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Where will it go? How children and adults reason about force and motion

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ABSTRACT

Even infants can recognize physically impossible patterns of motion, seem to expect correct trajectories, and as they develop motor skills, move as necessary to achieve a goal. Yet in adulthood, the majority of people perform poorly when asked to make explicit predictions about motion in the same problems, and are influenced by irrelevant surface features. To characterize the changes that occur during development and the nature of individual differences, we developed a new assessment of force and motion that is age appropriate for both 6-year-old children and adults. Participants at both ages were generally able to reason at above-chance levels about motion in one dimension, although adults showed superior performance. On problems involving motion in two dimensions, adult males did better than boys, but adult females were equivalent to girls. These data provide the basis for a reinvigorated investigation of the factors supporting the development of the ability to think about force and motion.

1. Introduction

A stick strikes a hockey puck sliding across the ice. Where will it go? From a physics professor's standpoint, this problem is a simple one, similar to problems in most college-level, introductory physics courses. However, students often struggle to achieve the coherent conceptual understanding of force and motion that these problems are meant to measure (diSessa, 2013; Vosniadou & Skopeliti, 2014). Conceptual confusion is evident even in students who appear to be performing well in physics courses (Hestenes, 1985a, 1985b; ; Viennot, 1979). Many high-performing students generate correct *scalar* mathematical solutions by using a strategy of matching variables in functions, but do not show conceptual mastery when probed more deeply (Halloun & Hestenes, 1985b; Hammer, 1989; Larkin, McDermott, Simon, & Simon, 1980; Van Heuvelen, 1991). Mastery of the underlying physics is inhibited by the vector nature of core concepts such as velocity, acceleration, and force. Accurately solving problems regarding motion in two dimensions requires successful vector addition and students generally lack a precise understanding of vector quantities and vector mathematics (Flores, Kanim, & Kautz, 2004; Nguyen & Meltzer, 2003).

Adults' difficulties with basic concepts of force and motion may appear puzzling, however, when considered in the light of developmental research with very young children. Infants often show surprisingly good performance in recognizing causal interactions and in attending to specific details of the forces involved in motion events, such as expecting larger forces to result in more motion (Cohen & Oakes, 1993; Göksun, George, Hirsh-Pasek, & Golinkoff, 2013; Hood, 1998; Kotovsky & Baillargeon, 2000; Leslie & Keeble, 1987; Oakes & Cohen, 1990). In addition, by the time they have left toddlerhood, children are able to walk, run, push, pull,

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throw, and catch to achieve a variety of desired outcomes in a way that involves taking account of complex concepts such as friction.

Ideally, apparent adult difficulties could be reconciled with the seemingly advanced abilities of children by directly comparing their performance on force and motion problems. However, there is wide variety in the methodologies used with different age groups. Studies of early childhood often use looking-time and other recognition paradigms, while studies with adults typically use explicit prediction paradigms. When adults do not have to make explicit predictions, they do much better. For example, Kaiser, Proffitt, Whelan, & Hecht (1992) presented adults with a simple pendulum problem – if the string on the pendulum is cut while the bob is at its apex how should it fall? When participants viewed five videos to *recognize* which was correct, they did well. When shown a static image of five potential paths and asked to *predict* which was correct, the same participants did poorly, often selecting a physically-impossible drawing (i.e., one depicting motion that would not occur under the specified conditions). Thus, adults typically succeed in the types of recognition tasks used with children. Similarly, both children and adults show success in action but errors when asked to reflect. For example, Krist, Fieberg, and Wilkening (1993) asked adults and children to identify how fast a ball needed to be launched off a platform to hit a target, as the height of the platform and distance of the target changed. When child and adult participants were asked to *predict* the required speed, performance was poor, at both ages. However, when the same participants were instead asked to *act*, to throw the ball with sufficient speed, performance was better.

We can also compare children and adults using experimental techniques more comparable to those used with adults, involving explicit prediction. In this case, children struggle with reasoning correctly, just as adults do (Hood, 1995; Kaiser, McCloskey, & Proffitt, 1986; Kaiser, Proffitt, & McCloskey, 1985; Kim & Spelke, 1999). For example, both children and adults make incorrect predictions about scenarios involving multiple components of motion (i.e., velocity or acceleration in different dimensions), often partially or completely ignoring one of the components of motion (diSessa, 1982; Göksun et al., 2013; Halloun & Hestenes, 1985a). Thus, much like adults succeeded when tested in a manner comparable to methods relied upon with children, children struggle when tasks require prediction. It is worth noting that dimensionality affects the difficulty of prediction problems, but not action or perception problems. This difference can be attributed to the fact that, for a single dimension the quantities can be reduced to scalars with different signs indicating the direction, but vector addition is required when the motion spans more than one dimension. Overall, the perception-action system appears to be much "smarter" than the cognitive system, for reasons that have yet to be well specified.

One conclusion from this body of research might be that there are no age-related differences in understanding force and motion. But this conclusion would be premature. The variation in paradigms used with children and adults has obscured the goal of determining whether children and adults differ at all in their understanding. Describing any natural age-related change and elucidating the factors associated with conceptual advance might allow the design of better educational support to address the areas where understanding lags.

In exploring age-related change, we also need to address individual differences. Although performance is poor overall on prediction problems, some people gain conceptual mastery of force and motion. While it has been argued that physics may just be too hard for most people, in a categorically different way than other difficult topics (Sobel, 2009), many researchers in the physics community reject this idea (Lasry, Finkelstein, & Mazur, 2009). They suggest that specific aspects of individual cognitive profiles interact with the specific experiences that people encounter in informal and formal settings to determine their progress on particular physics problems. One example might be that spatial skills are involved because force, acceleration, and velocity are vector quantities. Consider again a stick striking a hockey puck sliding across the ice. The first step in solving this problem is noticing how the direction of the force of the strike compares to the direction of the hockey puck's motion. If they are in the same direction (i.e., zero degrees difference) the magnitude of the puck's velocity will increase, but its direction will not change. If they are in the opposite direction (i.e., 180 ° difference), the magnitude of the puck's velocity will decrease and might even become negative (i.e., its direction would be reversed). Between these two simple extremes, the puck's acceleration may result in a change of both the magnitude and direction of the puck's velocity. The underlying features of these problems suggest spatial thinking might be a potential explanatory factor for individual differences in whether physically-possible predictions eventually develop. Furthermore, variations in attention to the spatial aspects of these problems has been suggested as a key difference between unsuccessful novices and experts (Larkin, 1981, 1982, 1983; Van Heuvelen, 1991) and as an important predictor of initial success across all STEM disciplines (Uttal & Cohen, 2012). Spatial thinking has also been shown to explain individual differences on force and motion problems specifically (Kozhevnikov, Motes, & Hegarty, 2007).

Appropriate examination of the development of physics ideas, of individual differences, and of the factors related to differential development of physically-possible ideas requires a conceptual test that provides quantitative results. This test must be presented in a format that is age-appropriate for a wide age-range, but does not rely on either recognition or action, given that the perception-action system appears to undergo little developmental change. Here we present a novel digital test of understanding of force and motion (called the Hedgehog Game) that meets these criteria, allowing the investigation of the development of naïve ideas of force and motion from the age at which children first enter school and begin formally instruction through adulthood. Participants' performance is compared across two age groups to evaluate change over time. We also test whether measures of spatial thinking might explain individual differences that emerge in this task.

2. Method

2.1. Participants

Fifty-eight adults between the ages of 18–65 (M = 23.21 years, 28 male) from a major northeastern U.S. city participated in this