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KNOWLEDGE ON ACCELERATED MOTION AS MEASURED BY IMPLICIT AND EXPLICIT TASKS IN 5 TO 16 YEAR OLDS

Received: 12 February 2009; Accepted: 21 February 2010

ABSTRACT. The present study aimed at investigating children's and adolescents' understanding of constant and accelerated motions. The main objectives were (1) to investigate whether different task formats would affect the performance and (2) to track developmental changes in this domain. Five to 16 year olds (N=157) predicted the distances of a moving vehicle on the basis of its movement durations on both a horizontal and an inclined plane. The task formats involved: (1) nonverbal action tasks, (2) number-based missing-value word problems, and (3) verbal judgments. The majority of participants of all age groups based their reactions in the first two task types on the assumption of a linear relationship between time and distance—which is correct for motions with constant speed but incorrect for accelerated motions. However, in the verbal judgments that tapped conceptual understanding, children from the age of 8 years onwards correctly assumed that an object rolling down an inclined plane would accelerate. The role of the task format in evoking erroneous beliefs and strategies is discussed.

KEY WORDS: cognitive development, explicit knowledge, implicit knowledge, misconception research, physics

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Previous research has shown that children already hold various beliefs about physical phenomena that develop before formal education through their experiences with the physical world (e.g. diSessa, 1993; McCloskey & Kaiser, 1984; Smith, Carey & Wiser, 1985; for an extensive review of studies on students' conceptions of physics, see Duit, 2009). Sometimes, these beliefs are in accordance with the physical laws (e.g. Baillargeon & Hanko-Summers, 1990; Clement, Brown & Zietsman, 1989; Ebersbach & Resing, 2007; Krist, Fieberg & Wilkening, 1993). For instance, preschoolers seem to understand the basic functional relationships between speed, distance, and time in motion at a constant speed (Wilkening, 1981). However, children, adults, and even experts also hold beliefs—or misconceptions—that contradict the accepted physical laws (e.g. Halloun & Hestenes, 1985a; Rohrer, 2002, 2003; Weil-Barais & Vergnaud, 1990; for an overview, see

International Journal of Science and Mathematics Education (2011) 9: 25–46

Duit, 2009). A prominent example of such misconceptions is the expectation of children and adults that objects being dropped from a moving carrier would fall straight down instead of following a parabolic path (Caramazza, McCloskey & Green, 1981; Kaiser, Proffitt & Anderson, 1985a; Kaiser, Proffitt & McCloskey, 1985b; McCloskey, 1983).

Examining students' correct or incorrect beliefs of physical phenomena is not only relevant for the domain of developmental psychology but it is also of central importance for education as these beliefs often serve as a basis for the acquisition of formal knowledge (diSessa, 1993; Elby, 2001; Hammer, 1996; Vondracek, 2003). If prior knowledge is not in line with the physical laws, it might impede the acquisition of correct concepts, in particular, as misconceptions are highly resistant towards change even if conflicting evidence is provided (e.g. Chi & Roscoe, 2002). Accordingly, they often continue to exist even after physics education (Armstrong, 1995; Mestre, 1991).

Developing an appropriate understanding of physical phenomena is tightly linked to scientific thinking, by which people—based on theory and evidence—may generate an internal model about a phenomenon including the relevant variables and how they interact (e.g. Kuhn & Pearsall, 2000; for a review, see Zimmerman, 2007). The longitudinal LOGIK study revealed that primary school children already possess basic scientific thinking skills (Bullock & Ziegler, 1999; Bullock & Sodian, 2000; Weinert, Bullock & Schneider, 1999). The children discriminated between "hypothesis" and "evidence" and often chose the relevant test to ascertain which variables would yield an effect on the dependent variable (Sodian, Zaitchik & Carey, 1991). Despite their early competencies, young children often failed to control for other variables while manipulating the focal variable. Nevertheless, these early scientific thinking skills might substantially contribute to children's understanding of physical concepts.

In the present study, we examined children's and adolescents' understanding of constant and accelerated motion. Research so far has demonstrated that people possess correct as well as incorrect beliefs concerning acceleration. On one hand, younger children were surprised if an object rolling down an inclined plane decelerated instead of accelerated (Kim & Spelke, 1992). Similarly, they looked longer if a free-falling object apparently fell with constant speed instead of an accelerated one (Friedman, 2002). In addition, adults correctly took into account both the distance and the angle of an inclined plane to judge the time an object needed to roll down it (Anderson, 1983). On the other hand, people also hold misconceptions concerning accelerated motion. For instance, secondary school students incorrectly assumed a linear relationship between travel time and distance in motion on an inclined plane (Suarez, 1977). In addition, students who had already received formal physics education exhibited the Galileo bias by assuming that all objects fall with the same rate because they ignored air resistance (Oberle, McBeath, Madigan & Sugar, 2005). There is thus a striking discrepancy between early accurate beliefs and misconceptions in the domain of physics.

One possible explanation for these discrepant findings is that different types of knowledge representations have been tapped by using different task formats (e.g. Frank, Kanim & Gomez, 2008; Krist et al., 1993; Oberle et al., 2005). In general, one can distinguish between implicit and explicit knowledge (e.g. Dienes & Perner, 1999). Implicit knowledge is often acquired through experiences, without the intention to learn. It remains largely subconscious, is hardly verbally expressible by the individual, and thus, often only becomes apparent in actions or fast decisions. Methods for tapping implicit knowledge involve, for instance, the measurement of "looking" times (Kim & Spelke, 1992) or other nonverbal judgments. Explicit knowledge, on the other hand, is mainly acquired through formal education. It is consciously accessible and verbally expressible and may be tapped, for instance, by verbal questions (Proffitt, Kaiser & Whelan, 1990) or in numerical calculation tasks (Suarez, 1977). The difference between knowledge representations might account for the discrepancy as described above. Misconceptions were often demonstrated when explicit knowledge is tapped, while implicit task formats revealed better performances (Anderson, 1983; Pine & Messer, 1999; Scherr, 2007).

The main aim of the present study was to compare the performance in tasks involving accelerated motion that was presented in different formats. In addition, the performance of different age groups was examined and compared to gain a better understanding of the conceptual development in this domain. We investigated whether children and adolescents correctly assumed that the distance covered by an object freely rolling down an incline is nonlinearly related to its travel time, while the two variables are linearly related in a situation in which an object travels at a constant speed on a horizontal plane. Three task formats were used: (1) *action tasks* requiring estimations of the distance as function of time in both constant and accelerated motion, (2) identical tasks presented as missing-value *word problems*, and (3) *verbal judgments*.

The action tasks tapped into implicit knowledge as they involved no numbers, either in the presentation of the tasks or concerning the responses. They instead required spontaneous estimations that should measure people's intuitive understanding. In addition, the realistic context of the action tasks aimed at activating experience-based, implicit knowledge that was expected to already exist in young children in the domain of motions. The missing-value word problems and verbal judgments, in contrast, tapped into different types of explicit knowledge asking for conscious, elaborated responses. The word problems—with three numerical values being presented and a fourth that had to be estimated (or calculated, if possible)—required explicit numerical responses and thereby assessed knowledge of the actual mathematical relationships between distance and time. In the verbal judgments, we explicitly posed the question whether the speed in each motion condition would increase or remain constant. This type of task format tapped into the more general understanding of acceleration and thereby provided an illuminating basis for comparisons with the performance in the more concrete implicit action tasks and explicit word problems.

Based on previous studies (e.g. De Bock, Verschaffel & Janssens, 1998; De Bock, Verschaffel, Janssens, Van Dooren & Claes, 2003; Van Dooren, De Bock, Hessels, Janssens & Verschaffel, 2005), it was expected that, in particular, the word problems, presented in a missing-value format, would provoke solutions that reflect a linear relationship between travel time and distance. This would be correct in the present study for motion on the horizontal plane, but not for motion on the inclined plane. Assuming a linear relationship between two variables is a common and robust heuristic that yields a solution quickly and without much cognitive effort (Gillard, Van Dooren, Schaeken & Verschaffel, 2009). However, this strategy is also often erroneously applied to problems that involve nonlinear relationships (e.g. De Bock, Van Dooren, Janssens & Verschaffel, 2002; Van Dooren, De Bock, Depaepe, Janssens & Verschaffel, 2003; Van Dooren, De Bock, Hessels, Janssens & Verschaffel, 2004; Van Dooren, De Bock, Janssens & Verschaffel, 2007, 2008).

METHOD

Design

The type of motion (constant versus accelerated) and travel time (1, 2, 3, 4, 5, 6, and 7 s) were varied, as within-subject variables. Task format (action tasks, word problems, verbal judgments) and age group (kindergartners;

second, fifth, and tenth graders) served as between-subject variables. Kindergartners were not presented with the word problems because of their restricted skills to read and write. Estimated travel distance served as a dependent variable that was either indicated by the participants as a certain position on the track (action tasks) or expressed as a number (word problems).

Participants completed two blocks of trials—one involving constant motion and one involving accelerated motion. In the action tasks, all travel times were presented twice within each block to enhance the reliability of the data. In the word problems, travel times were presented only once because less intra-individual variation was expected due to the higher explicitness of the task that required numerical values as responses instead of rough estimations of locations. The order of the trials was randomized within a block, while the sequence of presentation of constant and accelerated motion was counterbalanced between participants of the same age group. In the end, all children were asked to provide verbal judgments.

Participants

Participants were 28 kindergartners (11 boys, 17 girls; mean age = 5 years 7 months, standard deviation (SD) = 9 months), 44 second graders (21 boys, 23 girls; mean age = 8 years 5 months, SD = 5 months), 46 fifth graders (30 boys, 16 girls; mean age = 10 years 11 months, SD = 5 months), and 39 tenth graders (18 boys, 21 girls; mean age = 16 years 2 months, SD = 5 months) who had already been taught the concept of acceleration in the physics course. They were primarily Caucasians coming from middle class families of a medium-sized city in Germany and spoke German. The participants were recruited randomly and took part voluntarily with the informed consent of their parents.

Material

The action tasks were presented as a three-dimensional setup that resembled the two-dimensional sketches as provided in the word problems (see Appendix 1). The setting in the action tasks consisted of a 200-cm-long wooden track that was either situated evenly on the ground (constant speed) or lifted on one end generating an incline (accelerated motion). A small barrier was fixed on one end of the track, representing the starting point of the motion. It remained closed all the time.

In the constant speed condition of the action task, the track was presented horizontally. A model tractor with a small engine was placed behind the barrier. While no further information concerning the motion type was given, this tractor should represent a relatively slow, constant motion due to its engine, which was additionally emphasized by using the phrase “drive along” instead of “rolling down” as used in the acceleration condition. In the accelerated motion condition of the action task, in contrast, the track was elevated on the end where the barrier was situated. Behind the barrier, a toy trolley without engine or brakes was placed. The trolley was used to indicate free, unimpeded acceleration. The different travel times of each vehicle (i.e. 1 to 7 s) were presented by the same nonrhythmic, fuzzy noise via computer. This sound was neutral with regard to the type of motion to avoid participants inferring the type of motion just by the sound.

The word problems referred to the same problem situation as the action tasks but were presented as paper-and-pencil tests. Each trial (i.e. seven travel times each with constant versus accelerated motion) was depicted on a single page of a booklet. It showed a sketch of the setting (see Appendix 1) stating that the vehicle would need 10 s to travel 200 cm. In addition, a certain travel time, numerically expressed in seconds, was provided. In accordance with the missing-value format, the participant had to infer how far (in centimeters) the vehicle would have traveled in this trial and to write down the answer. The verbal judgments were requested at the end of each task type: either verbally (in the action tasks) or written (in the word problems).

Procedure

Participants of each age group were randomly assigned to either the action condition involving individual testing or to the word problem condition involving the testing in small groups. Both tasks were followed by the verbal judgment task.

Participants in the constant speed task in the action condition were asked to imagine that the tractor was “driving along” the track, while in the accelerated motion task participants should imagine that the trolley would “roll down” the track. In both tasks, a sound lasting 8 s was played to indicate the time it would take the tractor/trolley to cover the whole distance from the barrier until the end. When the sound was over, the vehicle would have reached the end of the track that was marked by a flag placed by the experimenter. In the following trials, the participant should imagine that the vehicle would move along the track by either “driving along” (the horizontal plane) or “rolling down” (the incline). The vehicles never really moved in the experiment. Participants had to indicate how far the vehicle would have moved—given the travel time they heard—by placing the flag at the corresponding position on the track. Afterwards, the flag was always returned to the original position.

To check for the understanding of the task, the test started with two trials including sounds of 8 and 0.5 s that were excluded from the following analyses. The participant was supposed to place the flag at the very end and almost at the beginning of the track, respectively. The experimenter gave feedback in both cases and corrected the positions if necessary. In the main test, travel times between 1 and 7 s were presented by sounds. After all trials of one type of motion were completed twice, the second block followed involving the trials of the other type of motion. To focus the attention of the participant on this change in conditions, the experimenter explained that a different task would follow now and changed the setting in front of the participant.

Participants in the word problem condition received a paper-and-pencil test on both types of motion (see Appendix 1). The seven travel times were presented in random order and the participants were encouraged to estimate the distances if they were not able to calculate them.

In the end, all participants completed the verbal judgment. Participants in the action condition saw each task setting (constant versus accelerated) again and were asked to imagine that the vehicle would really drive along/roll down the track. They were asked to decide for each vehicle as to whether it would become faster or travel with the same speed. In the word problem condition, the booklet showed at the end a sketch of each of the two settings on two separate pages, together with the written question as to whether each vehicle would become faster or would travel with the same speed on the track. The answers had to be marked. The sequence of response alternatives was randomized.

RESULTS

General Effects on the Distance Estimations in Action Tasks and Word Problems

Checking for general effects on the distance estimations, a 7 (travel time: 1, 2, 3, 4, 5, 6, and 7 s)×2 (motion type: constant versus accelerated)×2 (task format: action task versus word problem) analysis of variance

(ANOVA) was computed separately for each age group. The factor “task format” did not apply for kindergartners who only completed the action tasks. In the following, Greenhouse–Geisser values including the adjusted degrees of freedom instead of Wilks' lambda will be quoted to indicate within-subject effects if sphericity could not be assumed (for example, see Hays, 1994).

The analyses revealed an effect of travel time in all four age groups (kindergartners: $F(3.6, 87.4) = 111.19$, $\eta^2 = 0.82$; second graders: $F(3.2, 126.2) = 145.00$, $\eta^2 = 0.78$; fifth graders: $F(3.3, 120.3) = 481.42$, $\eta^2 = 0.93$; tenth graders: $F(1.7, 64.5) = 588.69$, $\eta^2 = 0.94$; all $p\text{s} < 0.001$) with repeated contrasts, indicating longer distance estimations for longer travel times ($p\text{s} < 0.010$). Only kindergartners failed to differentiate between 5 and 6 s. Neither the motion type nor the task format yielded main effects in any age group, $p\text{s} > 0.14$. For second graders, there was an interaction between travel time and task format, $F(3.2, 126.2) = 8.36$, $p < 0.001$, $\eta^2 = 0.17$, with the action task yielding a larger effect of time than the word task. No other effects were significant (for mean estimations, see Appendix 2).

Action Tasks

To unravel whether participants in the action tasks assumed that the speed remained constant or the motion accelerated, we calculated separate ANOVAs including polynomial contrasts for each age group and motion type with travel time as an independent measure and distance as a dependent measure. For the constant speed condition, a linear trend became significant in all age groups ($p\text{s} < 0.001$). For kindergartners, a quadratic trend also yielded significant results ($p = 0.015$). In the accelerated motion condition, a linear trend became significant in all age groups ($p\text{s} < 0.001$) while for kindergartners and second graders a quadratic trend also yielded significant results ($p\text{s} < 0.01$). The fact that a linear trend as the simpler model explains the data similarly well as more complex polynomial trends can be taken as an indicator that distance estimations for the inclined plane were rather linear.

To rule out artifacts due to averaging, the data of the action tasks were also analyzed on an individual level based on the repeated measurement data. Individual curve estimations were run as polynomial contrasts were not suitable due to the small number of data points. As a linear model is a special case of a quadratic model that, therefore, always explains at least as much variation as a linear model, a more diagnostic power model was fitted to the estimations of each participant separately for each motion type. Mean R^2 values, as fit indices of a linear model, ranged between 0.63 and 0.89 (see Appendix 3). Across both motion conditions, there were two kindergartners for which a linear model (as well as a power model) failed to reach significant fit ($p > 0.10$).

Comparing the fits of both models, paired *t* tests on the residuals, transformed into absolute values, were computed for each participant. The alpha level was raised up to 10% to account for decreased power in individual testing. In both motion conditions—constant and accelerated—a linear model fitted individual estimations either significantly better or similarly well as a power model. There was one kindergartner and one fifth grader in the constant speed condition as well as one second grader and one tenth grader in the acceleration condition for whom a power model yielded a significantly better fit. Individual analyses thus confirmed the finding on the group level that distance estimations were linearly related to travel time in both motion conditions.

Word Problems

The numerical responses of the second, fifth, and tenth graders in the word problems were also analyzed using polynomial contrasts for group data and curve estimations for the individual data. On the group level, for both the constant speed and the acceleration conditions, a linear trend became significant in all age groups (*p*s < 0.001). For second graders in the acceleration condition, a cubic trend yielded a significant result too, $p = 0.022$.

Next, individual curve estimations were calculated. Mean fit indices of a linear model ranged between 0.85 and 0.97 (see Appendix 3). A linear model yielded a significant fit for almost all participants in both motion conditions, except for six second graders and two fifth graders in the constant speed condition and five second graders and one fifth grader in the acceleration condition. However, a power model also failed to explain sufficient variation in these cases except for the two second graders, indicating rather unsystematic responses.

Comparing the absolute deviations of the individual estimations from each model revealed that a linear model fitted either significantly better (*p*s < 0.10) or similarly well as a power model in both motion conditions. For no participant did a power model yield a significantly better fit, suggesting that also the word problems were solved by assuming constant speed in both motion conditions.

Verbal Judgments

The proportion of participants who correctly assumed constant speed for motion on the horizontal plane and acceleration for motion on the inclined plane was similar in the two motion conditions (i.e., constant versus accelerated: kindergartners, 57% versus 61%; second graders, 61% versus 68%; fifth graders, 76% versus 83%; tenth graders, 97% versus100%, respectively).

Chi-square tests indicated that kindergartners in both motion conditions and second graders in the constant speed condition failed to perform above chance (Fisher's exact test, $p > 0.05$). The remaining groups made significantly more correct verbal judgments than expected by chance (constant speed: fifth graders, $\chi^2(1, n = 46) = 12.52$, $p = 0.001$; tenth graders, $\chi^2(1, n = 39) = 35.10$, $p < 0.001$; acceleration: second graders, $\chi^2(1, n = 44) = 5.82$, $p = 0.023$; fifth graders, $\chi^2(1, n = 46) = 19.57$, $p < 0.001$; tenth graders, 100% correct judgments). In addition, the proportion of correct verbal judgments increased with age in both the constant speed and the accelerated conditions [$\beta = 0.28$ (0.07), Wald (1) = 15.96, odds ratio = 1.32 and $\beta = 0.34$ (0.09), Wald (1) = 15.59, odds ratio = 1.40, respectively; ps < 0.001].

DISCUSSION

The main objective of the present study were: (1) to investigate the performance of children and adolescents in tasks involving constant and accelerated motion under different task formats and (2) to track the developmental changes of knowledge in this domain. We found that the task format significantly affected the performance of children and adolescents. While from the second grade onwards, the majority of participants correctly declared in their verbal judgments that the speed of the vehicle on an inclined plane increases but remains constant on a horizontal plane, most participants' responses in the word problems and the action tasks suggest inadequate beliefs concerning accelerated motion. Participants appeared to base their inferences concerning the covered distance on the assumption of constant speed both in the horizontal and in the inclined plane conditions, which is wrong for the latter case. Accordingly, the main developmental progress was found in the verbal judgments, while the performance for action tasks and word problems barely improved between the ages of 5 and 16. In the following, the findings concerning the word problems and action tasks will be discussed in more detail, followed by a comparison of the performance in all three task types.

Word Problems

The large majority of participants in the present study used proportional reasoning strategies to solve the word problems, independently of the type of motion (i.e., constant versus accelerated). They thus assumed a linear relationship between distance and travel time. This is in line with previous findings (e.g., De Bock et al., 1998; Van Dooren et al., 2005) showing that a missing-value format provokes the use of proportional reasoning.

Furthermore, the performance in the word problems revealed no significant developmental change with age: 16-year-old tenth graders were almost as likely as 8-year-old second graders to solve the word problems in both motion conditions proportionally. This suggests that the proportional strategy emerges early and remains robust across development, though the tenth graders had already received formal instruction on accelerated motion in school. How might the predominance of the proportional strategy be explained? First, this strategy does not require much cognitive effort, but may nevertheless lead, in many cases, to good approximations of the correct solution. The correct formula for the relationship between distance and time in accelerated motion, in contrast, is mathematically more complex and demanding: $s = 0.5a \times t^2$ with s as distance, a as acceleration, and t as time. It is known from previous research that students often misinterpret quadratic formulas and draw wrong conclusions concerning their graphical appearance (Ellis & Grinstead, 2008). In this respect, the proportional strategy is just easier to apply. Second, the central bias in the present study—the assumption of constant speed on an inclined plane—might be traced back to a so-called common sense belief that objects in free fall travel with constant speed (Champagne, Klopfer & Anderson, 1980; Halloun & Hestenes, 1985a; Shanon, 1976). The belief of constant speed is not as odd as it might appear at first glance, as it reflects in fact, well-accepted historic views of leading scientists, such as Aristotle (diSessa, 1982). It is also known that even physics experts exhibit difficulties in adequately interpreting the concept of acceleration (Reif & Allen, 1992). The assumption of constant speed in free fall might have been applied to the motion on an inclined plane too, resulting in the belief of a linear relationship between travel distance and time. Common sense beliefs that contradict the actual physical laws may not only impair performance in problem solving, but might also hamper the acquisition of correct knowledge (Halloun & Hestenes, 1985b).

Action Tasks

While the poor performance in the word problems confirmed our hypothesis so far, the performance in the action tasks that were used to assess implicit knowledge did not. We had assumed that children collect many experiences with regards to acceleration in their daily life (e.g. rolling a model car down an incline or coasting down a hill), which should contribute to relatively accurate implicit knowledge on accelerated motion. However, participants of all age groups based their estimations in the action tasks, on the assumption of constant speed in both the constant and accelerated motion conditions.

Several reasons might account for the unexpectedly poor performance in the action tasks. First of all, the fact that people collect experiences in relation to a certain physical phenomenon in their everyday lives does not imply per se that their implicit knowledge accords with the physical laws (e.g., see Freyd & Jones, 1994). In fact, people sometimes apply incorrect implicit strategies if they appear useful and effective, that is, for instance, in situations that require fast and imprecise predictions (Gillard et al., 2009; Kozhevnikov & Hegarty, 2001).

Second, participants in the action tasks (as well as in the word problems) might have applied a simplified strategy that accounted only for one relevant variable (i.e. the travel time) that was varied with equidistant intervals, but not for the second variable (i.e., the orientation of the plane). Previous research on physical phenomena demonstrated that people may provide relative adequate dynamic judgments when only a single variable had to be considered, but performed significantly poorer if they had to take into account multiple variables (Gilden & Profitt, 1989; Proffitt & Gilden, 1989). Moreover, they used heuristics that were based on a single dimension of information that was more salient (Frank et al., 2008; Trowbridge & McDermott, 1980). Participants in the present study thus might have ignored the orientation of the plane and only considered the linearly graduated travel time in their estimations, which was perhaps perceptually more salient.

A third potential reason for the poor performance in the action tasks refers to the reaction that was required by the task. It has been demonstrated that adults perform better in judging the possibility of visually presented physical events than in actually reasoning about such events (e.g., Bertamini, Spooner & Hecht, 2005; Kaiser et al., 1985a,b; McCloskey, 1983; Shanon, 1976). Even younger children discriminated between possible and impossible accelerated motion that was presented visually (Friedman, 2002; Kim & Spelke, 1992). The action tasks in our study required concrete reasoning in relation to the distance. This particular property might also account for the fact that children and adolescents performed relatively poorly. In verbal judgments that involved the simple decision of which event was impossible (i.e. constant speed versus acceleration), their performance was significantly better.

Finally, one might also hypothesize that the superficial similarity of both motion conditions in this study may have enhanced the activation of the same implicit belief involving constant speed, even if the situations actually differed. We used, in the action tasks, the same noisy sound to indicate the travel duration to prevent participants from inferring the type of motion solely from the sound. Aiming at generating a neutral indicator of duration, this sound was neither rhythmic nor was it said that it was the actual sound of the vehicle. Instead, it only served to represent certain travel times in a nonquantitative manner. However, if the participants used this sound only to infer the motion type, they would not have discriminated between the two motion types in the verbal judgments.

Verbal Judgments

Participants reflected a considerably better conceptual understanding of acceleration in the verbal judgments than in both the action tasks and word problems. Moreover, most participants did not realize that their verbal judgments contradicted their responses in the action tasks and word problems. Although participants were not systematically asked for this, there was almost no participant explicitly stating in the end, after providing the correct verbal judgment concerning acceleration, that he or she provided wrong responses earlier in the other task. It thus seemed that the participants possessed a correct global understanding of acceleration while they made rather inconsistent inferences in the concrete tasks.

The striking discrepancy between the performances in the different tasks might be related to the theoretical framework involving the assumption of three different levels of knowledge, as put forward by Reed & Saavedra (1986). The lowest level holds specific knowledge that refers to concrete referents. The next level is more abstract, allowing the detection of trends in specific data. The highest level comprises principles and generalizations that allow for the explanation and prediction of phenomena. This framework relates also to the model of diSessa (1993) who proposed a continuum between the superficial, phenomenological understanding of familiar phenomena on one end and the elaborated understanding of fundamental physical laws on the other. The action tasks and word problems of the present study could be assigned to the second level of the model of Reed and Saavedra, comprising knowledge that supports the inference of underlying trends or rules in a set of events. The judgment task, in contrast, seems to be related to the highest level of principles as this task taps the abstract understanding of acceleration. Our findings confirm the assumption of different knowledge representations that are not necessarily consistent and may simultaneously contain discrepant beliefs. However, while the theoretical approaches, as described above, suggest a hierarchical organization of knowledge that becomes more and more abstract, our findings contradict this idea. It seems possible that a person might generate a global understanding of a physical phenomenon, but at the same time fail to apply this conception to concrete problems. A similar effect was demonstrated by Halloun & Hestenes (1985a), showing that students could annunciate Newton's laws but failed in applying them to a particular problem. In addition, Cahyadi & Butler (2004) demonstrated that students performed better in problems including the motion of vertically moving balls if the situation had to be considered under idealized conditions (i.e. without air resistance) than under real-world conditions. In the domain of counting, Gelman & Meck (1983) provided some evidence that children might acquire the more general principles before the actual skills. While these children still make errors in counting due to a lack of skills, they are able to detect counting errors. Similarly, one could assume that the children in our study possess the general principle of acceleration before they can actively apply it to make concrete forecasts on the action or word task level. These findings emphasize the fact that a deep understanding of scientific concepts requires not only general but also case-specific knowledge. Even if people have the factual knowledge that an object accelerates, ancillary knowledge is required that specifies in which situation and how this factual knowledge might be applied (Oberle et al., 2005; Reif & Allen, 1992).

The results of the present study have important implications for teachers and education. First, the task format may significantly affect the performance of students. As shown here, task characteristics may obscure correct conceptual knowledge by activating inappropriate strategies. Missing-value word problems, in particular, strongly provoked proportional reasoning, even when situations actually did not involve proportional relationships. Second, and related to the first issue, there is a strong tendency to assume proportionality in a variety of problems. This behavior may be attributed, among others, to the mathematical simplicity of proportional relationships as well as to their extended exercise during the mathematics curriculum. Given the fact that relatively young children are also already able to grasp nonproportional relationships, as they appear for instance in exponential processes (Ebersbach, Van Dooren, Goudriaan, & Verschaffel 2010; Ebersbach, Van Dooren, Van den Noortgate & Resing, 2008; Ebersbach & Wilkening, 2007), it might be possible that formal, explicit instruction on nonlinear phenomena, such as the relation between time and distance in accelerated motion, may occur too late—or at least it has to address pupils' prior knowledge much more explicitly. The earlier confrontation and discussion of nonlinear models in school might prevent the establishment of the concept and create a fixation on rigid proportional strategies. Third, physics education has to develop students' sensitivity towards the terminology of concepts to prevent confusion, such as the ones that frequently appear between velocity and speed or between speed and position (Trowbridge & McDermott, 1980, 1981). Fourth, it is also important to teach not only the general, abstract concept but also to build and use a repertoire of case-specific knowledge that may be accumulated, organized, and applied in corresponding problems (Hestenes, 1992; Reif & Allen, 1992). The integration of such experientially based, phenomenological knowledge that refers to concrete situations of a certain phenomenon into a global concept is central, as erroneous performance in physics problems can often be traced back to the use of distinct and inconsistent ideas (diSessa, 1993; White, 1983).

Future research should aim at overcoming the strong reliance on the proportional strategy, for instance, by directly confronting pupils with their contradictory beliefs. In terms of the conceptual change approach (e.g. Carey, 1985; Vosniadou, 1994; Vosniadou & Verschaffel, 2004), the conscious realization of this conflict might initiate a fundamental reorganization of knowledge resulting in appropriate models for both constant and accelerated motion. It is, however, important to introduce this conflict as a meaningful and relevant one for students—otherwise, cognitive conflict will hardly yield a positive effect on learning (see also Limón, 2001). In addition, the task presentation and instruction could be adjusted to provoke more analytical reasoning and, thus, a better performance. Finally, the direct observation of acceleration in this particular context could help to dispel the misconceptions described (see also Reed, 1984; Reed & Saavedra, 1986).

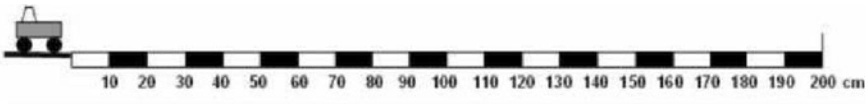
The present study can thus only be seen as one attempt to investigate the conceptual understanding of accelerated motion of children and adolescents. To gain broader insights, it could be illuminating to use in-depth interviews to uncover not only their superficial beliefs, but also their underlying argumentation and rationales for these beliefs. If the roots of the misconceptions are known, they might be easier to dismantle. Furthermore, one might think of designing the action tasks in a more realistic way to enhance the similarity with everyday experiences of accelerated motion.

ACKNOWLEDGEMENTS

The Swiss National Fund is gratefully acknowledged for supporting this research by providing the first author a research fellowship at the University of Leuven, Belgium.

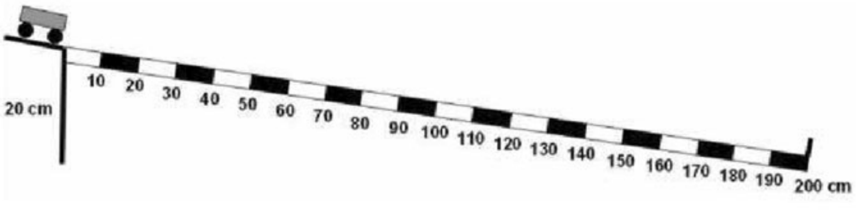
APPENDIX 1

Example of two items of the word problems (constant and accelerated motion).



The car rides 200 cm within 10 seconds.

How far does it ride within 1 second? Answer: .... cm

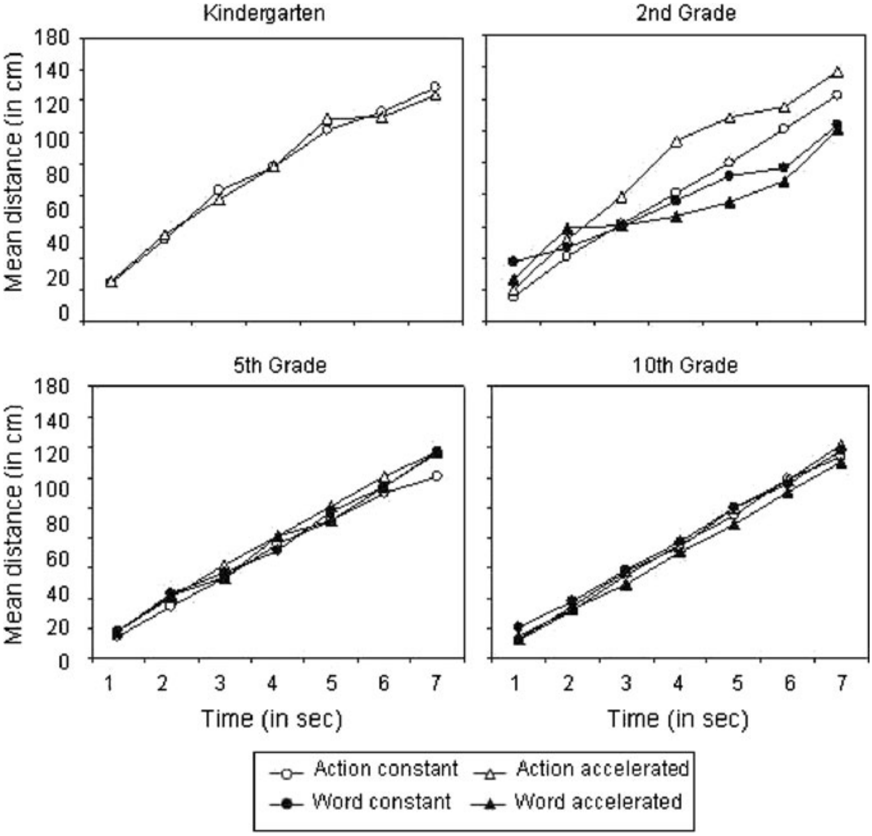


The trolley rolls 200 cm within 10 seconds.

How far does it roll within 1 second? Answer: .... cm

APPENDIX 2

Mean estimated distances in the action tasks and word problems for constant and accelerated motion, separately for each age group.



APPENDIX 3

TABLE 1

Mean R^2 values as fit indices of the linear model (individual curve estimations)

		Type of motion	
Task format	*Age group*	*Constant*	*Accelerated*
Action tasks	Kindergarten	0.63 (0.17)	0.63 (0.16)
	Second grade	0.77 (0.15)	0.76 (0.11)
	Fifth grade	0.87 (0.06)	0.89 (0.06)
	Tenth grade	0.86 (0.11)	0.87 (0.10)
Word problems	Second grade	0.85 (0.15)	0.91 (0.11)
	Fifth grade	0.93 (0.13)	0.90 (0.16)
	Tenth grade	0.97 (0.08)	0.96 (0.11)

Values in parentheses indicate SDs

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