleading: perception, or so he suggests, should be regarded as an ongoing activity that draws on prior sensitization and attunement and is focused by education of attention. The major difference between a Piagetian or an information integration task and t_A responding resides in the handling of the time dimension. Unless tasks are presented in the format of reasoning problems (as, e.g., in Acredolo, Adams, & Schmid, 1984), visual information about distances and velocities is always (if implicitly) available as well as information about when objects start. In the more traditional paradigms, participants have to estimate comparatively long temporal durations between visible start and stop, whereas in the t_A paradigm, they have to extrapolate short durations, focusing on stop points only. This difference alone may render the discrepancies between our findings and previously reported results intelligible.

Four questions remain. Law et al. (1993) had observed a distance bias in adults, which we found only in children. In their study, the bias might have come about through characteristics of the display: authors had used numerals that moved close to the computer screen's edge; this may have induced a number of effects that need to be studied in their own right. Why did performance of our participants in the Faster condition decline with increasing velocity ratio and decreasing Δt_A? Velocity as such is irrelevant for correct t_A perception; it may rather act as a distractor (cf. Oberfeld & Hecht, 2008). In turn, a possible effect of Δt_A may have been dominated by distance information in the Closer condition, and the drop to chance performance at $\Delta t_A = 0.5$ s and velocity ratio 1:0.5 may indicate limitations of the visual system at extreme stimulus values. Eventually, why is prediction-motion more difficult than relative judgment? This may have to do with response measures: if an interceptive action task was used, performance might improve because it is often quite good even with infants (Kayed & van der Meer, 2009; van Hof, van der Kamp, & Savelsbergh, 2008). A comparative study, utilizing all three t_A paradigms, appears warranted.

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