Any Way the Wind Blows:
Children's Inferences about Force and Motion Events

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The mobile child is a mecca of force, whether kicking a ball around a playground, hurling toys during a tantrum, or pulling on mom's shirt as she tries to leave the room. Though each of these 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 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 *help* 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., state change, etc.) by work with both adults (e.g., Choi & Scholl, 2006; Fugelsang et al., 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, Tzelnic, & Carey, 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). While 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, specifically 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 towards 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 and interactions among forces, and provides a framework for examining how we organize patterns of forces in our representations of events.

Göksun and colleagues (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. Further, while 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 (e.g., perpendicular to one another), as opposed to when they were arranged within a single dimension (e.g., 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 and colleagues (2013), understanding of force and motion is governed in part by categorical differences in events, progressing from an understanding of a single causal force, to enabling forces, and ultimately preventative relations. Additionally, children's impoverished ability to reason about forces across two dimensions intersects with proposed prototypical representations of *enable* and *prevent*. Though 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 the bounds of successful reasoning during childhood.

The Inference Problem

While 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 travelling down the center of the fairway, when suddenly it curves to the right. From the path, the golfer can *infer* not only the presence of a second force on the ball, ‘the wind,’ but can also 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 produce it. Note that while 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(s)) 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.” Though 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.

Though this research hints at similar patterns of performance to Göksun and colleagues' (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, while 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 upon 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 amongst 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 and colleagues (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 1) the developmental progression in which understanding progresses from single force *cause* events to *enabling* events to *prevent* events, and 2) 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 present 5- and 6-year-olds with a novel game that builds upon the paradigm of Göksun and colleagues (2013) by testing reasoning about patterns of forces that lie both within and outside of the conceptual categories of force dynamics. Importantly, whereas Göksun and colleagues (2013) examined children's ability to predict the endpoint of a small ball as a result of various configurations of forces, our tasks ask children to infer the location of causal forces given an outcome. Though there are many variables to consider (e.g., strength and timing of forces), we simplify the problem space here by looking only at interactions of forces in which the forces are equal in strength and applied simultaneously. While most categories can be demonstrated with either equal (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*, as 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 further 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, prevent*; Göksun, et al., 2013; Wolff & Song, 2003).

Two types of inference problems are presented. In the first, children are asked to *identify* the force(s) responsible for an observed result, mirroring the binding of causes to effects in everyday events. The second asks 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, trials span 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 allows us to ask 1) whether children's inferences, like their predictions, may emerge categorically in a manner supported by the force dynamics framework, and 2) whether limits in children's reasoning exist when moving beyond these conceptual categories.

Methods

Participants

Participants consisted of typically developing 5-year-olds (N=17; M=65.73 mos, SD=2.85 mos, 6 males) and 6-year-olds (N=13, M = 78.77 mos, SD=3.44 mos, 5 males) from the suburbs of a Northeastern city in the United States. Data from an additional four children were excluded due to inattention to the task (3), and technical difficulty (1).

Materials

A large circular table (33.5 inches in diameter) covered with a layer of blue felt formed the platform for the game. A green foam ball (5.5 inches in circumference) served as the object acted upon. Forces were applied to the ball via two directional RoadPro 12-Volt Tornado Fans 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. Children were presented with a series of problems and the fans remained off in each unless specified. Finally, a red felt square (9 X 9 inches) marked the location of the ball following the application of force(s).

Procedure

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

Familiarization. Each child was first familiarized to 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 was 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 Figure 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 they 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).

Figure 1. Set-up 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.

Identification trials. In the identification task, children were asked to pinpoint the forces acting upon 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 Figure 2). For each trial, the experimenter manually rolled the ball along a path towards 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 of the identification trials was randomized for each participant.

In the *enable* orientation, fans were placed side-by-side at the edge of the table, such that they would both 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 each potential end state in succession and was 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, as either yields the same result in isolation. The single fan trial was classified as a *cause* trial, as it requires reasoning only about 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 towards the second, away from the second fan towards the first, 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, as again only a single force was required in each. 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.

Figure 2. Identification trials broken down by trial type and number of forces involved. For each trial, ball was manually rolled from center of 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.

Intervention trials. Intervention trials required children to utilize 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 Figure 5). 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 that the child could observe the result of their intervention.

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

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.

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

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 allow 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 in which 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 ($N=17$) and 6-year-olds ($N=13$), $\chi^2(1) = 1.121$, $p = .290$, $V = .069$, nor between males and females, $\chi^2(1) = 1.605$, $p = .205$, $V = .082$ on identifying forces responsible for an observed result. All subsequent analyses were therefore 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 to 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, 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 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 p (one-tailed) $< .001$, $OR = 2.80$.

For trials in which two forces were responsible for producing a given result, comparisons to chance were broken down by trial type. For *enable* trials, 97% of children answered correctly, significantly more than expected by chance (50%), exact binomial p (one-tailed) $< .001$, $OR =$

1.93. For *prevent* trials, 80% of children answered correctly, significantly more than expected by chance (33%), exact binomial p (one-tailed) $< .001$, OR = 2.42. For *two-dimensional* trials, 60% of children answered correctly, significantly more than expected by chance (33%), exact binomial $p < .01$, OR = 1.82 (see Figure 4).

Figure 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, as participants only had two choices (one or two fans) as opposed to the other orientations, which contained three choices (fan 1, fan 2, both fans). Performance was above chance for all trial types (all $ps < .01$). $*p < .0125$

A Chi Square test reveals significant differences in performance across trial types (Note: 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 to *two-dimension* problems, Fisher's Exact Test, $p < .001$, $V = .375$, but not *prevent* problems, Fisher's Exact Test, $p = .080$, $V = .165$. Within two force problems, there was no 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 a trial (*enable*, *prevent*, *two-dimension*) within the task, $\chi^2(2) = .931$, $p = .628$, $V = .063$.

Intervention Trials

Chi-square tests revealed no differences between 5- and 6-year-olds, $\chi^2(1) = 1.135$, $p = .287$, $V = .098$, nor between males and females, $\chi^2(1) = .654$, $p = .419$, $V = .074$ on the correct placement of a fan to achieve a desired result. All analyses were therefore collapsed across these variables.

Children's performance on intervention trials were compared to 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 p (one-tailed) $< .001$, OR = 6.94. For *enable* trials, 90% of children responded correctly, significantly more than expected by chance, exact binomial p (one-tailed) $< .001$, OR = 7.20. For *prevent* trials, 82.8% of children responded correctly, significantly more than expected by chance, exact binomial 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 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 p (one-tailed) $< .001$, OR = 4.8.

A Chi Square test reveals 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 to *two-dimension* problems, $\chi^2(1) = 24.310$, $p < .001$, $V = .637$, but not *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 to *enable*, $\chi^2(1) = 27.149$, $p < .001$, $V = .673$, 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 Figure 5).

Figure 5. Proportion of correct responses for intervention trials as a function of trial type. 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, two-dimension*) within the task, $\chi^2(2) = .476, p = .788, V = .073$.

Discussion

The current study extends the paradigm of Göksun and colleagues (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- to 6-year-old children can make the inferences necessary to 1) bind causes to effects in environments with multiple possible causers, and 2) coordinate forces to achieve a result. While we do not observe the same categorical progression in children's reasoning seen in the study of predictions (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). Further, we demonstrate 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, Tzelnic, & Carey, 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, in which 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 and colleagues (2013) included both the prototypical exemplar (i.e., direct opposition) and a two-dimension trial, as both involved *preventing* the forward motion of the ball. While children in that study did not make adult-like predictions in prevent trials even by the age of 5, 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 the age of 5

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- to 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. While 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 upon an event, performance was significantly worse on two-dimension trials as compared to arrangements of forces prototypical of force dynamics relations seen in language. These results are in line with an established trend in developmental research in which 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 in which the strength and timing of forces is held constant, drawing attention to one fan in any manner (i.e., 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 naïve 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* or *help*. Importantly, it appears as though children are only relying on the dominance principle 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, as 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, differences across tasks in two-dimension trials may also be due in part to the nature of the tasks, with free response tasks 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) as well as the timing (simultaneous vs. sequential) and relative strength (same or unequal) of forces vary across studies and may affect both the rate of success in these tasks and the prevalence of common errors. While 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 present body of work to date 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*: cause, 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 2003, 2007; Wolff, Klettke, Ventura, & Song, 2005; Wolff & Song, 2003; 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 towards force interactions in the event. Thus, a second, though 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 naïve conceptions such as the dominance error. Though speculative, future research should test these possible relations between language and reasoning.

Conclusion

The present 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 suggest that this may be due in part to a lack of integrative representation for these events. Overall, our findings extend our understanding 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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