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Any way the wind blows: Children's inferences about force and motion events

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ABSTRACT

Göksun, George, Hirsh-Pasek, and Golinkoff (2013) used *force dynamics*, or the semantic categories defined by spatial arrays of forces, to study the development of preschoolers' predictions about the outcomes of forces working in concert. The current study extends this approach to problems requiring inferences about causal factors. In total, 30 5- and 6-year-old children were asked to identify and coordinate forces to achieve a result. Problems varied in the number and orientation of forces, mirroring spatial arrays characteristic of categories like *prevent* (i.e., opposing forces). Children successfully inferred causes of single- and dual-force events, performing best when problems reflected the spatial arrays of forces described in language. Results support force dynamics as a valuable framework for the development of force and motion representations.

Introduction

The mobile child is a mecca of force, whether kicking a ball around a playground, hurling toys during a tantrum, or pulling on his mom's shirt as she tries to leave the room. Although each of these

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forces affects the world, the primary approach in the psychology of causal perception has been to consider forces in isolation (e.g., Baillargeon, 1994; Cohen, Rundell, Spellman, & Cashon, 1999; Leslie, 1982, 1984; Oakes & Cohen, 1990; Rakison & Krogh, 2012; Saxe, Tenenbaum, & Carey, 2005; Saxe, Tzelnic, & Carey, 2007). This approach overlooks the tapestry of forces that contribute to the outcome of an event. Whether the child *keeps* his mother from leaving or she exits *despite* the child's efforts depends not only on the strength of the child's tugging but also on its relation to the force of the mother walking. As children's causal knowledge develops, they must learn to interpret their own actions and the forces around them in this broader context.

Defined as the interaction between entities in space resulting from multiple forces (Talmy, 1988; Wolff, 2003, 2007), force dynamics theory encompasses not only simple cause–effect relations but also these scenarios in which two or more forces affect the trajectory of an entity in an event. The semantic categories of force dynamics such as *enable* and *prevent* yield a useful framework with which to look beyond isolated causes and allow for a more systematic and complex view of interacting forces in space. Recent research shows that the development of children's predictions about single- and dual-force events is captured well by these categories, with representations building from single-force *cause* events to more complex *enabling* and ultimately *preventative* interactions (Göksun, George, Hirsh-Pasek, & Golinkoff, 2013). We extend this analysis by considering another facet of children's representations of caused motion: inferring causers from effects. Inferring causers in the world, such as the presence and direction of wind from the curved path of a golf ball in flight, is an essential aspect of navigating and accurately conveying information about force and motion. We ask whether the patterns observed in children's predictions extend to their ability to infer causers from observed effects. Our aim is to show that inferences about caused motion, much like predictions, emerge categorically in a manner supported by one force dynamics framework developed from the linguistic literature.

Force dynamics

Research in event perception traditionally emphasized the perception of causality from a Michottean perspective (Michotte, 1963), studying direct causal events in which an object in motion (i.e., an agent) contacts a stationary object (i.e., a patient), causing the patient to immediately move along the agent's trajectory. The spatiotemporal contiguity between the paths of the two objects creates the perception of causality, a finding consistently supported and extended (e.g., to state change events) by work with both adults (e.g., Choi & Scholl, 2006; Fugelsang, Roser, Corballis, Gazzaniga, & Dunbar, 2005; Schlottmann, Ray, Mitchell, & Demetriou, 2006) and infants (e.g., Cohen & Amsel, 1998; Leslie & Keeble, 1987; Muentener & Carey, 2010; Newman, Choi, Wynn, & Scholl, 2008; Rakison & Krogh, 2012; Saxe et al., 2007). These studies are typically in support of a physicalist account of causal perception, in which the transmission of some physical quantity (e.g., energy, momentum) is considered necessary and sufficient for the perception of causal interactions (Shultz, 1982). Although such conclusions reflect a valid part of causal knowledge, they oversimplify the complexity of everyday causal interactions by overlooking additional factors relevant to the perception of causality, and specifically of caused motion. For example, a vital component of a causal motion event, *trajectory,* has received relatively little attention in the literature but is influential in adults' causal perception (Straube & Chatterjee, 2010; Wolff, 2007). Moreover, the environment often contains multiple kinetic forces working in concert, and theories of causal perception must scale up to consider how these defining features of causation are perceived in the context of these complex yet commonplace occurrences.

At least one framework addresses the limitations of previous physicalist accounts of causality. Built from the work of Talmy (1985, 1988) and Jackendoff (1990) in the domain of language, the *force dynamics model* asks how language might offer a window into the spatial arrays of coordinated forces that underpin caused motion events (Wolff, 2003, 2007). This model of force dynamics expands our view of caused motion, suggesting that we distinguish among conceptual categories of causal interactions: *cause* (one force that moves an object), *enable* (a secondary force that promotes the motion in the intended direction), *prevent* (a secondary force that hinders the motion in the intended direction), and *despite* (a secondary force that hinders the motion in the intended direction but is overcome by the primary force) (Wolff, 2007). For example, when a boat is moving toward a port, a secondary force, “the wind,” might *prevent* the boat from doing so by changing its direction. In contrast, if the boat were pushed by the wind toward the port, the force of the wind would *enable* the boat to reach it. This force dynamics model allows us to expand the scope of research on causal perception to include trajectories as well as interactions among forces and provides a framework for examining how we organize patterns of forces in our representations of events.

Göksun et al. (2013) took the initial step in applying this framework to the development of children’s reasoning about physical force and motion events. In a novel board game, 3- to 5-year-olds were asked to predict the path of a small ball when influenced by a single force or two forces arranged to reflect the force dynamics categories of *cause, enable,* and *prevent.* The results show a developmental trend, with 5-year-olds better at predicting the path of the ball than younger children. Furthermore, whereas children were best at predicting the result of single-force *cause* trials, they were significantly worse at predicting the result of two concordant forces in *enable* trials and still worse when forces were not concordant, as in *prevent* trials. Within the *prevent* scenarios, children also performed poorest when the two forces were arranged across two dimensions (i.e., perpendicular to one another) as opposed to when they were arranged within a single dimension (i.e., in direct opposition).

The developmental progression of children’s predictions demonstrates the value of force dynamics in capturing meaningful distinctions between events. As shown by Göksun et al. (2013), understanding of force and motion is governed in part by categorical differences in events, progressing from an understanding of a single force to *enabling* forces and ultimately *preventative* relations. In addition, children’s impoverished ability to reason about forces across two dimensions intersects with proposed prototypical representations of *enable* and *prevent.* Although we can apply a category like *prevent* to motion in two dimensions, such as a soccer goalie preventing a ball from entering the goal by deflecting it to the side of the net (Wolff, 2003, 2007), Talmy’s (1988) semantic analysis suggests that the most prototypical conceptual representations of force dynamics relations represented in language are characterized by motion in a single dimension, such as the goalie preventing the ball from entering the net by kicking it back along its initial line of motion into the field of play. This may be reflected in children’s poorer reasoning about forces in two dimensions, further supporting how force dynamics captures both the development and bounds of successful reasoning during childhood.

The inference problem

Although the ability to predict the outcome of two forces working in concert reflects a valid component of knowledge about force and motion, it does not fully reflect the range of judgments carried out when interpreting everyday events. Consider a golfer admiring a well-struck ball traveling down the center of the fairway, when suddenly it curves to the right. From the path, the golfer not only can *infer* the presence of a second force on the ball, “the wind,” but also can make an informed judgment regarding the wind’s direction, using this information to plan his next shot. These types of causal inferences, in the face of noisy environments containing multiple forces, reflect a critical yet understudied component of causal knowledge: Children’s representations of caused motion must also support the binding of an observed trajectory to the force(s) that produces it. Note that whereas all types of problems require making inferences in the sense of applying a broader mental representation to a specific instance or problem, here we use the term *inference* (i.e., working backward from an observed result to its cause or set of causes) to contrast with previous work on prediction (i.e., anticipating a result given a cause or set of causes). Recent research suggests that being able to infer multiple causers may be an understudied but critical foundation to scientific reasoning (Kuhn, Ramsey, & Arvidsson, 2015).

Research on intuitive physics suggests that these types of inferences regarding force interactions may be particularly difficult—even for older children. diSessa (1982) presented sixth-grade students with a computer task in which they were to propel a moving object to a goal via a series of “kicks.” Although some students’ strategies reflected an understanding that kicks concordant with a motion speed the object up (i.e., *enable*) and kicks in the opposite direction of motion slow it down (i.e., *prevent*), they struggled with motion in two dimensions. Specifically, students worked from an incorrect conception that the object’s motion would be determined entirely by the force they imparted irrespective of the object’s motion prior to the new force. This response, which is uniquely problematic for forces in two dimensions, is an example of a well-documented *dominance* error, in which the strongest or most recent force is thought to determine the result regardless of any other applied forces (Halloun & Hestenes, 1985; Pauen, 1996). A significant stumbling block even for adults (Halloun & Hestenes, 1985), the dominance error fundamentally reduces events to a series of independent causes, overlooking the coordination of forces in an event.

Although this research hints at similar patterns of performance to Göksun et al.'s (2013) study of prediction, further work is needed to show that children's representations of caused motion events support reasoning about causers in the same way that they support reasoning about effects. First, although students in previous research showed understanding of *enabling* and *preventing* forces (diSessa, 1982), such inferences were not explicitly tested and compared relative to one another nor to an understanding of forces across two dimensions. Second, inference can be assessed in several ways. The ability to intervene in an event reflects sophisticated knowledge of how forces combine to achieve a result, but everyday inferences are likely to be more simplistic, requiring only the identification of causers among an array of possibilities in the environment. Indeed, research in the development of intuitive physics suggests that success in more passive tasks often precedes success in tasks requiring more active responses (e.g., Keen, 2003).

Similar to the approach of Göksun et al. (2013), systematically applying the force dynamics framework allows us to isolate whether children's inferences about caused motion reflect underlying representations that are captured by a force dynamics framework. Specifically, we ask whether the categories demarcated by force dynamics continue to highlight meaningful differences in children's reasoning, including (a) the developmental progression in which understanding progresses from single-force *cause* events to *enabling* events to *preventative* events and (b) the relative inability of children to reason about interactions lying outside of these categories (i.e., problems in two dimensions). Varying the type of task also allows for a more nuanced understanding of children's representations of these events, with the potential to reveal a blossoming ability to recognize forces prior to the ability to apply that knowledge in support of more active interventions.

The current study

We presented 5- and 6-year-olds with a novel game that builds on the paradigm of Göksun et al. (2013) by testing reasoning about patterns of forces that lie both within and outside of the conceptual categories of force dynamics. Importantly, whereas Göksun et al. (2013) examined children's ability to predict the endpoint of a small ball as a result of various configurations of forces, our tasks asked children to infer the location of causal forces given an outcome. Although there are many variables to consider (e.g., strength and timing of forces), we simplified the problem space here by looking only at interactions of forces in which the forces are equal in strength and applied simultaneously. Although most categories can be demonstrated with either equal forces (e.g., preventing motion from a primary force by matching it with an equal secondary force) or unequal forces (e.g., preventing motion from a primary force by adding a stronger secondary force), this decision does prohibit the examination of *despite* because unequal forces would be required (i.e., one force must overcome another). For example, a boat can be *prevented* from reaching shore by a current equal to the motor's force, holding the boat in place, or by a current more powerful than the motor, pushing the boat farther from shore. For a boat to reach shore *despite* the current, however, the motor must be stronger than the opposing current. The decision to exclude *despite* also mirrors previous work in which the focus has been primarily on the other three categories (*cause, enable,* and *prevent*) (Göksun et al., 2013; Wolff & Song, 2003).

Two types of inference problems were presented. In the first, children were asked to *identify* the force(s) responsible for an observed result, mirroring the binding of causes to effects in everyday events. The second asked children to *intervene* by coordinating one force with another to achieve a desired result. This task reflects the more complex, open-ended reasoning about force interactions previously tested in studies of inference (e.g., diSessa, 1982). In both tasks, arrangements of forces spanned multiple categories of force dynamics (i.e., *cause, enable,* and *prevent*) as well as interactions less prototypical of force dynamics relations (i.e., those in *two dimensions*). Doing so allowed us to ask (a) whether children's inferences, like their predictions, may emerge categorically in a manner supported by the force dynamics framework and (b) whether limits in children's reasoning exist when moving beyond these conceptual categories.

Method

Participants

Participants consisted of typically developing 5-year-olds ($n = 17$; $M_{age} = 65.73$ months, $SD = 2.85$; 6 boys) and 6-year-olds ($n = 13$; $M_{age} = 78.77$ months, $SD = 3.44$; 5 boys) from the suburbs of a northeastern city in the United States. Data from an additional 4 children were excluded due to inattention to the task ($n = 3$) or technical difficulty ($n = 1$).

Materials

A large circular table (33.5 in. in diameter) covered with a layer of blue felt formed the platform for the game. A green foam ball (5.5 in. in circumference) served as the object acted on. Forces were applied to the ball via two directional RoadPro 12-volt Tornado Fans (Palmyra, PA, USA) equipped with mounts that could be attached anywhere along the circumference of the table. Both fans were set on the highest setting and fed through a single extension cord so that they could be turned on simultaneously. Throughout the following series of problems the fans remained off unless specified. Finally, a red felt square (9 × 9 in.) marked the location of the ball following the application of force(s).

Procedure

The experiment comprised four phases: familiarization, warm-up, identification, and intervention. To control for learning effects, the order of identification and intervention trial blocks was randomized. Within each block, the order of orientations (*enable, prevent,* and *two-dimension*) was also pseudorandomly selected. All sessions were video-recorded for later coding.

Familiarization

Each child was first familiarized with the fans. The experimenter turned on one fan and allowed the child to feel the wind. The child was then shown the second fan and told, "This fan is the same as that the first one." Finally, the experimenter demonstrated the mounts, clipping the fan on various places around the table.

Warm-up trials

Two warm-up trials were administered (see Fig. 1). The first was a single-force prediction task. The ball was placed in the center of the table with a single fan directed at the ball from a random location on the edge of the table. The child was asked to indicate where he or she thought the ball would travel by placing the red square along the edge of the table. The fan was then turned on, and the child observed the result.

In the single-force intervention task, each child was asked to place a single fan to achieve a desired result. The ball was placed in the center of the table, with the red square set at a new random location on the edge of the table. The child was asked to make the ball reach the square by choosing where to mount a fan along the edge of the table. The experimenter mounted the fan according to the child's response and then turned on the fan so that the child could observe the result. Warm-up trials were always presented in the same order (prediction then intervention).

Identification trials

In the identification task, children were asked to pinpoint the forces acting on the ball from an observed result. The ball was placed in the center of the table, and both fans were oriented in one of the three arrangements described below (see Fig. 2). For each trial, the experimenter manually rolled the ball along a path toward a given end state, and the child was asked to identify whether one or both fans would be needed to achieve the presented result. The order of hypothetical paths within each orientation was randomized for each participant.

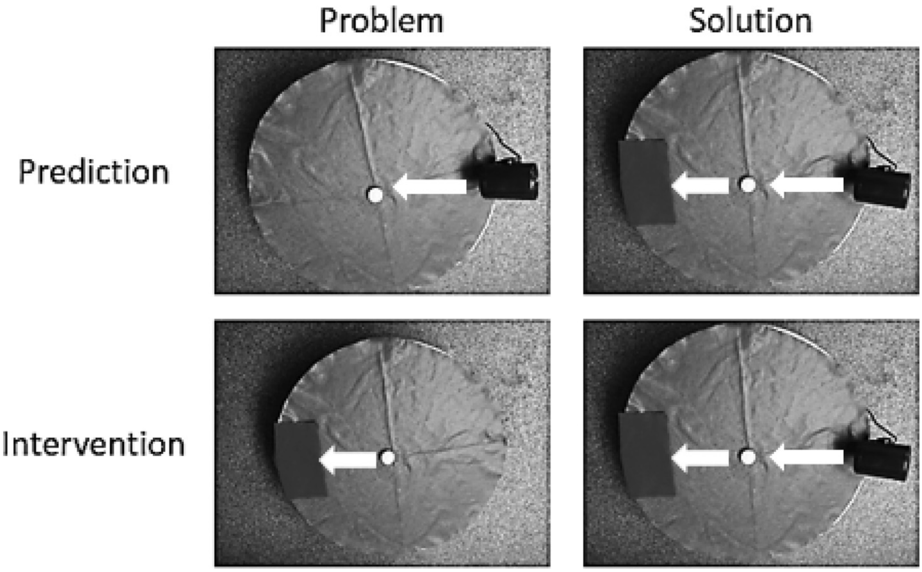

Fig. 1. Setup and solutions for warm-up trials. In the prediction problem diagram, the arrow designates the direction of the force imparted by the fan. In the intervention problem diagram, the arrow designates the desired motion of the ball.

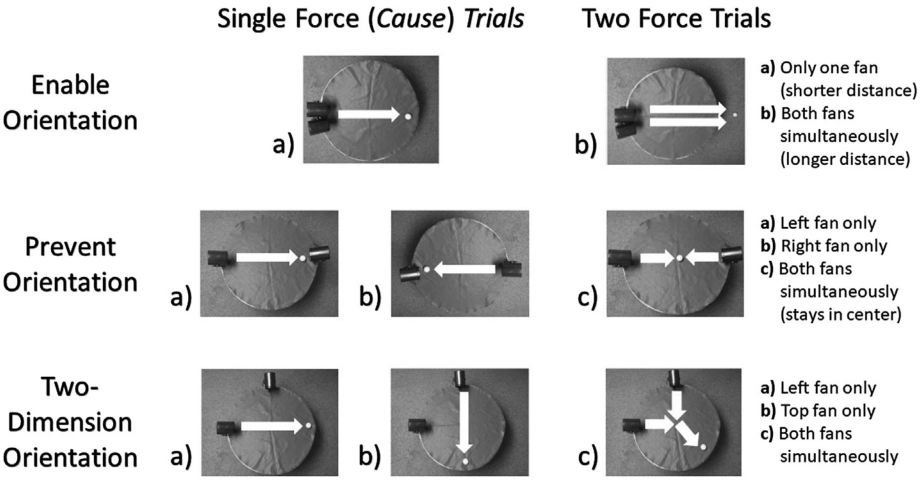

Fig. 2. Identification trials broken down by orientation and number of forces involved. For each trial, the ball was manually rolled from the center of the table to the location depicted. Children were asked to identify the fan(s) responsible for the demonstrated path. Arrows demonstrate the forces applied to the ball by the fans. Answers are described to the right of the images.

In the *enable* orientation, fans were placed side by side at the edge of the table, such that they both would blow the ball in the same direction. Here, trajectory remains constant and distance is the critical variable. Because distance is relative, the child was first presented with two possible end locations to establish a comparison. The first location was at the edge of the table (one fan), and the second was over the edge and onto the floor (two fans). Across two trials, the child was then presented with each potential end state in succession and asked whether one or both fans were needed to produce the result. For the location at the edge of the table (one fan), the child was not required to differentiate between the two fans because either one yields the same result in isolation. The single fan trial was classified as a *cause* trial because it requires reasoning about only a single force. The two-force trial served as the *enable* trial.

In the *prevent* orientation, fans were arranged at opposite edges of the table, such that their forces on the ball directly opposed one another. In three successive trials, the child saw the experimenter roll the ball either away from the first fan toward the second one, away from the second fan toward the first one, or not at all, keeping it in the center. For each of the three trials, the child was asked to identify which fan(s) would be needed to produce the result. The single-force trials were classified as *cause* trials because again only a single force was required in each one. The two-force trial served as the *prevent* trial.

The *two-dimension* orientation was used to reflect force interactions not prototypical of a force dynamics category. Fans were placed 90° apart around the edge of the table. In three successive trials, the child saw the experimenter roll the ball either 180° away from one of the fans, 180° away from the other fan, or along a path splitting the angle between the two fans, 135° from both. For each of the three trials, the child was asked to identify which fan(s) would produce the result. Again, the single-force trials were classified as *cause* trials. The two-force trial served as the *two-dimension* trial.

Intervention trials

Intervention trials required children to use two forces to achieve a desired result. The ball was placed in the center of the table, and the red square was placed to designate the desired goal location. One fan was clipped onto the table; its placement varied based on the desired arrangement, as described below (see Fig. 3). Importantly, all placements of the fan required that another fan be introduced to move the ball to the red square. The child was asked to place the second fan such that, when both fans were turned on, the ball would reach the red square. After each trial, fans were turned on simultaneously so the child could observe the result of his or her intervention.

The single-force intervention trial administered during the warm-up phase was scored and counted as the *cause* trial.

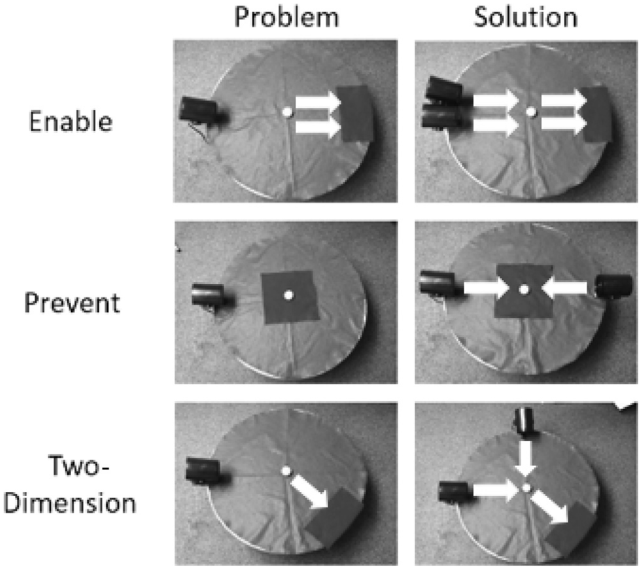

Fig. 3. Intervention problems (left column) and solutions (right column) for two-force trials. Arrows in the problem column demonstrate target motion (no motion in *prevent*). Double arrows represent the goal of faster motion toward the intended goal.

For the *enable* trial, the red square was placed 180° from the fixed fan. The child was asked to place the second fan in a position to help the ball reach the goal *faster*.

For the *prevent* trial, the red square was placed under the ball in the center of the table, with the fixed fan oriented at the ball. The child was asked to place the second fan in a position to keep the ball in the center of the table.

For the *two-dimension* trial, the red square was placed 135° away from the fixed fan. The child was asked to place the second fan in a position to make the ball travel to the red square.

Coding

Identification trials

Children were correct if they identified the fan(s) responsible for a presented result. All other responses were coded as incorrect.

Intervention trials

For intervention trials, the circumference of the table was divided into 45° zones. The first zone centered on the correct answer, with other zones continuing around the table. The span of these eight zones allows for non-overlapping regions centered around the correct answer as well as the common error of perseverating on a single force (i.e., dominance). In most instances, the zone of the child's response was clear. In situations where a response fell near a boundary, a protractor was used to identify the correct zone.

Results

Identification trials

Chi-square tests revealed no differences between 5-year-olds and 6-year-olds, $\chi^2(1) = 1.121$, $p = .290$, $V = .069$, or between boys and girls, $\chi^2(1) = 1.605$, $p = .205$, $V = .082$, on identifying forces responsible for an observed result. All subsequent analyses, therefore, were collapsed across these variables.

For trials in which a single force was responsible for producing a given result (i.e., *cause* trials), performance was compared with chance in two analyses described below. The first focused solely on *cause* trials from the *enable* orientation, for which chance was 50% (i.e., correct answer required identifying that one fan, as opposed to both fans, was responsible for the result but did not require differentiating between the individual fans). Children were above chance in single-force *cause* trials within the *enable* orientation, with 79% of children answering correctly, exact binomial test, p (one-tailed) $< .01$, $OR = 1.59$. A second analysis examined single-force *cause* trials across all other orientations, for which chance was 33% (i.e., children were required to differentiate between individual fans when answering that a single force was responsible). Across these trials, 93% of children answered correctly, also significantly more than expected by chance, exact binomial test, p (one-tailed) $< .001$, $OR = 2.80$.

For trials in which two forces were responsible for producing a given result, comparisons with chance were broken down by trial type. For *enable* trials, 97% of children answered correctly, significantly more than expected by chance (50%), exact binomial test, p (one-tailed) $< .001$, $OR = 1.93$. For *prevent* trials, 80% of children answered correctly, significantly more than expected by chance (33%), exact binomial test, p (one-tailed) $< .001$, $OR = 2.42$. For *two-dimension* trials, 60% of children answered correctly, significantly more than expected by chance (33%), exact binomial test, $p < .01$, $OR = 1.82$ (see Fig. 4).

A chi-square test revealed significant differences in performance across trial types (note that this analysis excluded all trials from the *enable* orientation to reduce comparisons across differing levels of chance), Fisher's exact test, $p < .0001$, $V = .338$. Bonferroni-corrected ($p < .0125$) post hoc comparisons showed that children's performance on single-force *cause* problems was significantly better when compared with *two-dimension* problems, Fisher's exact test, $p < .001$, $V = .375$, but not with *prevent* problems, Fisher's exact test, $p = .080$, $V = .165$. Within two-force problems, there was no

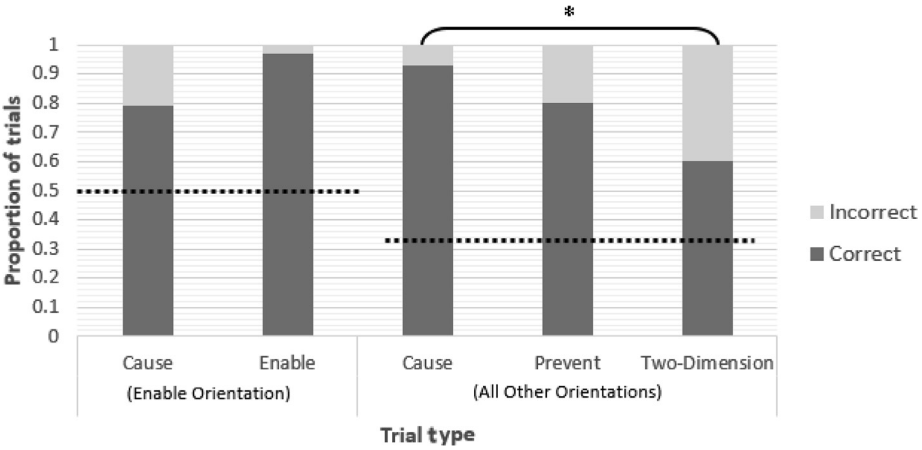

Fig. 4. Proportion of correct responses for identification trials as a function of trial type. Dotted lines represent chance (i.e., guessing). Trials from the *enable* orientation are analyzed separately because participants had only two choices (one or two fans) as opposed to the other orientations, which contained three choices (Fan 1, Fan 2, or both fans). Performance was above chance for all trial types (all *ps* < .01). $^*p < .0125$.

difference in performance between *prevent* and *two-dimension* trials, $\chi^2(1) = 2.857$, $p = .091$, $V = .218$. Finally, turning to the trials within the *enable* orientation, there was no difference in performance between *enable* and *cause* trials, Fisher's exact test, $p = .102$, $V = .265$.

Performance did not differ based on the order of the tasks, $\chi^2(1) = 0.026$, $p = .871$, $V = .011$. Thus, children did not perform better on identification trials even after receiving feedback from viewing the effect of their placements of fans in the intervention trials. Performance also did not differ based on the position of the orientations (*enable, prevent,* or *two-dimension*) within the task, $\chi^2(2) = 0.931$, $p = .628$, $V = .063$.

Intervention trials

Chi-square tests revealed no differences between 5- and 6-year-olds, $\chi^2(1) = 1.135$, $p = .287$, $V = .098$, or between boys and girls, $\chi^2(1) = 0.654$, $p = .419$, $V = .074$, on the correct placement of a fan to achieve a desired result. All analyses, therefore, were collapsed across these variables.

Children's performance on intervention trials was compared with chance (12.5%) for each trial type. For one-force *cause* trials, 86.7% of children responded correctly, significantly more than expected by chance, exact binomial test, *p* (one-tailed) < .001, *OR* = 6.94. For *enable* trials, 90% of children responded correctly, significantly more than expected by chance, exact binomial test, *p* (one-tailed) < .001, *OR* = 7.20. For *prevent* trials, 82.8% of children responded correctly, significantly more than expected by chance, exact binomial test, *p* (one-tailed) < .001, *OR* = 6.58. For *two-dimension* trials, 23.3% of children responded correctly, only marginally more than expected by chance, exact binomial test, *p* (one-tailed) < .10, *OR* = 1.86. Notably, the most common error in *two-dimension* trials, placing the fan directly across from the intended target (i.e., the dominance error), occurred in 60% of children, significantly more than expected by chance, exact binomial test, *p* (one-tailed) < .001, *OR* = 4.80.

A chi-square test revealed significant differences in performance across trial types, $\chi^2(3) = 43.517$, $p < .001$, $V = .605$. Bonferroni-corrected ($p < .008$) post hoc comparisons showed that children's performance on single-force *cause* problems was significantly better when compared with *two-dimension* problems, $\chi^2(1) = 24.310$, $p < .001$, $V = .637$, but not with *enable* and *prevent* problems, Fisher's exact tests, $p = 1.00$, $V = .052$ and $p = .731$, $V = .054$, respectively. Within two-force problems, children performed worse on *two-dimension* trials when compared with *enable* trials, $\chi^2(1) = 27.149$, $p < .001$, $V = .673$, and *prevent* trials, $\chi^2(1) = 20.883$, $p < .001$, $V = .595$. Children performed similarly across *enable* and *prevent* trials, Fisher's exact test, $p = .472$, $V = .106$ (see Fig. 5).

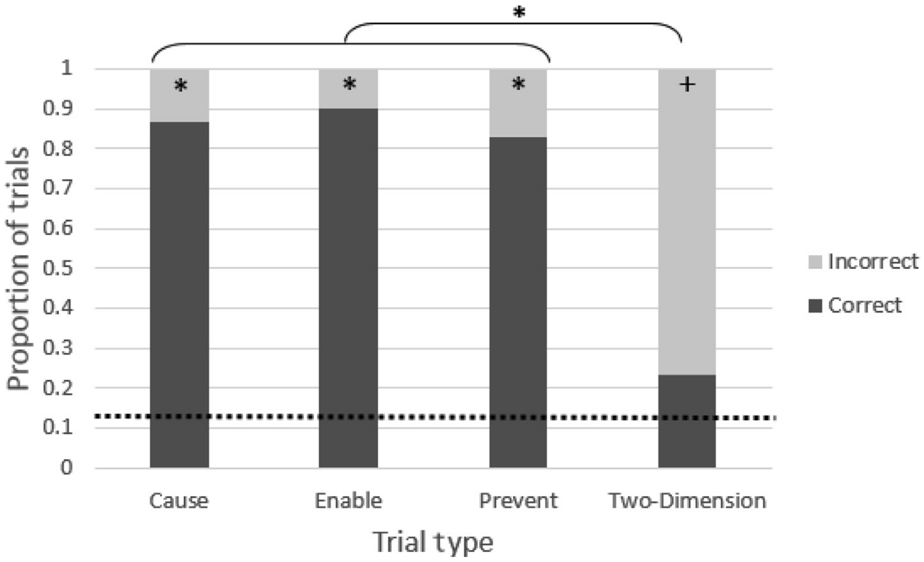

Fig. 5. Proportion of correct responses for intervention trials as a function of trial type. The dotted line represents chance (i.e., guessing). $^{*}p < .001$; $^{+}p < .10$.

Performance did not differ based on the order of the tasks, $\chi^2(1) = 0.005$, $p = .942$, $V = .007$. Thus, children did not perform better on intervention trials even after completion of the identification trials, which presented the correct orientations. Performance also did not differ based on the position of a trial (*enable, prevent,* or *two-dimension*) within the task, $\chi^2(2) = 0.476$, $p = .788$, $V = .073$.

Discussion

The current study extends the paradigm of Göksun et al. (2013) to further probe children's understanding of how multiple forces interact in space. We used the categories identified by those who study force dynamics as a window into children's event representations by asking whether 5- and 6-year-olds can make the inferences necessary to (a) bind causes to effects in environments with multiple possible causers and (b) coordinate forces to achieve a result. Although we did not observe the same categorical progression in children's reasoning seen in the study of prediction (Göksun et al., 2013), the results show that children can make inferences about causers when problems build on the prototypical representations of *cause, enable,* and *prevent* (i.e., forces within a single dimension). Furthermore, we demonstrated that children's inferences are robust only when forces are aligned according to these conceptual categories, delineating boundary conditions for reasoning that mirror the boundaries of the force dynamics framework. Together with previous work (diSessa, 1982; Göksun et al., 2013), these findings further underscore how the development of children's reasoning about force and motion flows from categorical conceptual representations and the utility of force dynamics in capturing these meaningful distinctions.

Inferences supported by force dynamics

When making inferences about arrays of forces, there were some commonalities between children's responses across identification and intervention problems. Children were adept at inferring the cause of an event when that cause was a single force. These findings accord with a wealth of literature concerning the early development of causal perception in these simple interactions (e.g., Cohen & Amsel, 1998; Leslie & Keeble, 1987; Muentener & Carey, 2010; Newman et al., 2008;

Rakison & Krogh, 2012; Saxe et al., 2007). Across both question formats, children also succeeded at inferring how two forces combine to produce a result when the arrangements of forces mimicked prototypical exemplars of the semantic categories of *enable* and *prevent.* We do not, however, see evidence for the progression observed in prediction research, where children perform best on *cause* trials, followed by *enable* trials and lastly *prevent* trials. This may be due to the exclusively older age group recruited for the current study.

The success on *prevent* trials may seem to be especially in conflict with previous work on prediction, but it is important to note that *prevent* trials in the work of Göksun et al. (2013) included both the prototypical exemplar (i.e., direct opposition) and a *two-dimension* trial given that both involved *preventing* the forward motion of the ball. Although children in that study did not make adult-like predictions in *prevent* trials even by 5 years of age, they were relatively more adept at reasoning about the prototypical examples, which is reflected in children's success on *prevent* trials in the current study. Thus, these two studies together suggest that by 5 years of age children have a relatively good understanding of interactions of forces that lie within the bounds of force dynamics and that their representations support both predictions and inferences about these force and motion events.

Boundary conditions of children's inferences

The success across both identification and intervention tasks suggests that 5- and 6-year-olds have a sound understanding of force interactions when those forces are arranged to mimic force dynamics categories. However, when forces acted across two dimensions, breaking the prototypical categories of force dynamics, children's ability did differ as a function of the type of inference required. Whereas children were above chance in *identifying* when two forces acted across multiple dimensions to produce a result, they were only marginally successful on these problems when asked to *intervene.* This pattern of results is underscored by comparisons across categories. Children performed equally well across two-force problems in the identification task, but when intervening on an event, performance was significantly worse on two-dimension trials as compared with arrangements of forces prototypical of the force dynamics relations seen in language. These results are in line with an established trend in developmental research where children demonstrate knowledge of physical principles in more passive recognition paradigms, but such knowledge is not evident in more active tasks at the same age (see Keen, 2003).

One potential contributing factor for children's poor performance in two-dimension intervention problems is reflected in the most common error made by children in this task. The majority of children in these trials placed the second fan directly across from the goal, ignoring the presence of the initial fan. This so-called *dominance error* treats each force independently, with sole focus on the fan the child controls. This type of error is well documented in work with older children and adults, with many holding to the idea that the strongest or most recent force alone determines the direction of motion (diSessa, 1982; Halloun & Hestenes, 1985; Pauen, 1996). Our result adds an interesting twist to this error, suggesting that even in situations where the strength and timing of forces is held constant, drawing attention to one fan in any manner (e.g., allowing the child to place one fan) can result in perseveration on that force.

In sum, we not only observe the emergence of correct inferences about those force interactions captured by force dynamics, we also mark the early emergence of naive conceptions about force interactions lying outside of those categories. The dominance error in particular reflects the possibility that poor reasoning for interactions lying outside of force dynamics is due to a lack of integrative representation such as those provided by categories like *prevent* and *enable*. Importantly, it appears as though children are relying on the dominance principle only in the two-dimension trials. While applying the dominance principle may lead to correct answers in some trials (e.g., single-force problems), it would lead to persistent errors in others (e.g., identifying only one fan as responsible when a ball travels farther in *enable* trials). Thus, it is likely that the forces are treated as independent only when an integrated representation of the interaction is absent. The reliance on this misconception also helps to explain the differing performance across identification and inference tasks given that a dominance response was not possible in two-dimension identification problems (i.e., no fan was placed directly across from the goal).

Questions for further research

Apart from known differences between tasks of recognition and action, the differences observed across tasks in two-dimension trials may also be due in part to the nature of the tasks, with free-response being more challenging than multiple-choice formats. For instance, children may have succeeded on multiple-choice questions through eliminating the single-force choices, leaving only the two-force option as viable. These differences underscore why caution should be taken when relating performance on these tasks to previous studies of force and motion understanding. Both differences in question format (multiple choice vs. free response) and the timing (simultaneous vs. sequential) and relative strength (same vs. unequal) of forces vary across studies and may affect both the rate of success in these tasks and the prevalence of common errors. Whereas we focused on relatively simple problems in the current study, future research should systematically investigate how these factors influence reasoning across the lifespan to provide a fuller picture of development in this domain. Research should also consider how the categorical distinctions observed in children's representations of caused motion might relate to their representations of other types of causal events such as state change or social causation (Muentener & Carey, 2010; Wolff, 2007).

Finally, the current body of work suggests that the semantic conceptualization of force dynamics is valuable in framing the development of reasoning about force and motion. Might this reflect a deeper interplay between causal language and reasoning about force and motion? Two possible hypotheses are worth further consideration. The first is what we deem an *event primary hypothesis.* To use different force dynamics verbs (e.g., *cause:* force, make; *enable:* help, allow; *prevent:* keep, stop), children might first need to differentiate and conceptualize the various causal events represented by force dynamics (George, 2014; George, Göksun, Hirsh-Pasek, & Golinkoff, 2014; Göksun, Hirsh-Pasek, & Golinkoff, 2010; Wagner & Lakusta, 2009; Wolff & Song, 2003; Wolff, 2003, 2007; Wolff, Klettke, Ventura, & Song, 2005; Wolff, Song, & Driscoll, 2002). Therefore, language may be related to physical reasoning in that language builds on those aspects of events that are most easy to reason about (i.e., forces acting in a single dimension). Alternatively, language may aid children in their organization of events, in this case drawing attention to force interactions in the event. Thus, a second, although not mutually exclusive, *language primary hypothesis* posits that language may play a role in drawing attention to some patterns of forces over others (George, 2014), contributing to disparities in reasoning. For instance, the semantic categories of *enable* and *prevent* highlight how forces interact across a single dimension; however, descriptions highlighting forces across two dimensions may maintain separation of these forces (e.g., the ball rolled down the ramp *and then* was blown by the fan), leading to naive conceptions such as the dominance error. Although speculative, future research should test these possible relations between language and reasoning.

Conclusion

The current study provides evidence that children are developing the ability to successfully reason, through inference in addition to prediction, about forces aligned with the conceptual categories of force dynamics; however, understanding of forces acting across two dimensions remains somewhat impoverished. The prevalence of dominance responses suggests that this may be due in part to a lack of integrative representation for these events. Overall, our findings extend our understanding of the development of children's representations of force and motion by demonstrating the robustness of the observed progression across a variety of reasoning tasks.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jecp.2018.08.002.

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