Children’s reasoning about rolling down curves: Arguing the case for a two-component commonsense theory of motion

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Abstract

Within the discussion of the development of commonsense theories of motion recent research has established that throughout middle childhood reasoning about motion down inclines changes with increasing age. To investigate this shift in more detail this study investigated 5- to 11-year-old children's understanding of motion down curved slopes, addressing the changing interaction of horizontal and vertical dimensions along a single trajectory. This allows to examine more closely the notion of children's ability to integrate horizontal and vertical motion knowledge as opposed to encountering a third conceptual reasoning component within the commonsense theories framework. Children (*N* = 115) participated in one of three motion conditions – straight incline, convex incline and concave incline. They predicted motions of two balls (heavy versus light) down the slopes, addressing comparisons between sections of the trajectory (shallow, intermediate and steep incline). The results suggest that children do appear to integrate information about horizontal and vertical motion when judging motion down inclines, arguing for a two-component commonsense theory system. The results are situated within the context of conceptual knowledge structures and potential implications for educational practice are discussed.

Key words: Curvilinear motion; commonsense theories; information integration; primary science.

1. Introduction

Predictions of motion events are likely based on reasoning whereby mental models are consulted, which act as prototypes of conceptual models, such as the behaviour of objects in free fall, and help a person simulate similar behaviour with new objects (Jonassen, 2003; Nersessian, 2008, 2013). In the field of scientific conceptions there are, broadly speaking, two main viewpoints on how knowledge exists and therefore what mental modelling of physical events is based on. The first view posits that scientific beliefs are tied to and constrained by ontological and epistemological presuppositions that lead to coherent belief structures – knowledge exists as theory (Vosniadou, 2002a, b, 2007, 2013; also see e.g. Chi, 2013). The second view argues that knowledge is not embedded within such theoretical frameworks. Rather, each basic scientific concept is loosely connected with others within an unstructured conceptual network – knowledge exists in elements that work together in larger, more complex systems appropriate to the scientific domain (diSessa, 2002, 2006, 2013). A third standpoint, however, suggests these two approaches do not have to be mutually exclusive – knowledge could instead exist as an integration of both theory and elements; a conceptual system which consists of different kinds of knowledge elements, such as beliefs, presuppositions and mental models (Brown & Hammer, 2013; Özdemir & Clark, 2007).

Based on the ubiquity of dynamic events in the everyday environment it has been reasonably well-established that children develop so-called commonsense theories of motion that help them process information and make inferences about how events should take place (Bliss & Ogborn, 1988; Bliss, Ogborn, & Whitelock, 1989; Hast & Howe, 2013a; Howe, 1998; Ogborn, 1985). Within this framework of commonsense theories there is a demarcation between reasoning about events involving downward motion and about events involving motion along horizontals. This differentiation is based on the relationship between support and falling – if an object has support it does not fall and if it does not have support it falls, until it is supported. Evaluating the two individually, for instance under consideration of object mass, it is clear to see that children think differently about objects falling down, believing an object should fall faster because it is heavier

(Baker, Murray, & Hood, 2009; Chinn & Malhotra, 2002; Hast, 2014; Hast & Howe, 2012, 2013a; Nachtigall, 1982; Sequeira & Leite, 1991; van Hise, 1988) and about objects rolling along even surfaces, believing that lightness of an object means it will be faster (Hast, 2014; Hast & Howe, 2012, 2013a; Inhelder & Piaget, 1958). Although there is some fluctuation across age groups (cf. Hast, 2014) these predictions appear to be rather stable across age groups, indicating that relevant knowledge differentiation – although incommensurate with scientific views – occurs early on.

However, motion down inclines presents a problem here – it includes both support and a significant element of downward motion, depending on the degree of incline. Recent research has expanded on the commonsense theory development by shedding light on how children reason about motion down inclines. Developmental changes were noted in this small body of work, indicating that younger children were more likely to suggest that a light ball should roll down a slope faster than a heavier ball whilst older children predicted the inverse (e.g. Hast, 2014; Hast & Howe, 2012, 2013a). These findings were noted alongside results from the same children which showed that with increasing age they would predict the light ball to roll faster along a horizontal, and the heavy ball to fall faster, in line with the knowledge differentiation process. This raises the question whether the three motion dimensions are governed by a common theory, by separate elements, or by a mix of the two. By examining the role of changing inclines, where at points the incline resembles more closely either fall or horizontal motion than at other points the representation of knowledge in relation to the two components can be examined in more detail. A key role in explaining the observed age-related shift for motion down inclines alongside seemingly stable predictions for horizontal motion and fall seems to be played by surface support and how salient this support is when reasoning about motion down inclines (Hast & Howe, 2013a). However, further research was deemed necessary to strengthen this view.

Initial answers are provided by work evaluating how children respond to changing incline angles of slopes and their understanding of the effect such changes have on objects rolling down these slopes. Past studies have, for instance, evaluated the impact that incline angle changes have on the distance objects travel after rolling down and leaving the slope (Ferretti, Butterfield, Cahn, & Kerkman, 1985; Inhelder & Piaget, 1958), or the impact of changes on object speed along the slope (Hast & Howe, 2013a; Howe, Tolmie, & Rodgers, 1992). Collectively this body of research indicates that children understand how changing the variable incline angle affects the variable object. However, this literature merely focuses on final outcomes of motion in response to incline changes rather than on intermittent outcomes and thus limits the insight into children's reasoning processes. One way of circumventing this issue of before-and-after comparisons is by examining motion along continuously changing slopes. This scenario can be found in curved inclines.

The aspect of reasoning about curvilinear motion is not uncharted territory. Several available studies in the literature depict investigations of this topic (e.g. Catrambone, Jones, Jonides, & Seifert, 1995; Cooke & Breedin, 1994; Kaiser, Jonides, & Alexander, 1986a; Kaiser, McCloskey, & Proffitt, 1986b; Kallai & Reiner, 2010; McCloskey, Caramazza, & Green, 1980; McCloskey & Kohl, 1983). Trying to make use of these studies to explore the topic at stake is, however, not possible for two reasons. Firstly, Kaiser et al.'s (1986b) study is the only one in this collection that provides insight into children's knowledge; all remaining studies focus exclusively on adults. Secondly, even this one study does not address motion *along* the curvilinear pathway but merely considers the trajectory an object would follow after exiting a curved tube. As such, there is a clear lack of useful data regarding children's predictions about motion along curvilinear pathways.

Yet it is precisely such data that would serve useful in trying to understand the age-related shift outlined above and may, as a consequence, help explore in more detail the development of commonsense theories of motion throughout childhood. In particular, such information can be used to evaluate whether children hold three separate beliefs about object motion – one for horizontal motion, one for fall and one for motion down inclines – or whether children's beliefs within their system of a commonsense theory are based on horizontal and fall only, with incline motion resulting from an interaction of the two. Curved pathways offer continuous change in the degree of support offered by the slope, from very shallow to very steep inclines. Given the significant role played by object mass in particular and its established effect on incline motion reasoning (e.g. Hast & Howe, 2012) the present study sought to address how children manipulate their reasoning of motion down curvilinear slopes under consideration of having to compare heavy and light objects. Specifically, to examine the foundation in knowledge representation, if knowledge exists as theory then all incline judgements should be highly similar to one another. If based on knowledge in pieces then judgements should vary according to the extent of vertical and horizontal dimension input.

2. Method

2.1 Participants

Participants were recruited from state primary schools located in the Greater London area. A total sample of 115 children (56 girls) was selected. This included 30 Year 1 children (15 girls; age *M* = 6.35 years, *SD* = 0.31), 28 Year 2 children (13 girls; age *M* = 7.37 years, *SD* = 0.28), 29 Year 4 children (14 girls; age *M* = 9.32 years, *SD* = 0.26) and 28 Year 6 children (14 girls; age *M* = 11.22 years, *SD* = 0.35). For each age group an approximately equal number took part in three conditions as outlined below.

2.2 Design and materials

The materials consisted of two transparent plastic tubes. One of the tubes was curved and could be positioned either with the curvature going *outwards*, with the shallow segment appearing first along the trajectory (see Figure 1a; referred to as the "outward" group), or going *inwards*, with the steep segment appearing first (see Figure 1b; referred to as the "inward" group). The other tube was straight (see Figure 1c; referred to as the "straight" group). Both tubes had a trajectory length of 100 cm. The straight tube's internal diameter was 6.5 cm and the curved tube's was 5.5 cm. Each tube was divided into three sections with endpoints A, B and C. Markings along the tube exteriors were placed at 33 cm (Point A) and at 67 cm (Point B) from starting point. Point C was the tube exit so was not explicitly marked. For the "outward" tube, Point A represented the end of the shallow segment and Endpoint C the end of the steep segment. For the "inward" tube, Point A represented the end of the steep segment and Endpoint C the end of the shallow segment. For both tubes, Point B represented the end of the middle segment which corresponds to the equivalent of all three segments in the "straight" tube. Two test balls were used; one was a bright pink standard table tennis ball and one was a dark green solid glass marble. Both balls were approximately 4 cm in diameter, but the table tennis ball weighed approximately 3 g, while the marble weighed approximately 75 g. In addition, a standard squash ball (approximately 4 cm in diameter) was used as practice ball.

[insert figure 1 about here]

2.3 Procedure

Children were worked with on an individual basis. The task was run in a quiet room in the child's school, separate from the classroom activities. Each child only contributed to one of the three tube presentation modes as shown in Figure 1, with equal distributions across age groups and gender for each mode. To begin, the researcher presented one of the three tubes and the practice ball to the child. The researcher held the tube in one hand to create a downward slope and the practice ball in the other hand, at the entry to the tube. The child was asked to explain what would happen if the ball were let go from that position. After providing a response the child was allowed to demonstrate this by releasing the ball into the tube. This control question was to ensure children understood the basic function of a slope as well as to familiarise them with the tube to be used in test trials. The researcher then removed the practice ball and introduced the two test balls at the same time, which were both given to the child but the child was not given any further information about the balls. After a brief familiarisation period the researcher again held the tube to create the same downward slope and indicated Point A on the exterior of the tube to the child. The child was asked to state whether, if rolling down the tube, one of the two balls would be faster or whether they would be as fast as each other to reach that point. If the child predicted that both would reach Point A at the same time the child was asked to provide a justification. If one of the balls was predicted to reach Point A first, the child was asked to indicate which of the two balls would be faster and why. The procedure was then repeated for Points B and C. The entire task lasted approximately 15 minutes per child.

3. Results

All children passed the control question for the practice ball so data from all children qualified for analysis. All justifications provided by the children referred to mass. Very rarely children also referred to texture but this always occurred in conjunction with mass and the analysis focused upon mass alone. For purposes of analysis, mass was broken down into 'heavy' and 'light'. No misattribution of mass was observed; no child stated the table tennis ball was heavier than the glass marble or vice versa. Scores were allocated by addressing whether the heavy or the light ball was predicted to be faster, or whether they would both have the same speed. In each case a score of 1 or 0 was allocated. For example, if a child predicted the heavy ball to roll down faster a score of 1 was given to "heavy faster" and a score of 0 for each of the other options. Mean scores were analysed using Friedman's ANOVAs and post hoc Wilcoxon signed-rank tests, with Bonferroni corrections applied (all significance thresholds $p \leq 0.025$). Effects of condition were analysed with Kruskal-

Wallis tests and post hoc Mann-Whitney tests. Effects of age were analysed with Kruskal-Wallis tests and post hoc Jonckheere-Terpstra tests. Effects of gender were analysed with Mann-Whitney tests. No significant gender effects were found, therefore this factor is not considered further. All data were analysed using SPSS 21.

3.1 Middle tube sections

Figure 2 shows the mean scores for the middle tube sections for the "outward" tube and for the "inward" tube as well as the average score for the "straight" tube, separated by age group. To establish a benchmark against which to evaluate the impact of incline degrees the "straight" tube condition is evaluated first. Looking at overall distributions of predictions, there was significant overall variation among mean scores for heavy-faster, light-faster and same-speed choices here, $\chi^2(2, n = 38) = 28.00$, $p < 0.001$. There was no overall significant preference for predicting either ball to be faster. However, heavy-faster predictions ($M = 0.63$, $SD = 0.44$), $T = 5$, $r = -0.78$, and light-faster predictions ($M = 0.36$, $SD = 0.43$), $T = 4$, $r = -0.62$, were both significantly more frequent than choosing the same-speed option ($M = 0.01$, $SD = 0.05$). There were no significant variations across the three sub-sections of the "straight" tube, indicating similar data patterns. There was significant variation with age for heavy-faster predictions, $H(3) = 14.12$, $p < 0.05$, with mean scores increasing with age, $J = 396$, $z = 3.60$, $r = 0.58$. There was also significant variation with age for light-faster predictions, $H(3) = 14.28$, $p < 0.05$, with mean scores decreasing with age, $J = 142$, $z = -3.67$, $r = -0.60$. There was no significant interaction of age with mean scores for same-speed predictions.

[insert figure 2 about here]

For the two middle tube sections there was significant overall variation among mean scores for heavy-faster, light-faster and same-speed choices, $\chi^2(2, n = 77) = 40.86$, $p < 0.001$. Heavy-faster predictions ($M = 0.57$, $SD = 0.50$) were not significantly more frequent than light-faster predictions ($M = 0.43$, $SD = 0.50$), but light-faster predictions were significantly more frequent than same-speed predictions ($M = 0.00$), $T = 6$, $r = -0.65$. None of the mean scores differed significantly between the two tube conditions. However, age-related shifts were noted. There was significant variation with age for heavy-faster predictions, $H(3) = 20.16$, $p < 0.001$, with mean scores increasing with age, $J = 1530$, $z = 4.45$, $r = 0.51$. There was also significant variation with age for light-faster predictions, $H(3) = 20.16$, $p < 0.001$, with mean scores decreasing with age, $J = 693$, $z = -4.45$, $r = -0.51$. There was no significant variation with age for same-speed predictions. Comparing them to the mean scores for the “straight” tube shows no significant differences.

3.2 Steep tube sections

Figure 3 shows the mean scores for the steep tube sections for the “outward” tube and for the “inward” tube, separated by age group. There was significant overall variation among mean scores for heavy-faster, light-faster and same-speed choices, $\chi^2(2, n = 77) = 72.18$, $p < 0.001$. Heavy-faster predictions ($M = 0.78$, $SD = 0.42$) were significantly more frequent than light-faster predictions ($M = 0.19$, $SD = 0.40$), $T = 5$, $r = -0.59$. Light-faster predictions, in turn, were significantly more frequent than same-speed predictions ($M = 0.03$, $SD = 0.16$), $T = 3$, $r = -0.36$. None of the mean scores differed significantly between the two tube conditions. There were no significant interactions of age with mean scores for any of the predictions. In contrast to the mean scores for the middle sections, mean steep section scores for heavy-faster predictions were significantly higher, $T = 3$, $p < 0.05$ $r = -0.34$, and light-faster predictions were significantly lower, $T = 3$, $p < 0.05$ $r = -0.37$. Same-speed predictions did not differ significantly.

[insert figure 3 about here]

3.3 Shallow tube sections

Figure 4 shows the mean scores for the shallow tube sections for the “outward” tube and for the “inward” tube, separated by age group. There was significant overall variation among mean scores for heavy-faster, light-faster and same-speed choices, $\chi^2(2, n = 77) = 57.22$, $p < 0.001$. Light-faster predictions ($M = 0.70$, $SD = 0.46$) were significantly more frequent than heavy-faster predictions ($M = 0.30$, $SD = 0.46$), $T = 4$, $r = -0.40$. Heavy-faster predictions, in turn, were significantly more frequent than same-speed predictions ($M = 0.00$), $T = 5$, $r = -0.55$. None of the mean scores differed significantly between the two tube conditions. There were no significant interactions of age with mean scores for any of the predictions. In contrast to the mean scores for the middle sections, mean shallow section scores for heavy-faster predictions were significantly lower, $T = 3$, $p < 0.05$ $r = -0.39$, and light-faster predictions were significantly higher, $T = 3$, $p < 0.05$ $r = -0.39$. Same-speed predictions did not differ significantly.

[insert figure 4 about here]

4. Discussion

The present study sought to examine more closely the development of commonsense theories of motion, in particular the aspect of motion dimension integration, with particular reference to object mass. This was done by addressing children’s predictions of heavy and light balls rolling down curved and straight slopes, providing insight into how children reason about trajectories with continuously changing amount of surface support. In doing so the research adds to a number of studies on curvilinear motion reasoning (Catrambone et al., 1995; Cooke & Breedin, 1994; Kaiser et al., 1986a; Kaiser et al., 1986b; Kallai & Reiner, 2010; McCloskey et al., 1980; McCloskey & Kohl, 1983) and expands on the exploration of how commonsense theories of motion develop throughout childhood by addressing the reasoning about continuous change of support within a single motion trajectory. The overall findings strengthen the current viewpoint that motion down inclines is not a third form of motion but the result of an interaction of conceptions about horizontal and fall (cf. Hast, 2014; Hast & Howe, 2013a). They further add to the discussion around whether conceptual knowledge exists as theory (Vosniadou, 2002a, b, 2007, 2013), in pieces (diSessa, 2002, 2006, 2013) or as a combination of both (Brown & Hammer, 2013; Özdemir & Clark, 2007).

In summarising the main findings it can be seen that, firstly, reasoning for those children who did not encounter any change along the entirety of the slope – the “straight” group – revealed the same age-related shift seen in previous research on motion down inclines (e.g. Hast, 2014; Hast & Howe, 2012, 2013a). Younger children were more likely to predict one ball rolling down faster because it was lighter than the other and older children were more likely to suggest the heavy ball would roll down faster because of its mass. At the same time, the children were consistent in their predictions across the three incline segments. The previous work suggested this shift might be due to different emphasis placed on the vertical and the horizontal component in the information integration process, with the physically available supported horizontal element having more salience for younger children. The results from the “straight” group therefore serve as a useful benchmark against which to compare the changing incline groups in order to address this notion.

Evaluating the two curved tube groups’ results against each other, parallel trends were noted. For the shallow segment children made similar predictions with little change across age groups, favouring the light ball as faster. This is an outcome seen in past horizontal motion reasoning tasks (Hast & Howe, 2012, 2013a; Inhelder & Piaget, 1958). For the steep segment children again made similar predictions across the four age groups, but believing the heavy ball to be faster than the light ball. Turning to past research this again is reflected in those studies examining children's understanding of object fall (Baker, Murray, & Hood, 2009; Chinn & Malhotra, 2002; Hast & Howe, 2012, 2013a; Nachtigall, 1982; Sequeira & Leite, 1991; van Hise, 1988). Whether the children's predictions are entirely equivalent to horizontal and vertical motion is difficult to say in the present study but previous work would lead to conclude that this is unlikely to be the case (cf. Hast, 2014). Looking at the middle segment for both groups the same age-related shift as noted for the "straight" group can be noted. Collectively, this indicates an interaction of age and condition factors when predicting motion along downward curvilinear pathways. Notably, there were no score differences between similar tube sections – both steep segments' scores were similar, as were both shallow segments'. Although they are not physically identical this does seem to suggest some consistency in how steepness and shallowness would impact motion.

It is, of course, possible that children assumed once one ball was ahead the other would simply not be able to overtake anymore. Research on speed change shows children typically anticipate speed changes in downward motion, both in fall and down straight slopes, to occur early along a trajectory in form of a quick burst followed by no further change, and to be more likely to happen for a heavy ball rather than a light ball (see e.g. Hast & Howe, 2013b). In the present context this would mean the heavy ball immediately advances at a faster rate and then cannot be overtaken by the lighter ball at any future point. The "inward" group would also show a similar pattern: once the degree of slope becomes sufficiently vertical, the heavy ball speeds up and is able to overtake the light ball. However, when looking at the "outward" group a different story appears to unfold. The heavy ball is initially shown to be faster, as might be anticipated given the significant downward element. Yet along the middle segment, for the two younger groups, the light ball has already taken over, and for all four groups it is the light ball that reaches the end of the shallow segment first. This initially seems to contradict the findings for the other two tube conditions but can again best be explained through the speed change research which has shown that children typically associate horizontal motion with deceleration – children's expectations are that a heavy ball will slow down at a faster rate than a light ball, with mass acting as hindrance to motion rather than help (Hast & Howe, 2013b).

In the context of commonsense theories of motion (Bliss & Ogborn, 1988; Bliss, Ogborn, & Whitelock, 1989; Hast & Howe, 2012, 2013a; Ogborn, 1985) the present study adds to the argumentation that conceptions about vertical and horizontal motion are differentiated on a psychological level in children's reasoning processes and that conceptions about motion down inclines are a result of a process of knowledge integration (Hast, 2014). In particular, what appears to be most significant in this integration process is the importance of the amount of support within a motion scenario as this clearly impacts on children's decisions about how a key variable, in this case mass, affects an object's motion. This lends credence towards the idea that commonsense theories first develop primarily on a physical level – support versus no support – and then shift to a more conceptual level – deciding which of the two components should have more impact on the interaction and why (see e.g. Mou, Zhu, & Chen, 2015). Future research is still needed to specify in more detail why the middle segment for all three conditions shows this age-related shift and what exactly determines the salience of support. For instance, one suggestion is that the degree of incline affects perceptions of salience of support (Hast, 2015), whereby with increasing age the vertical element plays a salient role at successively shallower inclines in children's reasoning about motion. However, this requires further systematic exploration of the physical perception of such support, perhaps in qualitative form or in a more self-directed manner (cf. Hast, 2014). Similarly, the apparent same attributions to the "shallow" and the "steep" segments across both tubes, even though not physically identical, would warrant additional examination.

Within the larger scale of scientific theory formation this research also contributes towards the discussion of whether conceptual knowledge exists as theory (Vosniadou, 2002a, b, 2007, 2013) or in pieces (diSessa, 2002, 2006, 2013). The data lean towards the latter of these views since children's decisions are not guided by a singular idea about motion down inclines – or else all patterns might have been expected to be more similar than different. It would therefore appear more likely that children's knowledge about motion down inclines is constructed through an integration of understanding of downward and horizontal motion. However, the possibility of these commonsense ideas of motion existing within an integrated knowledge model of both theories and elements (Brown & Hammer, 2013; Özdemir & Clark, 2007) should not be ruled out either, since it is plausible that the individual components of fall and horizontal are, in turn, governed by theoretical structures and the general principle of incline motion being a result of their interaction may also be founded in an overall theoretical structure – one that changes with increasing age. This may have further implications for approaching conceptual change in the science classroom.

Based on the evident flexibility in children's reasoning process about motion the present findings are supportive of previous suggestions regarding the order of teaching of concepts throughout primary school (e.g. Hast & Howe, 2012, 2013a). In particular they continue to promote the viewpoint that early science education should first consider the *differentiation* of motion dimensions (horizontal vs fall) followed by the *integration* (horizontal plus fall) rather than treating motion dimensions independently. The current structure of the recently revised National Curriculum for England (Department for Education, 2013) potentially promotes successful theory development, at least initially, since it brings together the teaching of both horizontal and fall into one key stage, as opposed to the previous curriculum (Department for Education and Employment, 1999) where the two were considered somewhat apart. However, the present study questions whether leaving this combination for the second key stage (ages 7-11 years) was the better option, given that mass-related conceptions in the individual dimensions arise earlier and show little change across age groups (cf. Hast, 2014; Hast & Howe, 2012, 2013a, b) and given that the curriculum still does not explicitly include anything on motion down slopes. The study therefore highlights the lack of early provision for the differentiation and integration of knowledge in response to the early development of commonsense theories of motion.

5. Conclusion

Children's understanding of motion down inclines appears to be the result of gradually changing conceptions with increasing age and these changes are linked to the degree of incline as well as the salience of horizontal and vertical elements when they interact. Children are competent in differentiating between the two elements and are generally able to connect them in meaningful ways, which enables them to deal with reasoning about motion down inclines. This provides a more detailed insight into the development of commonsense theories of motion, suggesting that with increasing age physical aspects of motion become less salient. This has potential consequences for teaching strategies and curricular structures in early science education, calling for a more systematic evidence-based incorporation of children's knowledge development.

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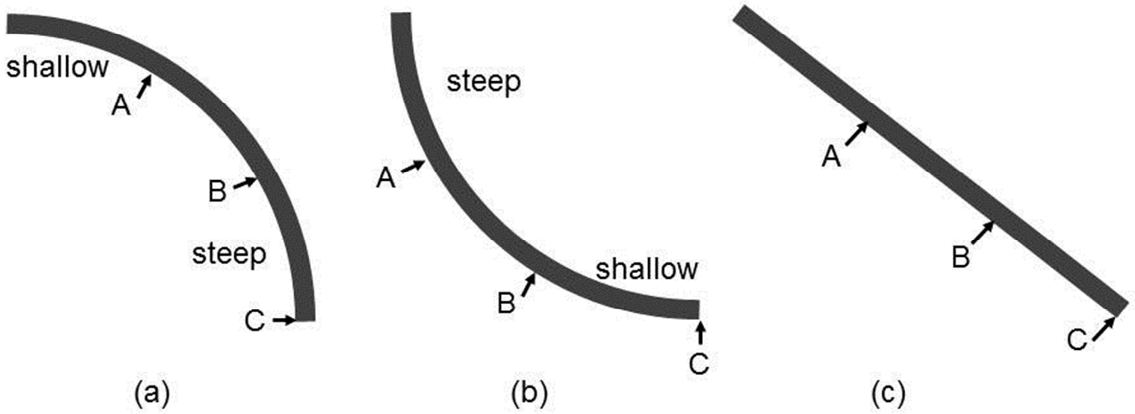

Figure 1. Modes of tube presentation; “outward” (a), “inward” (b) and “straight” (c). Endpoints A, B and C are indicated for each tube as well as the “shallow” and “steep” segments for (a) and (b).

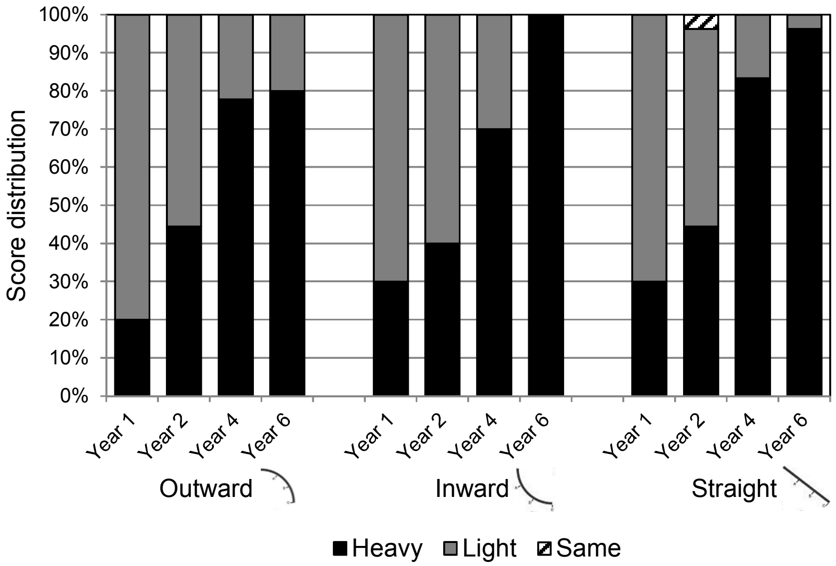

Figure 2. Mean score distribution for the middle sections of the "outward" and "inward" tube and the average of all three sections of the "straight" tube by age group.

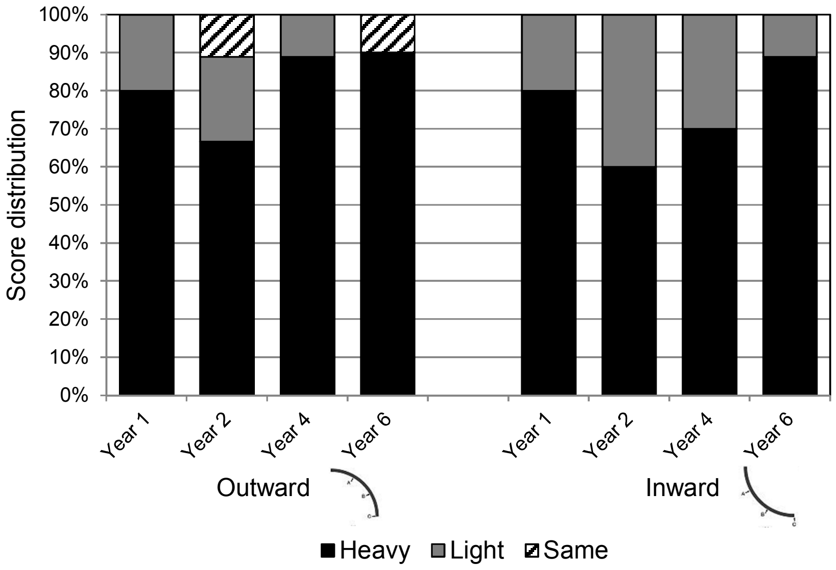

Figure 3. Mean score distribution for the steep sections of the "outward" and "inward" tube by age group.

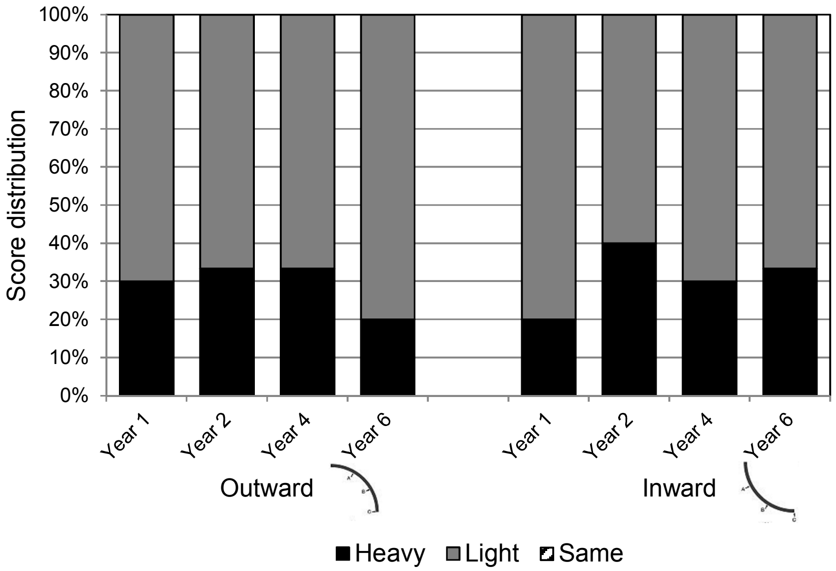

Figure 4. Mean score distribution for the shallow sections of the "outward" and "inward" tube by age group.