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Michaela Boone Upshaw

Infants' Understanding of Object Weight: Relations with Action Experience and Strength

Michaela Boone Upshaw

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Reading Committee:

Jessica Sommerville, Chair

Raphael Bernier

Kristina Olson

Program Authorized to Offer Degree:

Psychology

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Abstract

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Michaela Boone Upshaw

Chair of the Supervisory Committee:
Professor Jessica Sommerville
Psychology

Our ability to plan actions, interpret other people's behavior, and predict the outcomes of physical events is profoundly influenced by our understanding of object weight and the ability to recognize its consequences. Given its importance, it is perhaps unsurprising that an understanding of object weight begins in infancy. Prior work demonstrates that infants' understanding of object weight is primarily garnered through their interactions with objects and that they can apply this understanding in order to guide their actions. However, we know far less about other applications of this knowledge in infancy and whether bodily factors that influence the acquisition of experience interacting with objects play a role. This dissertation demonstrates that infants can apply an understanding of object weight in order to guide action in novel contexts (Chapter 2), interpret and predict the outcome of physical events (Chapter 3), and

understand another person's actions (Chapter 4). In addition, this dissertation demonstrates that strength, a bodily factor that gates the acquisition of experience interacting with objects, influences infants' understanding of object weight when observing another person's actions but not when reasoning about physical events. Altogether, these studies demonstrate that by the end of their first year, infants' understanding of object weight is already flexible (i.e., applied in areas outside of action production in familiar contexts) and sophisticated (i.e., used to reason abstractly about the outcome of physical events).

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DEDICATION

To my grandmother, Pauline, who inspired my love of psychology.

Chapter 1. INTRODUCTION

Our ability to successfully navigate the world depends critically on our understanding of objects and their properties. A chief aspect of this knowledge is the understanding of object weight. Our ability to plan actions, interpret other people's behavior, solve problems, and predict the outcomes of physical events is profoundly influenced by the ability to perceive object weight and recognize its consequences. To illustrate, imagine a typical trip to the grocery store. Inside the store, you load your cart with a loaf of bread, a bunch of bananas, some cans of tomato soup, and a gallon of milk. The bread, bananas, and soup are lifted easily. However, you make sure to heft the milk with your left arm, as your right arm is sore from a recent inoculation. As you shop, you observe the stockers loading empty shelves with new products. A young employee quickly hoists entire crates of soda into place, effortlessly, with a single hand for each one; in contrast, the older manager carefully places each crate of soda onto the shelf with both hands. As you check out, you place your products onto the conveyer belt, being mindful to keep the gallon of milk and cans of soup away from the bread and bananas, to avoid crushing or bruising them. While exiting the store, you see an errant shopping cart and a plastic grocery bag being carried by the wind toward your car. You race to catch the cart, arriving just in time, totally ignoring the grocery bag as it contacts your vehicle. As this anecdote illustrates, our understanding of object weight is perpetually recruited as we go about our daily lives.

In this dissertation, an understanding of object weight refers to a broad construct that can be separated into two distinct aspects (see Povinelli, 2012, pg. 7). The first, more basic, aspect of this understanding is thought to be shared across species and are direct applications of one's prior experience interacting with an object, in that prior experience interacting with an object is applied in order to guide subsequent interactions. For example, recruiting the appropriate amount

of force in order to manipulate an object, tracking the amount of effort it takes to manipulate an object, and planning the force of one's actions in anticipation of an object's weight, all reflect basic aspects of understanding object weight. This type of understanding is thought to be shared across species, as many organisms must cope with the weight of the objects that they encounter on a daily basis. In contrast, the other aspect of understanding object weight is considered to be uniquely human (Penn, Holyoak, & Povinelli, 2008a; Povinelli, 2012), as it involves going beyond experience interacting with objects in order to abstractly reason about object weight and its effects. For example, understanding that an object's weight influences the outcome of physical events, and that an object's weight can be inferred by observing how another conspecific interacts with an object, are relatively sophisticated abilities, as they require representing object weight as an enduring property of an object that exists and influences events independent of one's own actions. Given that both basic and sophisticated aspects of understanding object weight are important, this dissertation explores both. More specifically, the study presented in Chapter 2 investigates a basic aspect of understanding object weight (i.e., applying prior interactive experience in order to guide subsequent action), while the studies presented in Chapters 3 and 4 investigate more sophisticated aspects (i.e., reasoning about the effect of object weight in physical events and its influence on others' actions, respectively).

In addition, it should be noted that this dissertation explores the understanding of object *weight*, which is similar to yet distinct from related concepts such as mass and density. Specifically, mass is defined as the amount of matter in an object; density is the amount of matter in an object divided by its amount of three-dimensional space (i.e., volume); and weight is the pressing force of an object's mass due to the downward effect of gravity. Thus, events in which an object moves laterally are more accurately described as being influenced by mass (e.g., a run-

away grocery cart and plastic bag heading toward your car in the parking lot), and reasoning about object weight based on material is more accurately described as being influenced by density (e.g., understanding that a loaf of bread is lighter than a similar-sized liter of soda). However, given that the effect of gravity is approximately equivalent everywhere on Earth, the concepts of object mass and weight are often synonymous and can be conflated. In any case, the studies presented in this dissertation are best described as investigating the understanding of object weight, and not mass or density.

Investigating the understanding of object weight is a compelling and fruitful topic of inquiry for several reasons. First, an object's weight has consequences, both for actions and physical events, and these consequences must be anticipated in order to successfully navigate our surroundings. Perhaps the most frequent application of our understanding of object weight is in the context of action. We perform actions with objects constantly, so we must constantly take object weight into account. For example, we anticipate the weight of an object before acting upon it, so preparing to lift a gallon of milk versus a loaf of bread elicit different degrees of anticipatory force (Gordon, Westling, Cole, & Johansson, 1993). Yet, our understanding of object weight is not limited to our own actions—we also use this understanding when interpreting the actions of others. For example, when observing others performing actions, an understanding of object weight may help us to determine the other person's goals and may also provide insight into the other's bodily capabilities and phenomenological experiences. To illustrate, observing the youthful stocker quickly hoisting heavy products without breaking a sweat, while the older manager does so slowly and precisely with a stooped back, informs the observer about their respective goals (i.e., for the former, to restock the shelves swiftly, and for

the latter, to arrange the products purposefully), the relative strengths of each individual, and the amount of effort each is exerting while performing the action.

Our understanding of object weight is also important for interpreting and predicting the outcomes of physical events. This understanding is recruited when, to continue with the grocery store example, you make an effort to stop the cart, but not the plastic bag, from hitting your car. Moreover, understanding the consequences of object weight for physical events helps to solve tangible, concrete problems. For example, heavy objects are often used to secure other objects, such as anchors on boats or paperweights for loose documents. These applications of our understanding of object weight are considerably more abstract than applications of object weight that guide action, as the former requires representing and reasoning about object weight as an enduring property of an object, whereas the latter is a direct application of prior experience.

Another compelling reason for investigating the understanding of object weight is that it has the potential to illuminate how we learn from action experience, or the experience of moving and acting on objects in the environment. Action experience has long been considered a valuable tool for learning about the world (James, 1890; Piaget, 1954), and recent work has confirmed these early notions by demonstrating that action experience facilitates and structures perceptual and cognitive development in a range of domains, including spatial reasoning (Clearfield, 2004), social cognition (Sommerville, Woodward, & Needham, 2005), object and face processing (Libertus & Needham, 2011; Soska, Johnson, & Adolph, 2010) and even emotion understanding (Bertenthal, Campos & Barrett, 1984). Investigating our understanding of object weight uniquely addresses the role of action experience, as weight is an unobservable property that must be discovered by acting on an object. Albeit certain visual cues are often associated with weight, such as size and material, it is unknown whether a large box is empty or packed full until one

actually attempts to lift it. Thus, the understanding of object weight provides an elegant test case for examining whether and how action experience facilitates cognition.

Lastly, object weight provides an opportunity for investigating whether and how individual differences in bodily factors influence cognitive processes that are facilitated by action experience, such as the understanding of object weight. To illustrate this possibility, consider lifting a packed suitcase or re-arranging furniture in the living room. Certainly these actions are not the same for a child, college athlete, or elderly retiree. Indeed, not only is object weight an unobservable object property that must be acted upon in order to experience, but one's experience when acting on objects of different weight is not universally equivalent. In particular, strength has a profound impact on the ability to interact with objects, especially heavy objects. For example, strength impacts whether one can even acquire experience with a given object, as well as the amount of experience one can acquire with an object, due to differences in exerted effort and energy. In addition, strength influences the range of object weights that one can experience and one's perception of weight for objects outside of that range. For example, if I am unable to lift objects heavier than 100 pounds, then any object weighing more than 100 pounds is effectively the same weight to me, as I cannot manipulate anything beyond that threshold. In contrast, stronger individuals may be able to acquire experience with, and appreciate the difference between, a 100-pound object and a 150-pound object. Thus, the understanding of object weight can provide insight into whether differences in bodily factors that influence the acquisition of action experience influence cognitive processes stemming from action experience.

1.1 INFANTS' UNDERSTANDING OF OBJECT WEIGHT

Given the utility of understanding object weight and the ubiquity of its applications, it is perhaps unsurprising that the origins of this knowledge begin in infancy. Studying infants is

particularly valuable for examining the influence of action experience and bodily factors on the understanding of object weight. Though a mature understanding of object weight is undoubtedly influenced by action experience and bodily factors, it is difficult to isolate the effects of these influences in adults, given the wealth of prior experience that adults have and the potential influence of their *former* bodily traits (think of a retired athlete who, years later, is now out of shape). However, in infancy, the slate is cleaner—the effect of prior experience is minimal and in some ways estimable based on their degree of motor development—and their bodies are just beginning to take shape. This allows for a closer assessment of how an understanding of object weight is influenced by action experience and bodily factors.

Research on the development of infants' understanding of object weight began several decades ago (Mounoud & Bower, 1974; Piaget & Inhelder, 1974) and has focused primarily on infants' ability to apply their sensorimotor experiences with objects of different weight in order to guide their subsequent actions on objects. In sum, this work demonstrates that over the first year of life, infants progress from adapting their actions toward objects as a function of weight (e.g., Palmer, 1989), to anticipating an object's weight after previous interactions with the object (e.g., Mash, 2007), to finally inferring object weight based on visual cues (Gottwald & Gredebäck, 2015). For example, by 3 months of age, infants haptically discriminate between objects of different weight (i.e., they hold objects of novel weight longer), but this early ability is rather fragile and can only be accomplished when the objects are presented in the dark (Striano & Bushnell, 2005). By 6 months, infants haptically discriminate between objects of different weight, even in the light, and begin to adapt their actions toward objects as a function of weight, such as waving light objects with a single hand and lifting heavy objects with two hands (Itier, Provasi, & Bloch, 2001; Molina & Jouen, 2003; Palmer, 1989). By 9 months, after previously

lifting an object, infants anticipate the weight of that object when preparing subsequent lifting actions (Mash, 2007; Mounoud & Bower, 1974). Curiously, it is not until 11 months that infants use material information (e.g., Styrofoam) to infer an object's weight, and even then, infants need experience interacting with multiple objects made of that material in order to do so (Hauf & Paulus, 2011). Finally, by 12 months, infants generate force in anticipation of a novel object's weight, after experience interacting with visually similar objects (Gottwald & Gredebäck, 2015; Mash, Bornstein, & Banerjee, 2014). Altogether, this work shows that over the first year of life, infants become increasingly able to adapt and plan their actions according to object weight based on previous experience interacting with objects.

Distinct from advances in infants' ability to apply their experience with objects in order to guide subsequent action according to object weight is the ability to reason about the effect of object weight in physical events. This is an important development, as using object weight in order to predict and interpret the outcomes of physical events is more abstract than using prior experience with an object to guide action. Thus, evidence that infants adapt their actions toward objects as a function of weight does not necessarily mean that they understand the effect of object weight in physical events. However, there is evidence that infants begin to understand the effect of object weight in physical events during the latter half of the first year (Baillargeon, 2002; Hauf, Paulus, & Baillargeon, 2012).

Prior work has found that infants can reason about the effect of object weight in physical events by 9 months of age, though initially this ability is highly experience-dependent. For example, after interacting with two objects of different weight, infants expect that the heavier object will exert and resist greater force than the lighter object in a collision event (i.e., events in which one object hits another object, apparently causing it to move; Baillargeon, 2002).

Similarly, 9-month-old infants can infer an object's weight based on compression of a supporting surface but only after experience interacting with a soft platform and differently weighted objects (Hauf et al., 2012). In this study, infants' ability to infer object weight based on compression of a supporting surface was demonstrated by a preference to reach for the light object in the support event (as infants have a baseline preference for interacting with light rather than heavy objects; Hauf et al., 2012; Hauf & Paulus, 2011). However, by 11 months, infants no longer need to interact with the differently weighted objects in order to infer object weight based on compression information (Hauf et al., 2012), though they still need to interact with a soft platform, which demonstrates that this ability is still maturing. By 3 years of age, children understand that a heavy object will cause a flimsy supporting object to collapse without first needing to manipulate the flimsy support (Smith, Carey, & Wiser, 1985).

Beyond 12 months, infants' understanding of object weight becomes increasingly refined and is used to guide more sophisticated actions and reasoning. For example, in addition to guiding simple actions, an understanding of object weight begins to influence the production of more advanced actions, such as using a precision grasp to obtain objects (Forsberg, Eliasson, Kinoshita, Johansson, & Westling, 1991). Around 5 years of age, children understand more complex effects of object weight in physical events, such as knowing that both object weight and distance from the fulcrum determine whether a scale will balance (Messer, Pine, & Butler, 2008; Siegler, 1976). Interestingly, older children and even adults struggle with certain aspects of understanding object weight, such as differentiating between weight and density when determining if an object will float (Kloos, Fisher, & Van Orden, 2010), which underscores the difficulty of fully understanding the effect of this unobservable property.

In sum, prior work has found that infants are capable of applying their experience interacting with objects in order to guide subsequent actions according to object weight. However, we know far less about other applications of this understanding. For example, it is unknown if infants can apply their experience interacting with objects in order to guide subsequent action according to object weight in novel contexts. Furthermore, only a few studies have investigated infants' understanding of the effect of object weight in physical events (Baillargeon, 2002; Hauf et al., 2012), despite the fact that this type of understanding is qualitatively different and more abstract than the understanding of object weight that guides action production. Lastly, it is unknown if infants' understanding of object weight serves to inform their perception and understanding of others' actions, even though making sense of others' actions is a frequently recruited and important ability. The present dissertation sought to address these gaps.

1.2 OVERVIEW OF THE PRESENT STUDIES

This dissertation presents a series of studies that focus on 3 different aspects of the understanding of object weight. Each study extends upon prior work by probing unexplored aspects of this knowledge in infancy. Chapter 2 investigated infants' ability to plan actions according to object weight in a novel context. Chapter 3 investigated infants' ability to reason about the effect of object weight in a physical event. Chapter 4 investigated whether infants' understanding of object weight influences their perception and understanding of other people's actions. In addition to these main questions, Chapters 3 and 4 explored whether individual differences in strength, a bodily factor that gates the acquisition of experience interacting with objects, influences infants' understanding of object weight.

1.2.1 *Can infants apply object weight information acquired in one context in order to guide action in a novel context?*

Chapter 2 investigated whether infants can flexibly apply object weight information acquired by performing action in one context in order to guide action according to object weight in a novel context. Indeed, generalizing object weight information across contexts and situations, including contexts that one has no direct experience with, is a vital element of skilled and mature action production (Wolpert & Flanagan, 2010). As such, it is important to determine when and how this ability emerges during the course of typical development. In addition, Chapter 2 explored whether encountering unexpected object weight information affects infants' ability to guide their actions according to object weight. Though recent evidence suggests that learning is facilitated after encountering unexpected information, it is not yet clear whether learning is facilitated following *any* type of unexpected information, or if this effect is unique for information that violates physical principles (Gerken, Dawson, Chatila, & Tenenbaum, 2015; Schulz, 2015; Stahl & Feigenson, 2015). For example, infants who observed an object appear to pass through a solid wall learned other properties of the object (e.g., its sound) better than infants who observed the object stop at the wall that blocked its path (Stahl & Feigenson, 2015). Though this result is promising, it is not yet clear whether learning would be facilitated after encountering other types of unexpected information.

In the study presented in Chapter 2, infants directly interacted with two visually distinct objects of different weight (e.g., lifted and pushed the objects) and were then encouraged to retrieve the objects in a means-end task. We investigated whether infants would apply object weight information gleaned from lifting and pushing the objects (i.e., the familiar context) in order to guide their actions when attempting to retrieve the objects in the means-end task (i.e., the novel context). In addition, Chapter 2 compared performance between infants who held

accurate object weight representations, because they interacted with the same pair of objects throughout the task, to infants who held inaccurate object weight representations, due to a surreptitious reversal of the objects' color-weight pairings between the familiar and novel contexts. This manipulation served to reveal whether infants who held accurate object weight representations would be more successful in the novel context compared to infants who held inaccurate object weight representations (which should be the case if infants apply object weight information acquired in one context in order to guide action in a novel context). In addition, this manipulation explored whether encountering unexpected information influences infants' ability to guide their actions according to object weight in the novel context.

1.2.2 *Do infants understand the effect of object weight in physical events?*

Chapter 3 investigated whether infants can apply their understanding of object weight in order to interpret and predict the outcome of physical events. This type of understanding is qualitatively different than the understanding of object weight that is used to guide action, as infants must consider how object weight will influence the outcome of a physical event by abstracting upon, as opposed to directly applying, prior experience. If infants reason about the effect of object weight in order to interpret and predict the outcome of physical events, it would demonstrate that infants have an abstract understanding of object weight as an unobservable causal mechanism. Moreover, predicting the outcome of physical events is necessary for adaptive functioning, so examining how typically developing infants are able to accomplish this feat, including what type of experience is required in order to do so, is important.

Another unexplored issue that is addressed in Chapter 3 concerns individual differences in infants' understanding of the effect of object weight in physical events. Although prior work has found that action experience and extracting weight-relevant information via action is

important (Hauf et al., 2012; Itier et al., 2001; Palmer, 1989), it is unknown whether bodily factors that influence the nature and acquisition of this experience play a role. This possibility seems likely, given the importance of interacting with objects for understanding object weight. Accordingly, Chapter 3 explored whether strength, a bodily factor that gates the acquisition of infants' experience interacting with objects, has a downstream effect on their ability to reason about the effect of object weight in physical events. Thus, Chapter 3 has the potential to identify a new factor that could account for differences in infants' understanding of object weight.

In Experiment 1 of Chapter 3, infants interacted with a soft, compressible platform and were then presented with support events in which two visually identical objects of different weight were placed on top of the platform, which revealed that one object compressed the platform while the other object did not. I examined whether infants could apply their understanding of object weight and their experience interacting with the soft platform in order to infer the weight of the objects based on compression of the supporting surface. In addition to reasoning about the outcome of the support event, I also examined whether infants generate predictions for support events involving heavy and light objects. In Experiment 2 of Chapter 3, infants interacted with a soft platform and two visually distinct objects of different weight and were then shown support events that were either consistent with the causal effect of object weight (i.e., an object identical to the heavy object that infants had interacted with compressed the platform) or inconsistent with the causal effect of object weight (i.e., an object identical to the light object that infants had interacted with compressed the platform). If infants generate accurate predictions for the effect of object weight in support events, they should exhibit heightened attention to events that are inconsistent with the causal effect of object weight relative to events that are consistent with it. Importantly, neither event would appear surprising to an

outside observer, so differences in infants' attention cannot be attributed to visual anomalies. Indeed, the events are only surprising if infants apply their prior experience interacting with the objects and encoding their respective weights in order to generate expectations for the outcome of the support event. In addition, I examined relations between infants' strength, measured via a novel pull-force assessment, and their ability to interpret and predict the outcome of support events.

1.2.3 *Does infants' understanding of object weight influence their perception and understanding of another person's actions?*

Chapter 4 investigated whether and how infants' understanding of object weight influences their perception and understanding of another person's actions. Making sense of others' actions is a vital ability that transforms the social world from a chaotic mix of bodies in motion into a coherent and meaningful stream of information. Previous research demonstrates that infants' understanding of others' actions undergoes rapid development during the first year of life (Woodward, 1998), which is thought to be facilitated by advances in infants' own action production capabilities (Sommerville, Woodward, & Needham, 2005). Indeed, there is an abundance of work demonstrating that action production influences action perception and understanding (Hauf, Aschersleben, & Prinz, 2007; van Elk, van Schie, Hunnius, Vesper, & Bekkering, 2008) and vice versa (Casile & Giese, 2006; Knoblich & Flach, 2001). However, it is unknown whether infants' understanding of object weight, which is built via action experience, influences their perception and understanding of others' actions. Compellingly, there is evidence for this relation in adults (Alaerts et al., 2010a; Mima, Simpkins, Oluwatimilehin, & Hallett, 1999). For example, when observing others lifting objects, adults accurately estimate the weight of the object being lifted and the amount of effort that the other person is exerting (Shim,

Carlton, & Kim, 2004). This suggests that infants may also apply their understanding of object weight in order to recognize and understand another person's phenomenological experience of effort when acting on objects of different weight.

In addition to this main question, Chapter 4 investigated whether individual differences in infants' strength account for variability in infants' understanding of another person's effort when acting on objects of different weight. Action perception and understanding is a particularly compelling area in which to probe the role of strength, as research suggests that the influence of the body on cognition is greater in domains pertaining to action (Moseley, Kiefer, & Pulvermüller, 2016). Together, Chapters 3 and 4 will investigate whether strength has a non-existent or constant influence on infants' understanding of object weight, or whether the influence of strength is variable depending on the prominence of action in the task.

In Chapter 4, infants alternated between lifting, and watching an experimenter lift, three objects of different weight. During their production and observation of lifts, infants' neural activity was recorded via electroencephalography. In particular, I examined attenuation of the mu rhythm, a neural frequency recorded over sensorimotor areas that is linked to the shared neural system underlying action production and action perception (Marshall & Meltzoff, 2011). The degree of mu rhythm attenuation during action observation is thought to reflect the observer's understanding of the other person's action, with greater mu rhythm attenuation reflecting heightened perception and understanding of the other person's action. Infants' strength was also measured via a novel grip strength assessment, and I investigated relations between strength and variability in mu rhythm attenuation during action observation.

1.3 BROAD IMPLICATIONS OF THE PRESENT STUDIES

Beyond painting a more complete picture of infants' understanding of object weight, the present studies have the potential to inform major issues in the field. For example, a defining issue for developmental psychologists regards the nature of infants' conceptual representations. In particular, are infants' representations best characterized as context-specific (e.g., Adolph, 2000; Lockman & Adams, 2001; Revillo, Cotella, Paglini, & Arias, 2015; Shields & Rovee-Collier, 1992), or are infants' representations more accurately described as being broad, abstract and generalizable (e.g., Gerken, 2006; Téglás, Girotto, Gonzalez, & Bonatti, 2007; Téglás et al., 2011; Xu & Kushnir, 2013)? Indeed, in some ways, infants' representations seem highly restricted. For example, infants' ability to reproduce an action in delayed imitation tasks is dramatically influenced by whether the context (e.g., experimental setting) is the same or different from infants' original experience with the action (Hayne, Boniface, & Barr, 2000; Learmonth, Lamberth, & Rovee-Collier, 2004, 2005). Yet, in other ways, infants seem quite flexible, generative, and able to transfer knowledge from one context to another. For example, infants generate accurate predictions for never-before-seen events based on physical and statistical reasoning (Denison, Trikutam, & Xu, 2014; Téglás et al., 2007, 2011), and infants can extract and generalize patterns from one set of stimuli to another (Gerken, 2004; Gómez & Lakusta, 2004; Saffran, Pollak, Seibel, & Shkolnik, 2006).

The present studies inform this debate by investigating the flexibility of infants' representations of object weight. Specifically, Chapter 2 examined whether infants can transfer representations of object weight acquired via action in one context in order to guide action in a novel context. Chapters 3 and 4 examined whether infants' representations of object weight are sufficiently abstract in order to influence their understanding in areas outside of action

production (i.e., physical reasoning and action perception). Altogether, the present studies have the potential to show that infants' representations of object weight are relatively abstract and guide reasoning across contexts and areas. This could suggest that knowledge with wide ramifications, such as the understanding of object weight, is more readily generalized than knowledge with narrow ramifications, which may be the case in imitation (i.e., actions are often specific to the context they were learned in, such as learning a new recipe is specific to the kitchen). Alternatively, the present work could suggest that infants' representations of object weight are context-specific and develop in a piecemeal fashion.

The studies in this dissertation also inform the question of what factors facilitate early learning. Recent evidence suggests that encountering unexpected information facilitates learning over and above encountering expected information (Gerken et al., 2015; Stahl & Feigenson, 2015). To review the prior findings, infants who observed an object violate physical principles, such as appearing to pass through a solid wall, learned other properties of the object (e.g., its sound) better than infants who observed the object accord with physical principles, such as stopping at the wall that blocked its path (Stahl & Feigenson, 2015). The authors of this study claimed that learning was facilitated because the unexpected information violated physical principles. However, it seems distinctly possible that unexpected information of any type could facilitate learning, even if the information is only unexpected in light of recent experience (Schulz, 2015). Chapter 2 addressed this possibility by investigating infants' ability to guide their actions in a novel context after encountering unexpected object weight information. More specifically, after interacting with objects in the familiar context, some infants had the objects' color-weight pairings reversed, unbeknownst to them, before attempting to retrieve them in the novel context. As such, the object weight information was unexpected in light of infants' recent

experience with the objects but not because the objects violated any physical laws. If learning is uniquely facilitated following information that violates physical principles, infants who encounter unexpected object weight information should struggle to apply their updated representations of object weight in order to guide their actions in the novel context.

Alternatively, if infants rapidly learn after encountering unexpected object weight information, they should be able to quickly adapt and appropriately guide their actions according to the new object weight information.

Another hotly debated topic is what role, if any, does the body play in learning and cognition? Here, there is a lively debate between traditional cognitive theorists, who propose that the body plays a supplementary or even epiphenomenal role in cognition (Mahon & Caramazza, 2009) and embodied cognition theorists, who propose that the body plays a constitutive role in cognition (Barsalou, 2008). Although the present studies do not directly probe whether the body plays a causal or supplementary role in cognition, they do inform this debate. Specifically, Chapters 3 and 4 explore whether strength, a bodily factor that influences the acquisition of experience with objects, influences infants' understanding of object weight. If strength is related to infants' understanding of the effect of object weight in physical events (Chapter 3) and their perception and understanding of others' actions (Chapter 4), it would lend support to the argument that the body plays a broad and integral role in cognition. Alternatively, if strength is unrelated to infants' understanding of object weight in both studies, it would be consistent with the perspective that cognition is relatively encapsulated from the body. A third possibility is that the influence of strength on the understanding of object weight will vary between the two studies. If that is the case, it is more likely that an influence of strength will be found in Chapter 4, which investigated action perception, than in Chapter 3, which investigated physical

reasoning, as Chapter 4 is more dependent upon and related to action experience which is impacted by strength.

Altogether, this dissertation investigates the flexibility of infants' understanding of object weight by probing how this understanding influences areas outside of action production in familiar contexts. In addition, this work probes the development of a more sophisticated aspect of understanding object weight: reasoning about the effect of object weight in physical events. These studies also explore whether individual differences in bodily factors influence cognitive processes that stem from action experience—specifically, whether strength influences infants' understanding of object weight in physical events and when observing others' actions. These results will help to determine whether the influence of the body on cognition is variable, or constant, depending on the prominence of action in the task. More broadly, this dissertation will inform our understanding of the nature of infants' conceptual representations by investigating whether infants' representations of object weight are better characterized as abstract and generalizable or context-specific. In sum, this dissertation will advance our collective knowledge of infants' ability to learn about object weight and apply this understanding in new contexts and to interpret the physical and social world.

Chapter 2. TWELVE-MONTH-OLD INFANTS ANTICIPATORILY PLAN THEIR ACTIONS ACCORDING TO EXPECTED OBJECT WEIGHT IN A NOVEL MOTOR CONTEXT

Upshaw, M. & Sommerville, J. (2015). *Frontiers in Public Health*.

2.1 ABSTRACT

Planning actions in anticipation of object weight is fundamental to skilled action production. The present study investigated whether infants can apply weight information gained from direct actions on objects in order to plan their actions according to object weight in a novel and indirect motor context. In the present study, two groups of 12-month-old infants were provided with experience acting directly on two blocks of different weights and colors (70 g versus 470 g; red versus yellow). Subsequently, infants were administered a novel task in which the same blocks (standard condition; $n = 60$), or blocks of the reversed color-weight pairings (switch condition; $n = 60$), were placed out-of-reach, on top of a cloth, and infants were encouraged to retrieve the block by acting on the cloth. Infants in the switch condition produced more failed cloth pulls when retrieving the 470 g block, due to inadequate generation of anticipatory force, relative to infants in the standard condition. This demonstrates that infants' force on the cloth was prospectively generated based on their mental representation of the supported block's weight, which was formed through their previous direct actions on the object. Thus, infants use information about the weight of an object in order to anticipate how to obtain that object in a novel and indirect problem-solving context.

2.2 INTRODUCTION

The ability to successfully navigate the physical world depends critically on our knowledge and understanding of a wide range of object properties. Chief among these properties is object weight: representing and understanding the consequences of weight is central to our ability to plan actions on objects, understand other people's behavior, and predict event outcomes. Imagine helping a friend move to a new apartment: accurately representing object weight allows one to decide when to use a single hand versus two hands in order to lift a packed box, to recognize that when a box slips through one's friend's grasp it is likely because she has underestimated the weight of the box, and to understand that a box packed full of books, but not a box packed full of pillows, can serve to prop open an apartment door. Given the centrality of weight perception and the importance of understanding the impact of object weight on others' actions and event outcomes, it is perhaps unsurprising that the rudiments of weight perception can be traced back to infancy. Infants can discriminate objects on the basis of weight (e.g., Molina and Jouen, 2003), adjust their actions on objects according to weight (Palmer, 1989), and use information about the outcome of physical events (e.g., the degree to which an object compresses a supporting object) in order to determine the weight of an object (Hauf et al., 2012).

In addition to differentiating objects on the basis of object weight and adjusting actions online based on object weight, a critical component of weight perception involves generating actions in *anticipation* of an object's weight. Adults use their prior experience with objects (Gordon et al., 1993; Johansson & Westling, 1988) as well as visual cues that are typically associated with weight (e.g., size; Gordon et al., 1991a; Mon-Williams & Murray, 2000) in order to anticipatorily scale the force of their actions according to object weight. For example, adults generate greater lifting force when lifting an object that is anticipated to be heavy than one that is

anticipated to be light (Gordon et al., 1993). Evidence suggests that the origins of this ability can be traced back to infancy. After previous experience interacting directly with objects of varying weight, infants aged 9 months and older exert more force when lifting an object they expect to be heavy than an object they expect to be light (Mash, 2007; Mounoud & Bower, 1974).

The novel question addressed in the current study is whether infants can use information about the weight of an object garnered through their direct actions in order to anticipatorily plan their actions according to the object's weight in a novel and indirect motor context. Past work provides some evidence for anticipatory action planning in infancy. For example, infants pre-configure their hand shape in order to conform to the size, shape and orientation of an object prior to object contact (Barrett et al., 2008; Daum et al., 2011; Lockman et al., 1984; von Hofsten & Rönqvist, 1988), and the kinematics of infants' reaches towards objects, such as the speed of the reach, vary as a function of what infants intend to do with the object once they pick it up (Claxton et al., 2003). However, no existing work has investigated whether infants' ability to use representations of object weight extends to planning their actions as a function of object weight in a novel and indirect motor context.

The present study investigated whether 12-month-old infants would encode object weight information acquired through directly lifting an object and subsequently apply this information to scale the force of their actions on an intermediary object that supported the previously lifted object. We selected 12-month-old infants for this experiment because this is the age at which infants initially become highly successful at solving means-end tasks (i.e., tasks that require the infant to act on an intermediary object in order to obtain a goal object; Sommerville & Woodward, 2005). Infants first received a training phase in which they were encouraged to repeatedly lift two plastic blocks that were identical in size, shape, and material, but that varied

in weight (70 g versus 470 g) and in color (red versus yellow). Accordingly, one block was of standard weight for its size and material (70 g) whereas the other block was decidedly heavier (470 g). After the training phase, infants received a novel cloth-pulling task in which a single block was placed on top of a piece of cloth, such that the block itself was out of the infants' reach but the cloth was not. Thus, in order to retrieve the block infants must first act on the cloth. Infants in the standard condition were administered the cloth-pulling task using the same blocks that they interacted with during the training phase. In contrast, infants in the switch condition were administered the cloth-pulling task using blocks that were visually identical to those used in the training phase, but were actually of the reversed color-weight pairings, unbeknownst to infants (i.e., if the red block weighed 70 g during the training phase, it weighed 470 g during the cloth-pulling task).

Our goal was to investigate whether infants anticipatorily varied the force of their actions on the cloth based on their representation of the supported block's weight. We focused on instances in which infants attempted to pull the cloth in order to retrieve the 470 g block, yet, in doing so, failed to bring the block towards them, due to an under-application of force on the cloth ("failed cloth pulls"). We hypothesized that if infants accurately encoded the 470 g block's weight during the training phase, and then used this information to plan their actions on the cloth, infants in the switch condition should produce more failed cloth pulls when retrieving the 470 g block than infants in the standard condition. In other words, infants in the switch condition (but not infants in the standard condition) should underrepresent the weight of the 470 g block during the cloth-pulling task (i.e., represent the block weight as 70 g), due to the surreptitious reversal of the blocks' color-weight pairings after the training phase; consequently, when pulling on the

cloth, infants in the switch condition should anticipatorily generate force that is insufficient for retrieving the 470 g block, leading to failed cloth pulls.

Thus, the present study was designed to investigate whether infants would use their representation of the block's weight in order to guide their actions in a novel and indirect context, at the initial point at which infants were presented with the problem and in the absence of trial-and-error learning. A demonstration that infants use experience gained from directly acting on an object in order to guide their actions in a novel and indirect problem-solving context would provide evidence that infants form "motor inferences." That is, it would demonstrate that infants use information gained from prior experience in order to generate a novel action or motor plan that guides behavior in a new context.

2.3 MATERIALS AND METHODS

2.3.1 *Participants*

One hundred and twenty healthy, full-term, 12-month-old infants ($M = 12$ months, 16 days, range = 12 months, 2 days – 13 months, 21 days; 59 females and 61 males) participated in the study. Infants were recruited from a large city in the Pacific Northwest and were primarily Caucasian ($n = 82$; Asian: $n = 5$; Black: $n = 1$; Hispanic: $n = 1$; Multiracial: $n = 21$; and Other-race: $n = 3$; ethnicity data was not provided for $n = 7$ participants). Parents provided written informed consent before the testing procedures, and all study procedures were approved by the university's Internal Review Board before the research was conducted. Twenty-six additional infants were tested but excluded from the final sample due to fussiness ($n = 14$), experimental error ($n = 6$), not interacting with the blocks during the training phase ($n = 4$), or failing to solve the cloth-pulling task during both pre-test trials ($n = 2$). Infants were randomly assigned to the

standard condition ($n = 60$; $M = 12$ months, 17 days; 31 males), or the switch condition ($n = 60$; $M = 12$ months, 15 days; 30 males).

Participants sat in a high chair. In cases of excessive distraction or fussiness, infants were moved to their parents' lap (standard condition, $n = 11$; switch condition, $n = 13$). The study was conducted on a 61 cm x 91.4 cm x 76.2 cm wooden table with an attached sliding top, which allowed the experimenter to arrange the stimuli out of the infant's reach before starting each trial.

2.3.2 Procedure

Each infant took part in a training phase, followed by two cloth-pulling pre-test trials, and four cloth-pulling test trials. Infants were seated directly in front of the testing table throughout the experiment. The experimenter sat to the right of the infant, facing the adjacent side of the table, approximately 51 cm from the infant.

2.3.3 Training phase

The training phase was designed to allow the infant to directly interact with each block in order to discover and encode each block's respective weight properties. Infants were given two plastic blocks, one red and one yellow, each of different weights, one 70 g and one 470 g (color-weight pairing counterbalanced across infants). Each block measured 8.9 cm on each side. The 470 g block was weighted by inserting metal washers and cotton batting (included to eliminate noise from the washers) into the ordinarily hollow interior of the block and was sewn back together using plastic fishing wire. The 70 g block was not weighted, but was similarly stitched, in order to maintain an identical appearance (aside from color) to the 470 g block.

The training phase started with a free play period, in which the experimenter placed both the 70 g and 470 g blocks in front of the infant, and allowed the infant to freely explore and

manipulate them. The experimenter encouraged the infant to spend equivalent time interacting with each block, by directing infants' attention as appropriate, during the first 40 seconds of the training phase (i.e., free play period). During the next part of the training phase, the experimenter modeled an action with a single block, and the infant was encouraged to reproduce the experimenter's action. For example, the experimenter lifted and placed each block (separately, and one at a time) on top of an inverted plastic container (25.4 cm x 17.8 cm x 10.2 cm) that served as a platform, and infants were encouraged to reproduce the experimenter's lifting and placing action. Then, the experimenter lifted and dropped each block (separately, and one at a time) into a clear, plastic bucket (17.1 cm x 14.6 cm x 12.7 cm), and infants were again encouraged to reproduce the experimenter's lifting and dropping action. Each of these actions were modeled twice, and infants were encouraged to reproduce each action twice, with both the 70 g and 470 g blocks (in alternation; order counterbalanced across infants).

2.3.4 *Pre-test trials*

The goal of the pre-test trials was to determine that infants were capable of solving the cloth-pulling task, before administration of the test trials; given prior work, we anticipated that 12-month-old infants would readily solve this problem (Sommerville & Woodward, 2005). Two pre-test trials were administered with novel bath toys, which did not resemble the blocks used in the training phase. To administer the pre-test trials, the experimenter moved the sliding table top out of the infant's reach, laid a rectangular cloth (38.1 cm x 20.3 cm) on the table, and placed a bath toy (e.g., a multi-colored spaceship or a pink bug) on the far end of the cloth. The experimenter then tapped the toy, while saying, "*Can you get it? Can you get it?*" in order to encourage infants to retrieve the bath toy.

2.3.5 *Test trials*

After the pre-test trials, infants were administered two test trials with each block, for a total of four test trials.

For infants in the standard condition, the blocks used in the test trials were the same blocks used during the training phase (i.e., if the red block was 470 g during the training phase, it weighed 470 g during the test trials). For infants in the switch condition, the color-weight pairings were reversed from the training phase (i.e., if the red block was 70 g during training, it weighed 470 g during test trials). Test trials were administered using the same procedure as the pre-test trials: the experimenter moved the sliding table top out of the infant's reach, laid the cloth on the table, and placed either the 70 g or the 470 g block on the far end of the cloth (order counterbalanced across infants; block weight alternated on each test trial). The experimenter then tapped on the block while saying, "*Can you get it? Can you get it?*" before sliding the table top within the infant's reach, initiating the test trial. If the infant made no attempt to retrieve the block within ten seconds, the experimenter encouraged the infant to retrieve it again by tapping on the block and saying, "*Can you get it? Can you get it?*" Infants were given ten additional seconds to retrieve the block. If, after a period of twenty seconds, the infant still had not retrieved the block, the experimenter placed the block directly in front of the infant. Each infant was given several seconds at the end of every test trial to interact with the block before starting the next test trial, in order to encourage the infant's behavior and maintain his/her attention.

Importantly, while handling the blocks during the training phase and the test trials, the experimenter always lifted each block with a single hand, and controlled the pace and measure of her arm movements, so that no visual clues to block weight were provided to the infant.

2.4 CODING AND RELIABILITY

All sessions were video recorded, and coding was completed off-line by observers who were unaware of the weight of the blocks and of the conditions in which infants participated.

2.4.1 *Training phase*

First, we coded time spent in simultaneous hand-and-eye contact with each block (referred to hereafter as 'contact time'), in order to ascertain that infants had equal opportunity to interact with and encode the weights of both blocks. Second, we coded the number of one-handed and two-handed lifts performed with each block in order to determine that infants adjusted their lifting actions with each block based on its weight. Lifts were operationalized as manual actions that elevated at least one corner of the block off of the table as this demonstrated that the infant had used his or her own force to vertically displace the block.

2.4.2 *Pre-test trials*

In order to ensure that infants were able to solve the cloth-pulling task, we coded whether infants successfully moved the bath toy within reach through their actions on the cloth for each of the two pre-test trials. Infants who failed to solve the cloth-pulling task during both pre-test trials were excluded from subsequent analysis ($n = 2$; see Participants).

2.4.3 *Test trials*

The primary goal of the study was to determine whether infants varied the force of their actions on the cloth as a function of their expectation of the supported block's weight, which was based on their training experience. Accordingly, we coded the number of failed cloth pulls produced by infants when attempting to retrieve each block. Failed cloth pulls occurred

whenever infants attempted to pull the cloth in order to retrieve the supported block, but failed due to an under-application of force. Failed cloth pulls were formally operationalized as instances in which the infant's hand contacted the cloth and moved backward, yet failed to move the block any distance whatsoever. Furthermore, to ensure that infants' cloth-pulling actions were clearly directed towards obtaining the block (rather than directed towards the cloth itself), failed cloth pulls were only coded and analyzed if they appeared to be planfully and intentionally directed towards the goal of retrieving the block, using criteria established by previous work (Sommerville & Woodward, 2005; i.e., visual fixation on the block prior to reaching for and while pulling on the cloth; please see <https://sites.google.com/site/infantsactionplanningbyweight/> for a video example of a failed cloth pull).

2.4.4 *Reliability*

A second observer independently coded the number of failed cloth pulls for a randomly selected 25% of participants. Reliability was high across all four test trials: first 470 g block test trial, $K = .84$, interrater agreement = 90%; first 70 g block test trial, $K = 1.0$, interrater agreement = 100%; second 470 g block test trial, $K = .77$, interrater agreement = 83.3%; second 70 g block test trial, $K = 1.0$, interrater agreement = 100%.

2.5 RESULTS

2.5.1 *Training phase*

2.5.1.1 **Contact time**

Paired samples t-tests confirm that infants spent equal time interacting with the 470 g block (standard condition: $M = 34.65$ s, $SE = 1.57$ s; switch condition: $M = 36.35$ s, $SE = 1.53$ s)

and with the 70 g block (standard condition: $M = 34.12$ s, $SE = 1.76$ s; switch condition: $M = 36.22$ s, $SE = 1.91$ s) within each condition: standard condition: $t(59) = .41$, $p = .69$; switch condition: $t(59) = .07$, $p = .95$. Importantly, infants' contact time with the 470 g and 70 g blocks did not vary as a function of condition, as confirmed by independent samples t-tests: 470 g block: $t(118) = .77$, $p = .44$; 70 g block: $t(118) = .81$, $p = .42$.

2.5.1.2 Lifts

To address whether infants successfully encoded the blocks' respective weights during training, we analyzed one- versus two-handed lifts performed with each block (see Table 1 and Figure 1). Looking at the sample as a whole, paired samples t-tests confirm that infants performed more one-handed lifts with the 70 g block than with the 470 g block, $t(119) = 8.27$, $p < .001$, $d = .77$, and more two-handed lifts with the 470 g block than with the 70 g block, $t(119) = -3.31$, $p = .001$, $d = .27$. These findings provide evidence that infants adapted their actions on the basis of block weight, and, accordingly, that infants encoded the respective weights of the blocks during the training phase. Importantly, independent samples t-tests confirm that the number of block lifts performed during the training phase did not differ between conditions: one-handed lifts of the 70 g block, $t(118) = .13$, $p = .90$; two-handed lifts of the 70 g block, $t(118) = .55$, $p = .58$; one-handed lifts of the 470 g block, $t(118) = 1.07$, $p = .29$; two-handed lifts of the 470 g block, $t(118) = 1.36$, $p = .18$; and the total number of one- and two-handed lifts with both blocks, $t(118) = 1.18$, $p = .24$.

Table 1. Means (and standard errors) for the number of one- and two-handed lifts performed during the training phase.

Variable	Standard Condition		Switch Condition	
One-handed lifts				
70 g block	10.73	(.72)	10.90	(1.06)
470 g block	5.73	(.42)	6.53	(.62)
Two-handed lifts				
70 g block	3.25	(.67)	3.78	(.70)
470 g block	4.27	(.48)	5.38	(.67)

2.5.2 *Pre-test trials*

2.5.2.1 **Solve rates**

On average, infants were successful on 1.9 ($SE = .03$) out of two pre-test trials. An independent samples t-test confirms that performance on the pre-test trials did not differ by condition, $t(118) = .60$, $p = .55$, suggesting that infants in both conditions were equally and highly skilled at solving the cloth-pulling task.

2.5.3 *Test Trials*

2.5.3.1 **Failed cloth pulls**

In order to determine if performance on the cloth-pulling task varied by condition, test trial pair, or block weight, we conducted a $2 \times 2 \times 2$ repeated measures ANOVA on the number of failed cloth pulls performed on each of the four test trials. Block weight (70 g versus 470 g) and trial pair (1st pair versus 2nd pair) were within-subjects variables and condition (standard versus switch) was the between-subjects variable. We hypothesized that infants in the switch condition would produce more failed cloth pulls on the first 470 g block test trial than infants in the standard condition, that is, before infants in the switch condition were aware of the color-weight pairing reversal.

We found a main effect of block weight, $F(1) = 63.13, p < .001, \eta_p^2 = .41$. A follow-up paired samples t-test confirms that, overall, infants performed more failed cloth pulls on the 470 g block test trials ($M = .73, SE = .08$) than on the 70 g block test trials ($M = .10, SE = .03$), $t(118) = 7.84, p < .001, d = 1.0$. We also found a significant trial pair by condition interaction, $F(1) = 7.34, p = .008, \eta_p^2 = .075$. Follow-up, independent samples t-tests reveal that performance in each condition varied as a function of trial pair: infants in the switch condition performed more failed cloth pulls than infants in the standard condition on the first pair of test trials, $t(110) = 2.83, p = .006, d = .14$, but not on the second pair of test trials, $t(94) = -1.10, p = .27$. Critically, these effects were underscored by a hypothesized three-way interaction between block weight, trial pair, and condition, $F(1) = 5.52, p = .021, \eta_p^2 = .057$. Planned independent samples t-tests reveal that infants in the switch condition performed more failed cloth pulls on the first 470 g block test trial than infants in the standard condition, $t(115) = 2.71, p = .008, d = .49$; however, failed cloth pulls did not differ by condition on the first 70 g block test trial, $t(111) = 1.23, p = .22$, the second 70 g block test trial, $t(104) = .65, p = .52$, nor on the second 470 g block test trial, $t(101) = .94, p = .35$ (see Table 2 and Figure 2). Post-hoc paired samples t-tests reveal that infants in the switch condition reduced the number of failed cloth pulls from the first 470 g block test trial to the second 470 g block test trial, $t(47) = 3.58, p = .001, d = .50$, whereas infants in the standard condition did not, $t(51) = -.62, p = .54$.

Table 2. Means (and standard errors) for the number of failed cloth pulls performed during the test trials.

	Standard Condition		Switch Condition	
1 st Trial pair				
70 g block	.05	(.03)	.14	(.06)
470 g block	.58	(.09)	1.03	(.14)
2 nd Trial pair				
70 g block	.06	(.03)	.09	(.05)
470 g block	.68	(.15)	.50	(.12)

2.6 DISCUSSION

The primary goal of the current study was to investigate whether 12-month-old infants would apply object weight information gained through directly interacting with two blocks of the same size and shape but of different weights, in order to anticipatorily plan their actions according to object weight in a novel and indirect motor context. Specifically, following a training phase, during which infants were encouraged to act directly on the blocks (e.g., lift, drop, and freely manipulate them), infants received test trials in which they were encouraged to retrieve the same blocks (standard condition), or visually identical blocks of reversed color-weight pairings (switch condition), when the blocks were placed out-of-reach, on top of a piece of cloth. We investigated whether infants varied the force of their actions on the cloth on the basis of their mental representation of the supported block's weight, which was established during training.

The fact that infants preferentially used one hand to lift the 70 g block and two hands to lift the 470 g block during the training phase, and did so at equal rates across conditions, provides evidence that infants encoded the respective block weights and adapted their actions accordingly. Thus, we investigated infants' frequency of failed cloth pulls (i.e., instances in which infants pulled the cloth but failed to move the block due to an under-application of force) and compared the frequency of failed cloth pulls across the two conditions.

Infants across both conditions produced more failed cloth pulls when the supported block weighed 470 g versus 70 g. It is possible that this finding emerged because infants have come to expect that objects of this size and material weigh significantly less than 470 g, based on their everyday experience with visually similar objects; a non-mutually exclusive possibility for this result is that infants are generally conservative in their use of force. In either case, the critical question of interest was whether infants' production of failed cloth pulls would vary as a function of condition on the 470 g block test trials. Our results demonstrated that infants in the switch condition produced more failed cloth pulls on the first 470 g block test trial than infants in the standard condition. This finding suggests that infants encoded the color-weight pairings of the blocks during the training phase and used this information to anticipatorily plan their actions on the cloth according to their expectations of the supported block's weight.

Critically, the design of our experiment allows us to rule out the possibility that differences in the number of failed cloth pulls across conditions reflects infants' inability to adequately *adapt* their actions on the basis of online sensorimotor feedback. First, the test trials were administered in an identical manner across conditions: infants acted on the same cloth, in order to retrieve a block of identical weight. The fact that the physical properties of the task were identical across conditions, but that infants' mental representations of the block's weight differed, ensures that the difference in failed cloth pulls on the first 470 g block test trial across conditions was due to differences in infants' use of force in *anticipation* of the 470 g block's weight. The results from the training phase and pre-test trials also suggest that the results were not attributable to one condition having received more experience with the blocks during the training phase: across both conditions, infants spent equivalent time in contact with each block, and both conditions adjusted their behavior during the training phase based on the blocks'

respective weight properties. In addition, these results are not attributable to one condition being better able to solve the cloth-pulling task, as infants in both conditions solved the pre-test trials at equivalently high rates. Lastly, these findings cannot be explained by a general tendency for infants in the switch condition to underutilize force when acting on the cloth, as infants in both conditions were equally likely to produce failed cloth pulls on the second 470 g block test trial, and both conditions produced equivalent numbers of failed cloth pulls on the 70 g block test trials.

Interestingly, differences between the two conditions were found only on the first 470 g block test trial and not on the second 470 g block test trial. Infants in the switch condition significantly improved their performance between the first and second 470 g block test trials, decreasing the number of failed cloth pulls on the second 470 g block test trial relative to the first. In contrast, infants in the standard condition performed equivalent numbers of failed cloth pulls on both the first and second 470 g block test trials. This demonstrates that infants in the switch condition appropriately adjusted their behavior after discovering the color-weight pairing reversal on the first 470 g block test trial. In comparison, the standard condition did not adjust or improve their performance between the 470 g block test trials, despite having room for improvement (i.e., failed cloth pulls on the 470 g test trials exceeded those on the 70 g test trials).

An intriguing question regards *how* infants in the switch condition were able to increase their anticipatory force on the second 470 g block test trial based on sensorimotor feedback received on the first 470 g block test trial. As infants' ability to plan their grasp in anticipation of acting on an object undergoes rapid development in the first year of life (such as matching its shape, orientation and size; see Barrett & Needham, 2008; Lockman et al., 1984; von Hofsten & Rönqvist, 1988), we wondered whether changes in infants' hand posture contributed to their

increased generation of anticipatory force on the second 470 g block test trial. To investigate this possibility, we looked for changes in infants' hand configuration between the first and second 470 g block test trials for a subset of infants ($n = 40$), such as whether infants grasped the cloth with the thumb and opposing fingers or pulled the cloth with a flat and open hand. However, we did not find a systematic pattern of changes between infants' hand configuration on the first 470 g block test trial and their hand configuration on the second 470 g block test trial. This null result is similar to previous work demonstrating that infants' ability to anticipatorily configure their grasp when acting on intermediary objects lags behind their ability to do so when acting directly on objects, and is still developing well into the second year of life (Jovanovic & Schwarzer, 2011; McCarty et al., 1999). Nevertheless, it is possible that subtle changes in infants' hand configuration, such as their precise finger placement, contributed to their increased generation of anticipatory force on the second 470 g block test trial. However, as infants' ability to anticipatorily generate force according to object weight is diminished when executing developmentally mature hand configurations (e.g., pincer grasp; Forssberg et al., 1991; Mash, 2007), this possibility seems unlikely.

In addition, the present findings have implications for the development of the neural circuitry underlying motor planning, and force planning in particular, as well as implications for developmental disorders that are marked by deficits in such circuitry. Past research has established that the basal ganglia, a collection of sub-cortical nuclei situated in the midbrain, play a key role in motor planning, adaptive force control, and procedural learning by trial-and-error, among other abilities (Leisman et al., 2014; Pereira et al., 2000; Stocco et al., 2010). Research suggests that the basal ganglia matures earlier than most areas of the cerebral cortex and is nearly fully developed at birth (Chugani et al., 1987; Mukherjee et al., 2001). Importantly, basal ganglia

impairment has been implicated in several neurodevelopmental disorders, including Developmental Coordination Disorder (DCD), Attention Deficit Hyperactivity Disorder (ADHD), and Autism Spectrum Disorders (ASD). Moreover, individuals with such neurodevelopmental disorders also demonstrate a diminished capacity to plan, coordinate, and appropriately scale the force of their actions (Bo & Lee, 2013; Jucaite et al., 2003; Leisman et al., 2014; Qiu et al., 2010).

Our results support previous research establishing early maturation of the basal ganglia by demonstrating that 12-month-old infants can anticipatorily apply force according to an object's weight in novel contexts, and that they can rapidly adjust their behavior on the basis of sensorimotor feedback, both of which are supported in part by functioning of the basal ganglia. An interesting question for future research is whether variability in infants' ability to anticipatorily scale force and to adapt to sensorimotor feedback in our task at 12 months of age will be related to the expression of symptoms of DCD, ADHD, and/or ASD later on in development, given prior work demonstrating deficits in scaling force in this population at older ages (Lundy-Ekman et al., 1991; Fong et al., 2013; Smits-Engelsman et al., 2008). As such, it is foreseeable that the present task could be applied in the future as an early diagnostic marker or tool for neurodevelopmental disorders related to basal ganglia pathology.

In conclusion, this study demonstrates that a critical aspect of motor planning is already in place by the end of the first year of life: infants utilize representations of object weight gained from acting directly on objects in order to anticipatorily plan their actions in a novel and indirect motor context. This ability is a pervasive and important aspect of mature motor behavior, as we are often faced with the need to perform actions in novel situations and in which weight information plays a prominent role, such as loading a dolly when helping a friend move between

apartments. Based on these and related findings (Sommerville et al., 2012), we suggest that infants form “motor inferences”: they can flexibly combine information and/or representations gleaned from different motor acts in order to generate novel plans of action in the absence of trial-and-error experience.

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FIGURE 1. Mean number of lifts performed with each block during the training phase.

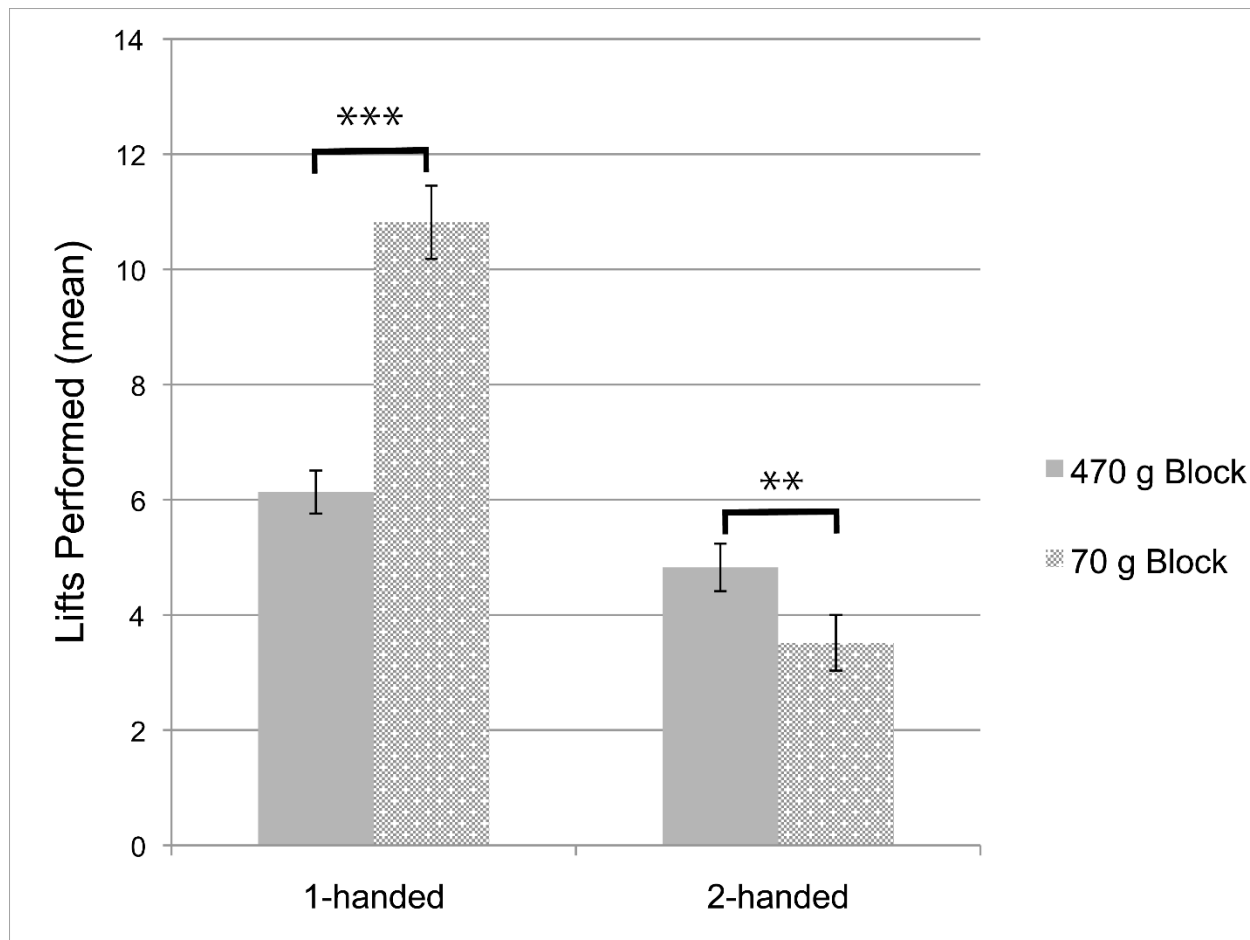


Figure 1. Mean number of lifts performed with each block during the training phase as function of the number of hands used (collapsed across conditions). Error bars represent standard error. ** $p = .001$. *** $p < .001$.

FIGURE 2. Mean number of failed cloth pulls when attempting to retrieve each block.

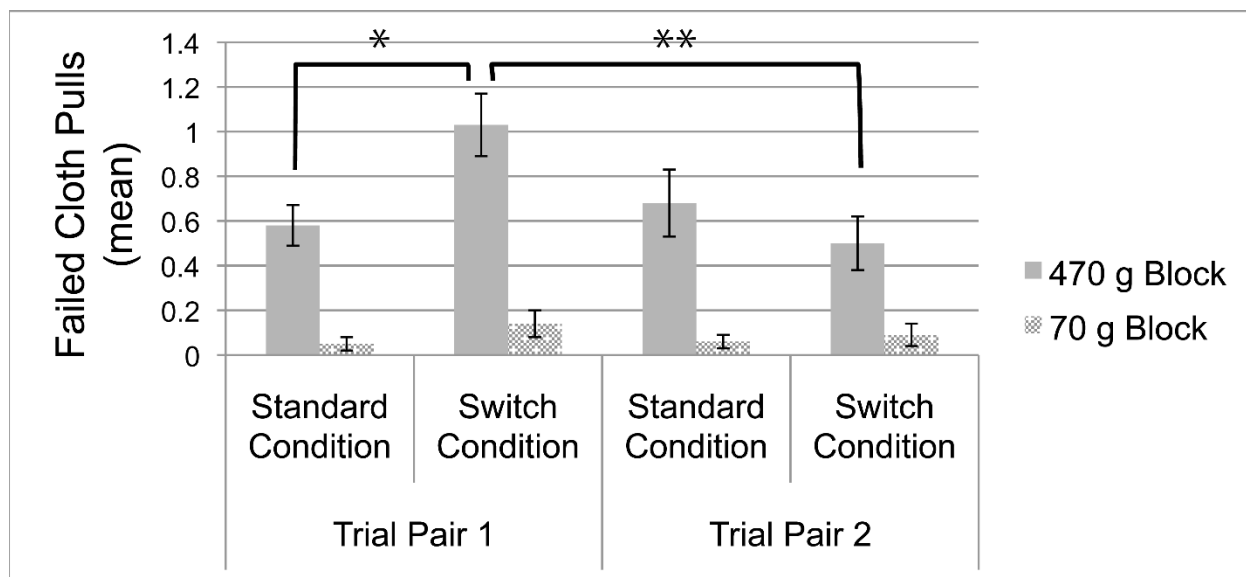


Figure 2. Mean number of failed cloth pulls when attempting to retrieve each block, presented as a function of trial pair and condition. Error bars represent standard error. * $p = .008$. ** $p = .001$.

Chapter 3. 10-MONTH-OLD INFANTS UNDERSTAND THE RELATION BETWEEN OBJECT WEIGHT AND COMPRESSION IN SUPPORT EVENTS

Upshaw, M. & Sommerville, J. (in prep, invited submission).

3.1 ABSTRACT

Previous research demonstrates that infants adapt and plan their actions based on an object's weight. However, less work has investigated how an understanding of object weight shapes the ability to predict and interpret the outcome of physical events, particularly in early ontogeny. The present studies investigate 10-month-old infants' understanding of the effect of object weight in support events – specifically, their understanding that an object's weight impacts whether or not a supporting surface will become compressed – and whether individual differences in strength, a factor that influences infants' experience acting on heavy and light objects, shapes this understanding. In Experiment 1, we demonstrate that infants can infer an object's weight based on whether or not it compresses a supporting surface. In Experiment 2, we demonstrate that infants generate predictions for the outcome of support events involving heavy and light objects (i.e., they expect heavy, but not light, objects to compress a supporting surface) using a violation-of-expectation paradigm. Strength, however, was unrelated to infants' performance in both experiments. These findings provide evidence that infants invoke a concept of object weight when interpreting and predicting the outcomes of physical events, demonstrating that the ability to reason about object weight as a causal factor in physical events is relatively sophisticated early in life.

3.2 INTRODUCTION

Our ability to successfully navigate the world depends critically on our understanding of objects and their properties. A prominent aspect of this ability is the understanding of object weight. Our capacity to plan actions, interpret other people's behavior, solve problems, and predict the outcomes of physical events is profoundly influenced by the ability to perceive object weight and recognize its consequences. For example, adults generate more force when preparing to lift heavy objects versus light (Johansson & Westling, 1988), can estimate the weight of an object that another person is lifting (Shim, Carlton, & Kim, 2004), and can use an object's weight in order to solve problems (e.g., lowering a heavy anchor to secure a boat). Though much research has been devoted to investigating how an understanding of object weight influences action production in both adults (Gordon, Westling, Cole, Johansson, 1993; Johansson & Westling, 1988) and children (Forssberg, Eliasson, Kinoshita, Johansson, & Westling, 1991; Mash, 2007), much less work has investigated how an understanding of object weight shapes the ability to predict and interpret physical events, particularly in early ontogeny. For example, as adults we understand that a paperweight can be used to prevent objects from moving (e.g., when placed on top of loose documents) as well as to cause objects to move (e.g., when thrown at another paperweight). We understand that object weight is often a causal factor in physical events, in that it leads to a variety of effects on other objects (e.g., move, pin down, compress). The present studies aimed to shed light on the emergence and development of one instance of this understanding in infancy: that an object's weight impacts whether or not a supporting surface will become compressed.

3.2.1 *Developments in the understanding of object weight*

There is an abundance of evidence showing that, after interacting with an object, infants adapt and guide their subsequent actions toward the object as a function of its weight. For example, by 6 months of age, infants haptically discriminate between objects of different weight (i.e., after holding an object, they hold a differently weighted object longer) and begin to adapt their actions toward objects as a function of weight, such as waving light objects with a single hand and lifting heavy objects with two hands (Itier, Provasi, & Bloch, 2001; Palmer, 1989). By 9 months, when preparing to lift an object, infants generate force in anticipation of an object's weight, though they require prior experience lifting the object in order to do so (Mash, 2007). By the end of the first year, infants generate force in anticipation of even a novel object's weight, but only after prior experience interacting with visually similar objects, (Gottwald & Gredebäck, 2015; Mash, Bornstein, & Banerjee, 2014). In addition, 12-month-olds can apply object weight information acquired by acting on objects in one context in order to guide action according to object weight in a novel context (Upshaw & Sommerville, 2015). In sum, this work demonstrates that over the first year of life, infants progress from adapting their actions toward objects as a function of weight (e.g., Palmer, 1989), to anticipating an object's weight (e.g., Mash, 2007), to applying object weight information in new situations (e.g., Upshaw & Sommerville, 2015).

However, applying object weight information acquired via action in order to guide subsequent action is distinctly different from understanding the effect of object weight in physical events. Specifically, the former is largely sensorimotor in nature and is a direct application of one's perceptual experience interacting with objects; in contrast, understanding object weight as a causal factor requires representing and conceptually reasoning about weight as a property of an object that exists and affects events independent of one's actions. Indeed, early

research suggested that a conceptual understanding of object weight did not emerge until late childhood and that, before then, children are only capable of adapting their actions according to object weight (Inhelder & Piaget, 1958; Piaget, 1952; see also Wang, Meltzoff, & Williamson, 2015).

However, subsequent research has demonstrated that a conceptual understanding of object weight is present at least by the preschool years. For example, 3-year-old children understand that a heavy object will cause a flimsy supporting object to collapse (Smith, Carey, & Wiser, 1985) and they choose to place heavy objects on top of rigid, rather than flimsy, supporting surfaces (Povinelli, Vonk, & Castille, 2012). Yet, this is not to say that conceptually reasoning about object weight is fully mature at 3 years of age. Even older children struggle to differentiate concepts such as density and weight (Smith et al., 1985) and have difficulty integrating the concepts of weight and distance from the fulcrum in balance tasks (Siegler, 1976). However, given that 3-year-olds understand the effect of object weight in support events, there is a compelling case for examining the development of this understanding at earlier ages.

Object weight looms large on the outcome of support events (i.e., when one object is placed on top of another object). For one, the distribution of an object's weight determines whether the object will stay on top of its supporting object; if too much of the object's weight is unsupported, the object will fall. In addition, object weight influences whether a supporting surface will become compressed when an object is placed on top of it. There has been much research on the development of infants' understanding of support events (Baillargeon & Hanko-Summers, 1990; Baillargeon, Needham, & DeVos, 1992; Hespos & Baillargeon, 2006; Needham & Baillargeon, 1993). For example, by 3 months of age, infants understand that objects released in mid-air cannot stay suspended (Baillargeon et al., 1992). By 5 months, infants understand that

objects will remain supported when placed on top of, and not beside, a supporting surface (Baillargeon, 1998), and, by 6 months, infants understand that there must be sufficient contact between the bottom of an object and its supporting surface in order for the object to remain supported (Baillargeon et al., 1992). Interestingly, it is not until the end of the first year that infants understand that asymmetrically shaped objects (e.g., L-shaped objects) will fall if the larger portion of the object extends off of the supporting surface (Baillargeon, 1998). However, it is unclear whether these past findings demonstrate an understanding of the effect of object weight in support events, or the effect of the distribution of mass (Baillargeon, 1995), as object shape and proportion of contact do not differentiate between these variables. Moreover, reasoning about physical events based on the appearance of an object is different than reasoning about the causal effect of an unobservable property like weight.

To our knowledge, there has only been one study that directly investigated infants' understanding of the effect of object weight in support events (Hauf, Paulus, & Baillargeon, 2012). In this study, 9-month-old infants interacted with a soft platform and two visually identical objects of different weight. Afterward, infants were presented with a support event involving these same objects, which illustrated the effect of object weight on the soft platform (i.e., the heavy object compressed the platform, while the light object did not). Infants were encouraged to reach toward an object; however, they were not allowed to interact with the object while arranged in the support event in order to confirm its weight properties. Reaching to the light object was taken to reflect that infants could discriminate between the two objects based on compression of the supporting surface (as infants have a baseline preference for interacting with light rather than heavy objects; Hauf & Paulus, 2011). Nine-month-old infants reached significantly more often to the light object in the support event, which demonstrates that they

could infer object weight based on compression information. A subsequent study established that 9-month-olds *require* experience interacting with a soft platform *and* the differently weighted objects in order to demonstrate this understanding, as without this experience, their reaches are no different from chance. However, by 11 months, infants can infer object weight without interacting with the differently weighted objects, though they still require experience interacting with a soft platform. Altogether, this suggests that infants' ability to reason about the effect of object weight in support events is initially highly dependent upon interacting with the objects but becomes less so by the end of the first year.

Though this study is a promising start, more work needs to be done to investigate the development of infants' understanding of the effect of object weight in support events. For one, a compelling follow-up question concerns whether younger, 10-month-old infants could infer object weight based on compression information after only interacting with a soft platform. If so, this would demonstrate that even younger infants can infer object weight based on compression information in a support event without direct experience with the differently weighted objects.

A separate, more compelling question, is whether infants generate predictions for the outcomes of support events. Indeed, predicting the outcome of an event is more difficult than reasoning about completed events (Keen, 2003; Keil, 2006), and many studies have shown that reasoning about completed events emerges before the ability to generate predictions for event outcomes (Hood, Carey, & Prasada, 2000; Keen, 2003; Krist, 2010; see also Brandone, Horwitz, Aslin, & Wellman, 2014; Cannon & Woodward, 2012, for examples in the social domain). Thus, evidence that infants reach to the light object in a support event based on the absence of compression does not necessarily mean that they predict light objects will sit on top of, and not compress, a soft surface. If infants generate accurate predictions for the outcome of support

events involving heavy and light objects, they should respond with heightened attention to events in which the light, but not heavy, object compresses the soft platform, relative to events in which the heavy, but not light, object compresses the soft platform. If so, this would demonstrate that infants represent object weight as an underlying causal factor in physical events and that they can use this understanding in order to predict the outcome of a support event, as opposed to recognizing that some objects compress supporting surfaces more than others.

A second goal of the present studies concerns individual differences in infants' ability to reason about object weight in support events. Specifically, given that infants' experience interacting with objects facilitates inferences about object weight based on compression information (Hauf et al., 2012) and that infants' everyday experience grounds in-task reasoning about physical events (Baillargeon, 1998; Newcombe, Sluzenski, & Huttenlocher, 2005), we predicted that factors that influence the acquisition of experience interacting with objects may have a downstream effect on infants' understanding of object weight in support events. Strength is a promising candidate factor, as strength has a profound impact on infants' ability to interact with objects, particularly heavy objects, and because strength has been demonstrated to shape infants' understanding of object weight in another domain (i.e., action perception; Upshaw, Bernier, & Sommerville, 2015). Another, non-mutually exclusive reason for predicting an influence of strength is potential variability in infants' ability to link object weight differences with different support outcomes (i.e., compressed or not compressed). That is, because weak infants may experience most objects to be heavy, including those that do not compress soft surfaces, they may be at a disadvantage when associating object weight differences to contrasting support outcomes. For these reasons, we predicted that strength would be related to infants' understanding of the effect of object weight in support events.

3.2.2 *Overview of the present studies*

The present studies investigate 10-month-old infants' ability to reason about the effect of object weight in support events using a paradigm adapted from previous work (Hauf et al., 2012). We chose 10-month-olds for this investigation, as this ability may just be emerging at younger ages. As a secondary aim, we explored whether strength, a factor that constrains or facilitates infants' acquisition of experience interacting with objects in their everyday lives, influences their ability to reason about the effect of object weight in support events.

In Experiment 1, we investigated whether 10-month-old infants can infer object weight based on compression of a supporting surface after only interacting with a soft platform. However, given evidence that 9-month-olds require experience interacting with the objects involved in the support event in order to infer object weight based on compression information (Hauf et al., 2012), we reasoned that 10-month-olds may need some additional help. As such, and in contrast with prior work (Hauf et al., 2012), infants were allowed to interact with both objects after reaching to one in the support event. In this way, they had an opportunity to learn the relation between object weight and compression over the course of the task. Importantly, we used different objects for each support event, so infants had no experience with the objects involved in each event before reaching to one. However, the objects used in each support event looked similar to each other (i.e., same size and shape but different color), so infants should be able to generalize their experience to novel objects (e.g., Hauf & Paulus, 2011). As in prior work (Hauf et al., 2012), we predicted that if 10-month-olds can infer the weight of an object based on compression information, they will be more likely to reach to the light block in the support event. In addition, if 10-month-olds are dependent upon experience interacting with similar objects in order to infer a novel object's weight based on compression information, they should become

increasingly likely to reach to the light block as the task progresses. However, if infants' reaches to the light block do not change over the course of the task, it would suggest that experience interacting with the objects does not influence this ability at this age. Regarding an effect of strength, we hypothesized that stronger infants, as assessed by a novel pull-force assessment, would be better able to infer object weight based on compression information than weaker infants.

In Experiment 2, we investigated whether 10-month-old infants generate predictions for the outcome of support events involving heavy and light objects, by comparing infants' attention to events that violate physical laws pertaining to object weight (i.e., light, but not heavy, objects compress a soft platform) to events that accord with these laws (i.e., heavy, but not light, objects compress a soft platform). Importantly, before seeing these events, infants interacted separately with a soft platform and two objects of different weight and color, but not while arranged in a support event. Thus, generating a prediction for the effect of object weight on the soft platform required abstractly combining their separate experiences interacting with the soft platform and differently weighted objects. We predicted that if infants generate accurate predictions for the effect of object weight in support events, they should exhibit heightened attention to events that are inconsistent with the causal effect of object weight relative to events that are consistent with it. Toward a role for strength, we hypothesized that stronger infants would exhibit greater attention to inconsistent events relative to consistent events in comparison to weaker infants.

3.3 METHOD: EXPERIMENT 1

3.3.1 *Participants*

Fifty-two healthy, full-term, 10-month-old infants ($M_{age} = 9$ months, 28 days; range = 9 months, 20 days – 10 months, 9 days; $n = 22$ females) participated in the study. Infants were

recruited from a large city in the Pacific Northwest and were primarily Caucasian ($n = 35$; Asian: $n = 4$; Black: $n = 3$; Hispanic: $n = 1$; Multiracial: $n = 8$; ethnicity data not provided for $n = 1$).

Parents provided written informed consent before participating, and all study procedures were approved by the university's Internal Review Board. Five additional infants were excluded from the final sample due to fussiness before four test trials had been administered ($n = 3$) or experimental error ($n = 2$).

3.3.2 *Stimuli*

Seven unique pairs of plastic blocks (8.9 cm per side) that were matched in outward appearance (i.e., same size, shape, and color) but contrasted in weight (70 vs. 720 g) were used during each of the eight test trials.¹ During test trials, each pair of blocks was placed atop a soft platform (68.6 x 20.3 x 10.2 cm). The soft platform was constructed by stuffing cotton batting inside a modified solid beige pillow case that was adhered to a piece of foam cardboard. An opaque screen (75 x 31.8 cm) was used while setting up each test trial to prevent infants from receiving additional information about the blocks (e.g., how the experimenter handled each block).

Infants' strength was assessed via a novel pull-force device. The pull-force device was constructed from a digital pull-force gauge (HF-500 Digital Push Pull Force Gauge, M & A Instruments) and a toy that easily extends and vibrates when stretched. The force gauge and toy were connected via a short piece of elastic. When infants pulled the toy, the force of their pulls traveled through the toy and was recorded via the force gauge.

¹ The same pair of blocks were used for test trials 1 and 8 but with a different block face rotated toward infants (one had an image of a tree and the other had an image of a dog). The different block faces, plus the time delay, make it unlikely that infants recognized the blocks on test trial 8.

3.3.3 Procedure

Infants sat in their parents' lap in front of a table and across from the experimenter. Infants were positioned at the table such that their navel was at table height, in order to facilitate their interaction with the blocks and cotton platform. Before testing procedures, infants were encouraged to play with three plastic bath toys (that did not resemble the weighted blocks) in order to acclimate infants to the testing room.

3.3.3.1 Cotton platform phase

At the beginning of the task, the experimenter introduced the cotton platform to the infant. First, she placed the cotton platform on the table approximately 38 cm away from the infant, and, while the infant was watching, demonstrated that the cotton platform could be compressed, by pressing down on the cotton platform with both hands for approximately 5 s. Next, the experimenter lifted both hands and pressed on the cotton platform alternately with a single hand for approximately 10 s. To retain infants' attention, the experimenter verbally marked the demonstration by saying, "*Look! See, I can press it down.*" Afterward, the cotton platform was advanced toward the infant and the infant was encouraged to manually interact with it for approximately 20 s. After 20 s, the experimenter retracted the cotton platform and placed it behind the occluding screen.

3.3.3.2 Test trials

While the cotton platform was behind the occluding screen, the experimenter placed one heavy and one light block on top of it, on the far left and right sides of the platform (~ 24 cm apart). The heavy block had the effect of fully compressing the cotton platform while the light block sat on top without any compression effect. The starting location of the blocks (i.e., whether

the heavy or light block was placed on the right side) was counterbalanced across infants and alternated every two test trials.

At the start of each test trial, the experimenter tapped the block on the right and said “*Look at this toy!*” and then tapped the block on the left and said “*Look at that toy!*” The experimenter then looked directly at the infant and asked “*Can you get a toy?*” before advancing the cotton platform toward the infant. Infants were given up to 10 s to reach for a block, while the experimenter looked directly at the infant to avoid cueing him or her toward either block. If the infant did not reach for a block within 10 s, the experimenter gave an additional verbal prompt (e.g., “*Can you get one?*”). After 3 verbal prompts or 30 s had elapsed, the experimenter randomly selected a block for the infant and continued with the rest of the test trial, in order to examine whether interacting with similar blocks facilitates subsequent inferences about a novel block’s weight based on compression information (infants reached for a block on 99.9% of all test trials).

During infants’ reach to the block, the experimenter rotated the cotton platform approximately 45°, so that the block that infants were *not* reaching toward was put out of reach. Rotating the platform was intended to limit infants’ actions to the block they initially reached for, as pilot testing revealed that infants often switched blocks (especially when infants’ initial reach was directed toward the heavy block). Infants were given up to 20 s to retrieve the block off of the cotton platform (if they did not do so spontaneously), and verbal prompts were provided every 5 s by the experimenter (e.g., “*Can you get it?*”). If infants did not retrieve the block within 20 s, or after 4 verbal prompts, the experimenter took the block off of the platform and placed it directly in front of the infant. Infants were given up to 15 s to freely interact with the

block. After 15 s (or if the infant stopped interacting with the block for 3 s), the experimenter retrieved the block and placed it out of sight.

After retrieving the block, the experimenter advanced the cotton platform toward the infant again, with the block that infants did not retrieve still on top. The experimenter encouraged the infant to retrieve this block by asking, “*Can you get that toy?*” Infants were given up to 20 s to retrieve the block off of the cotton platform and additional verbal prompts were provided every 5 s by the experimenter. If infants did not retrieve the block within 20 s, or after 4 verbal prompts, the experimenter took the block off of the platform and placed it directly in front of the infant. Infants were given up to 15 s to freely interact with that block. After 15 s (or if the infant stopped interacting with the block for 3 s), the experimenter retrieved the block, placed the occluding screen on the table, and began setting up the next test trial.

Infants were administered up to 8 test trials ($n = 3$ completed 4 test trials, $n = 18$ completed 6 test trials, and $n = 31$ completed all 8 test trials). If an infant became fussy before 8 test trials were administered, the experimenter discontinued the task and moved on to the pull-force assessment.

3.3.3.3 Pull-force assessment

Infants were given a short break between the test trials and the pull-force assessment to allow the experimenter to set up the device. The pull-force assessment began with the experimenter placing the extendable toy near the extent of infants’ reach. The experimenter then modeled pulling the toy and verbally encouraged infants to pull it. Infants were given repeated verbal encouragement to pull the toy, and the experimenter continued modeling pulls on the toy, if needed. The pull-force assessment was terminated when the infant grew fussy or began to turn

away from the pull-force device. Infants' maximum one-handed pull-force was used in analyses as a measure of infants' strength ($M = 7.97$ N, $SD = 2.06$, range: 5.2 – 14.2 N).

3.3.3.4 Ancillary measures

Before participating in the task, parents completed a 24-item motor abilities checklist (Upshaw et al., 2015), adapted from the Bayley Scales of Motor Development (Bayley, 2006). The motor abilities checklist presents motor development milestones in order of increasing difficulty and asks parents to indicate if they have observed their infant perform each listed behavior. The motor abilities checklist was used to validate the pull-force assessment, as a positive relation was expected between motor and muscular development (Woollacott, 1993). In addition, we investigated whether infants' motor development was related to their performance during the task. We used the total number of items that parents indicated that their infant could perform in analyses ($M = 15.3$ items, $SD = 2.75$, range: 7 - 21).²

Infants' body weight was measured to validate the pull-force assessment, as body weight is associated with strength in older children and adults (Wind, Takken, Helders, & Engelbert, 2010). Infants' average body weight was 9.36 kg ($SD = 1.24$, range: 7.00 – 12.80 kg).

3.3.4 Coding

All sessions were video recorded, and coding was completed off-line.

3.3.4.1 Cotton platform phase

The amount of time infants spent in manual contact with the cotton platform was coded in order to assess how long infants spent encoding the platform's compressible property. Manual

² One parent did not complete the motor abilities checklist.

contact was defined as the infants' hands touching the soft part of the cotton platform.³ On average, infants spent 14.1 s ($SD = 6.9$ s) in manual contact with the cotton platform.

3.3.4.2 Test trials

The dependent variable was which block infants reached to first at the beginning of each test trial. Reaches to the light block were taken to reflect that infants could infer the weight of the objects from compression information (hereafter referred to as "light block choices"). Infants' percentage of light block choices was calculated for the entire task (ranging from 4 to 8 test trials, depending on how many trials the infant completed) and for each test trial pair, to investigate potential changes in infants' light block choices during the task. To ensure reliability, a second coder, blind to study hypotheses, independently coded infants' light block choices for a randomly selected half of the sample. Across all administered trials, inter-rater agreement was high, 95.4% ($K = .90$). See Appendix A for description and results of a second, exploratory dependent variable (i.e., the number of hands infants used when reaching to each block).

We also coded the amount of time infants spent in manual contact with each block during the test trial. Manual contact was defined as the amount of time infants spent touching each block with one or both hands.⁴ On average, infants spent 12.9 s in manual contact with the light block and 13.6 s with the heavy block during each test trial. A paired samples t-test confirms that there was no difference in manual contact with each block during the entire task nor during each

³ A pilot sample ($n = 26$) was coded using the criterion of infants' hands touching the soft part of the cotton platform accompanied by contingent eye-gaze. However, the results of this coding were not significantly different from contact without contingent eye gaze, so subsequent work employed this more generous coding scheme.

⁴ A pilot sample ($n = 26$) was coded using the criterion of manual contact with the blocks accompanied by contingent eye-gaze. However, the results of this coding were not significantly different from contact without contingent eye gaze, so subsequent work employed this more generous coding scheme.

test trial pair (all p 's > .18).⁵ See Appendix A for description and results of two additional variables regarding infants' block interactions (i.e., action performed to retrieve each block and the number of hands used when retrieving each block).

3.4 RESULTS: EXPERIMENT 1

3.4.1 *Light block choices*

We predicted that if infants can infer object weight from compression information, they would be more likely to reach for the light block. As a first pass, we investigated whether infants' block choices were more likely to be directed toward the left or right sides of the platform. We found that infants were equally likely to choose a block on the left ($M = 49.6\%$ of all trials) or right sides ($M = 50.4\%$) of the platform, $t(51) = .10$, $p = .92$. Thus, block side was collapsed in all subsequent analyses.

Across the entire task, infants made significantly more light block choices than would be predicted by chance ($M = 58.04\%$, $SD = 20.08$), as revealed by a one-sample t-test, $t(51) = 2.89$, $p = .01$, $d = .40$ (see Figure 3). This confirms that infants could discriminate between the two blocks based on compression information and that they used this information to guide their reaching actions. To investigate potential changes in infants' block choices across the task, we analyzed the percentage of light block choices as a function of test trial pair. However, a repeated measures ANOVA with test trial pair (1, 2, 3 or 4) as the within-subjects variable did not find a significant effect of test trial pair, $F(3, 93) = .99$, $p = .40$, partial $\eta^2 = .03$ (however, note that the

⁵ We also coded the amount of time infants spent in weight-relevant contact (i.e., contact that provided information about the blocks' weight, such as lifting, pushing, or tipping) and the amount of time spent in weight-irrelevant contact (i.e., contact that did not provide information about the blocks' weight, such as tapping and mouthing). However, neither variable was associated with infants' light block choices, and the results did not differ from total manual contact time, so only those results are reported here.

sample size of this analysis was drastically reduced from $n = 52$ to $n = 31$). This suggests that infants' experience interacting with the blocks at the end of each test trial did not facilitate subsequent inferences regarding a novel block's weight.

3.4.1.1 **Relations between light block choices and strength**

To ensure the validity of the pull-force assessment, Pearson's correlations were conducted between infants' maximum one-handed pull-force and their motor development scores and body weight. Infants' maximum pull-force was positively correlated with motor development scores, $r(51) = .30$, $p = .03$, confirming that stronger infants were motorically advanced. Infants' maximum pull-force was also positively associated with their body weight, $r(52) = .33$, $p = .02$, confirming that stronger infants were heavier than weaker infants. The number of pulls infants performed during the assessment was marginally related to maximum pull force, $r(52) = .25$, $p = .08$, which could suggest that differences in motivation played a role. However, given significant relations with motor development and body weight, the pull-force assessment seems more accurately characterized as a measure of infants' strength.

Next, we investigated if pull-force was related to infants' light block choices. However, a Pearson's correlation revealed no significant relation between pull-force and infants' overall light block choices, $r(52) = .13$, $p = .36$, which suggests that strength did not influence infants' performance.

3.4.1.2 **Relations between light block choices and other variables**

After ruling out an effect of strength, we looked to other factors that may account for infants' light block choices. For example, the amount of manual contact with the blocks and cotton platform may have been important, as object interaction has been found to facilitate infants' ability to infer object weight from compression information (Hauf et al., 2012).

Pearson's correlations were conducted between infants' overall light block choices and manual contact time with the blocks and cotton platform. This revealed no relation between light block choices and contact time with heavy block, $r(52) = .09, p = .51$, or the cotton platform, $r(52) = .04, p = .76$, though there was a significant relation between light block choices and contact time with the light block, $r(52) = .31, p = .02$. This suggests that infants who more frequently chose the light block were more likely to interact with the light block during the test trials.

Next, we investigated if motor development influenced infants' light block choices. Pearson's correlations were conducted between motor development scores and infants' overall light block choices, which revealed no association between the two measures, $r(51) = .14, p = .31$. Lastly, we conducted a Pearson's correlation between the number of completed test trials and infants' overall light block choices. This revealed a significant association between the number of completed test trials and infants' light block choices, $r(52) = .41, p = .003$, which suggests that infants who were better able to infer object weight from compression information were more likely to persist in the task.

3.5 DISCUSSION: EXPERIMENT 1

The results of Experiment 1 demonstrate that 10-month-old infants can infer object weight based on compression of a supporting surface after interacting with a soft platform. This was reflected by a significant tendency to reach to the light block in the support event. The lack of changes in infants' light block choices during the task suggest that interacting with the blocks at the end of each test trial did not facilitate subsequent inferences about a novel block's weight based on compression information. As such, this experience may not have been necessary for 10-month-old infants to infer object weight based on compression information.

In addition, Experiment 1 found that infants who spent more time interacting with the light block were more likely to choose the light block in the support event. One possibility for this relation is that infants simply played more with whichever block they chose first. However, this does not seem to be the case, as we did not find a negative relation between light block choices and contact time with the heavy block. Another possibility is that infants simply preferred interacting with the light block; however, infants spent equal time in contact with the light and heavy blocks. Finally, this relation could suggest that experience interacting with the light block, specifically, had a facilitative effect on inferring object weight in support events. However, this seems improbable. If anything, interacting with the *heavy* block seems more suited to inferring object weight in support events, as the light block does not cause compression and is of similar weight to other objects that infants regularly interact with. Rather, we interpret this finding as demonstrating that infants who were better able to infer object weight from compression information preferred to interact with the light block, as they had inferred the block's weight beforehand and were purposefully reaching toward it.

Experiment 1 also found that infants who completed more test trials made more light block choices. Indeed, there was significant variability in the number of test trials that infants completed, so it is interesting that infants who completed more test trials were more likely to choose the light block. This suggests that infants who were better at inferring object weight from compression information were better equipped to persist in the task. Lastly, and contrary to our hypothesis, strength was unrelated to infants' light block choices.

Though the findings of Experiment 1 are promising evidence that infants can apply experience interacting with a soft platform in order to infer object weight based on compression information, they also support an alternate low-level interpretation. Specifically, infants may

have rapidly learned the association between ‘light object weight’ and ‘absence of compression’. This interpretation of these results is distinctly different and less rich. Experiment 2 aimed to disambiguate between these two interpretations, as infants were in a situation with no possibility for associative learning. More importantly, Experiment 2 examined whether 10-month-old infants generate predictions for the outcome of support events involving heavy and light objects, which is a more abstract ability than inferring object weight from the outcome of a support event.

3.6 METHOD: EXPERIMENT 2

3.6.1 *Participants*

Forty-nine healthy, full-term, 10-month-old infants ($M_{age} = 9$ months, 29 days; range = 9 months, 18 days – 10 months, 8 days; $n = 25$ females) participated in the study. Infants were recruited from a large city in the Pacific Northwest and were primarily Caucasian ($n = 36$; Asian: $n = 1$; Black: $n = 1$; Hispanic: $n = 1$; Multiracial: $n = 9$; ethnicity data not provided for $n = 1$). Parents provided written informed consent before participating, and all study procedures were approved by the university’s Internal Review Board. Four additional infants were excluded from the final sample due to fussiness before four test trial pairs had been administered.

Infants participated in one of four counterbalancing orders. The two counterbalanced variables were the color of the heavy block (red or yellow) and which test event was presented first on test trial pairs 1 and 3 (consistent or inconsistent). We aimed for at least $n = 10$ in each order, but continued to test infants (blind to condition) for as long as study funds permitted. This resulted in $n = 12$ in the *red block heavy, consistent event first* counterbalancing order, $n = 11$ in the *red block heavy, inconsistent event first* order, $n = 12$ in the *yellow block heavy, consistent event first* order, and $n = 14$ in the *yellow block heavy, inconsistent event first* order.

3.6.2 *Stimuli*

Infants interacted with one pair of plastic blocks that were the same size and shape (8.9 cm per side) but differed in color (red and yellow) and weight (70 and 720 g) throughout the task (color-weight pairings were counterbalanced across infants). In addition, infants interacted with a soft platform (68.6 x 20.3 x 10.2 cm), constructed by stuffing cotton batting inside a modified solid beige pillow case and adhered to a piece of foam cardboard.

During test events, infants saw a pair of blocks sitting atop the cotton platform, such that one block fully compressed the platform while the other block did not. During test events, the block that compressed the platform was always presented on the right side of the cotton platform (relative to the infant). In this way, the cotton platform looked identical during each test trial (i.e., the right side was compressed while the left side was not), but the color of the block causing the compression effect switched between test trials. Test trials were presented on a stage (88.9 cm wide x 83.8 cm high x 61 cm deep) that had black opaque curtains surrounding each side. Two spotlights were affixed at the top of the stage, facing down, to illuminate the stimuli.

Infants' strength was assessed using the same pull-force device as in Experiment 1.

3.6.3 *Procedure*

Infants sat in their parents' lap positioned between a table and the stage. Before testing procedures, infants were encouraged to play with three plastic bath toys (that did not resemble the weighted blocks) in order to acclimate infants to the testing room. Parents were instructed not to direct their child's behavior and to refrain from talking, looking at, or gesturing toward the stage during the test trials. Parental compliance was ensured offline.

3.6.3.1 Cotton platform phase

During the cotton platform and block interaction phases, infants sat with their navel at table height. The experimenter introduced the cotton platform to the infant by placing it on the table approximately 45 cm away from the infant. While the infant was watching, the experimenter demonstrated that the cotton platform could be compressed by pressing on it with both hands for approximately 10 s. Next, the experimenter lifted both hands and pressed on the cotton platform alternately with a single hand for a total of 15 s. To retain infants' attention, the experimenter marked the demonstration by saying, "*Look! See, I can press it down.*" Afterward, the cotton platform was advanced toward the infant and the infant was encouraged to manually interact with it for approximately 20 s. After 20 s, the experimenter retrieved the cotton platform and placed it out of sight.

3.6.3.2 Block interaction phase

After the cotton platform phase, infants were administered the first block interaction phase. During block interaction phases, infants were encouraged to freely interact with one block for 20 s (either the light or heavy, order counterbalanced across infants). After 20 s had elapsed, the experimenter retrieved that block and gave infants the other block for an additional 20 s. After that, the experimenter gave both blocks to the infant and encouraged the infant to interact with both for an additional 20 s. Thus, each block interaction phase lasted approximately 60 s.

Infants were administered four block interaction phases, before each of the four test trial pairs. All block interaction phases were identical except that the cotton platform phase was only administered before the first block interaction phase, and the order of the blocks given to infants was swapped during the third and fourth interaction phases.

3.6.3.3 Test trials

After each block interaction phase, infants stayed facing the table while the test trials were set up. Once set up, parents were prompted to turn to face the stage (placing their infant approximately 115 cm from the stimuli) which marked the beginning of the test trial. Infants were shown one consistent test event and one inconsistent test event during each test trial pair (test event order counterbalanced across infants and alternated between test trial pairs).

Consistent test events were events in which the block compressing the cotton platform was visually identical to the heavy block that infants had interacted with (and the block sitting atop the cotton platform was the same color as the light block that infants interacted with). In contrast, inconsistent test events were events in which the block compressing the cotton platform was visually identical to the light block that infants had interacted with. Infants' looking to each test event was coded on-line by a blind experimenter. Test events were presented until infants looked away for 2 consecutive seconds. At the end of each test trial, parents turned to face the table.

3.6.3.4 Pull-force assessment

Infants were administered the pull-force assessment in the same manner as in Experiment 1. Infants' maximum one-handed pull force was used as a measure of infants' strength ($M = 7.6$ N, $SD = 2.0$, range: 5 – 13.1 N).⁶

3.6.3.5 Ancillary measures

Before participating in the task, parents completed a 24-item motor abilities checklist (Upshaw et al., 2015). The total number of items that parents indicated that their infant could perform was used in analyses ($M = 13.7$ items, $SD = 3.7$, range: 4 - 21).

⁶ Two infants did not register any pulls and were consequently excluded from analyses on infants' strength.

3.6.4 Coding

All sessions were video recorded. Infants' looking to each test event was coded online using jHab (Casstevens, 2007), a software program for calculating looking times. Contact time with the blocks and cotton platform was completed off-line.

3.6.4.1 Cotton platform phase

The amount of time infants spent in manual contact with the cotton platform was coded to assess how long infants spent encoding the platform's compressible property. Manual contact was defined as the infants' hands touching the soft part of the cotton platform. On average, infants spent 13.0 s ($SD = 6.7$ s) in manual contact with the cotton platform.

3.6.4.2 Block interaction phase

The amount of time infants spent in manual contact with each block during the block interaction phases was coded. Manual contact was defined as touching the block with one or both hands. During each block interaction phase, infants spent an average of 28.2 s in manual contact with the light block and 27.4 s with the heavy block. Paired samples t-tests confirm that there was no difference in manual contact between the heavy and light blocks during each block interaction phase nor during the task as a whole (all p 's $> .38$).

3.6.4.3 Test trials

The amount of time infants spent looking at each test event was coded on-line by a blind experimenter. Test events were presented in pairs and only pairs in which both test events were administered without error or parental interference were included in analyses. As such, $n = 2$ are missing data from test trial pair 2, $n = 1$ from test trial pair 3, and $n = 2$ from test trial pair 4. To ensure reliability, a second coder, blind to study hypotheses and test event order, independently

coded infants' looking for a randomly selected half of the sample. Pearson's correlations between the first and second coder were high (r 's ranged from .94 - .99 across all test trials). In addition, the coders agreed on the outcome of 93% of all trials (i.e., which test event was attended to longer within each test trial pair). Disagreements were equally distributed across the two test event types (3 disagreements were in favor of inconsistent test events and 4 were in favor of consistent test events).

3.7 RESULTS: EXPERIMENT 2

3.7.1 *Looking to inconsistent test events relative to consistent test events*

To investigate if infants looked longer to inconsistent test events relative to consistent, a $4 \times 2 \times 2 \times 2$ ANOVA was conducted with test trial pair (1, 2, 3, or 4) and test event type (inconsistent or consistent) as within-subjects variables, and test event order (consistent or inconsistent test event first on test trial pair 1), and heavy block color (red or yellow) as between-subjects variables (*note*: $n = 44$ infants were included in this analysis as infants needed data from all four test trial pairs). This revealed a significant main effect of test trial pair, $F(3, 120) = 4.61$, $p = .004$, partial $\eta^2 = .10$. Post-hoc tests reveal that infants looked longer on the first test trial pair ($M = 9.96$ s) relative to the other test trial pairs (all p 's $< .02$), though there were no differences in looking between the second ($M = 7.85$ s), third ($M = 6.96$ s), and fourth ($M = 7.03$ s) test trial pairs (all p 's $> .33$; see Figure 4). As longer looking on initial test trials relative to later test trials is not of theoretical interest and is commonly found in infancy research (e.g., Leslie, 1982), this result will not be considered further.

As hypothesized, there was a significant main effect of test event type, $F(1, 40) = 5.73$, $p = .02$, partial $\eta^2 = .13$. There was also an uninterpretable 3-way interaction between test trial pair, heavy block color, and test event order, $F(3, 120) = 3.99$, $p = .01$, partial $\eta^2 = .09$, such that

infants in the *yellow block heavy, consistent event first* counterbalancing order looked longer on test trial pair 1 relative to other infants. Given that this effect was not predicted, is not of theoretical interest, and that the study is underpowered to assess higher-order interactions, this interaction is not considered further. There were no other main effects or interactions.

To investigate the main effect of test event type, and given that there was no interaction between test event type and test trial pair, infants' average looking to inconsistent and consistent test events was calculated across all four test trial pairs. A paired samples t-test reveals that infants looked longer to inconsistent test events ($M = 4.34$ s, $SD = 2.23$) relative to consistent test events ($M = 3.66$ s, $SD = 1.88$), $t(43) = 2.29$, $p = .03$, $d = .35$. If the entire sample of $n = 49$ infants is used (i.e., including infants with data from only three test trial pairs), this difference is maintained, $t(48) = 2.50$, $p = .02$, $d = .36$.

To confirm these results, looking to inconsistent and consistent test events was compared using a non-parametric test. A binomial test confirms that more infants looked longer to inconsistent test events relative to consistent test events ($n = 32$ of 49; 1 infant looked equally to both events), $p = .03$. This analysis confirms that infants generate accurate expectations for the effect of object weight in support events, as most looked longer to events that seemed to violate physical laws.

3.7.1.1 Relations between looking to inconsistent test events and strength

To ensure the validity of the pull-force assessment, Pearson's correlations were conducted between infants' maximum one-handed pull-force and their motor development scores. Infants' maximum pull-force was positively associated with motor development scores, $r(47) = .43$, $p = .002$, confirming that stronger infants were motorically advanced. In addition, infants' maximum pull-force was unrelated to the number of pulls performed during the

assessment, $r(47) = .19, p = .19$. Together, these relations validate the pull-force assessment as an accurate measure of infants' strength.

Next, we investigated if maximum pull-force influenced infants' attention to the test events. A Pearson's correlation was conducted between pull-force and the proportion of looking to inconsistent test events relative to total looking during the task (using all infants with pull-force data). This found no relation between the two measures, $r(47) = -.15, p = .31$, which suggests that strength did not influence infants' attention.

3.7.1.2 Relations between looking to inconsistent test events and other variables

With an effect of strength ruled out, we looked to other factors that may account for infants' attention. Pearson's correlations were conducted between the proportion of looking to inconsistent events over total looking during the task and manual contact time with the blocks and cotton platform. This revealed no relation between the proportion of looking to inconsistent events and contact time with the heavy block, $r(49) = -.16, p = .28$, light block, $r(49) = .03, p = .82$, or cotton platform, $r(49) = .20, p = .17$.

Next, we investigated if motor development influenced infants' attention during the task. Pearson's correlations were conducted between motor development scores and the proportion of looking to inconsistent test events over total looking during the task. This revealed no association between motor development and the proportion of looking to inconsistent events, $r(49) = .03, p = .86$, which suggests that motor development did not influence infants' attention.

3.8 DISCUSSION: EXPERIMENT 2

Experiment 2 demonstrates that 10-month-old infants generate accurate predictions for the outcome of support events involving heavy and light objects. This was demonstrated by

longer looking to events in which the block compressing the soft platform looked identical to the light block that infants had interacted with compared to events in which the block compressing the soft platform looked identical to the heavy block that infants had interacted with.

Importantly, infants' predictions for the effect of object weight in support events were generated *without* having interacted with the blocks while arranged in the support event, so there was no opportunity for associative learning. This suggests that by 10 months, infants have a genuine ability to predict and reason about the causal effects of object weight in support events and were not simply learning an association in Experiment 1. However, contrary to our hypothesis, strength was unrelated to infants' attention during the task. Possible reasons for this null finding are explored in the general discussion.

3.9 GENERAL DISCUSSION

The present studies investigated infants' understanding of the effect of object weight in support events—specifically, their understanding that compression of a supporting surface is influenced by the weight of the object placed on top of it. Experiment 1 investigated whether 10-month-olds can apply experience interacting with a soft platform in order to infer an object's weight based on compression of the soft platform. We found that infants reached significantly more often to the light block (rather than the heavy block) in the support event, which suggests that infants could infer object weight based on compression information. In addition, we found no difference in infants' light block choices over the course of the task, which suggests that interacting with the blocks at the end of each test trial did not facilitate their ability to infer a novel block's weight based on compression information. As such, this experience may not be necessary for 10-month-old infants to infer the objects' weight. Though the results of Experiment 1 are also subject to an alternate, low-level interpretation—specifically, that infants quickly

learned the association between light object weight and absence of compression, given their impressive statistical learning capabilities (Saffran, Aslin, & Newport, 1996)—Experiment 2 ruled out this possibility, as there was no opportunity for associative learning. More importantly, Experiment 2 demonstrates the sophistication of infants’ understanding of object weight, by showing that infants generate accurate predictions for the outcome of support events involving heavy and light objects. Specifically, we found that infants looked longer to events in which the light, but not heavy, object compressed the soft platform relative to events in which the heavy, but not light, object compressed the platform. Overall, these two studies demonstrate that 10-month-old infants are flexible in their ability to reason about the effect of object weight in support events. That is, after experience interacting with a soft platform, infants can infer an object’s weight based on whether or not it compresses a soft platform, and they can predict whether a soft platform will become compressed based on experience with an object’s weight. This strongly suggests that infants have an abstract ability to reason about the causal effects of object weight, as they can reason about these effects based on varying pieces of information.

The present studies extend prior work that has investigated the development of infants’ understanding of object weight in support events. For one, Experiment 1 demonstrates that as early as 10 months, infants can infer an object’s weight based on compression of a supporting surface. Prior work suggested that this ability was present at 11 months, and that at 9 months, infants need experience interacting with both the differently weighted objects and a soft platform in order to infer object weight based on compression information (Hauf et al., 2012); thus, the present study shows that even 10-month-old infants can infer object weight based on compression information after only interacting with a soft surface. Albeit, it is an open question whether even younger infants could infer object weight based on compression of a supporting

surface if they interacted with objects that were similar to the objects involved in the support event (in addition to interacting with a soft platform). Future work should investigate this possibility, though, notably, the present findings suggest that this experience is not necessary for 10-month-olds to infer object weight based on compression information. Experiment 2 also corroborates prior work that has employed action tasks to investigate infants' understanding of object weight in support events (Experiment 1; Hauf et al., 2012). In particular, Experiment 2 confirms the conclusion suggested by action tasks—that infants can reason about the effect of object weight in support events—by demonstrating convergence with a novel looking time measure. Establishing agreement between action and looking time measures highlights the robustness of infants' understanding of object weight in support events, as this understanding is exhibited via various behaviors and under a range of experimental conditions.

An important contribution of the present work is that it demonstrates that, in addition to reasoning about support events upon seeing the outcome, 10-month-old infants are capable of the more difficult feat of generating predictions for the outcome of support events. Indeed, reasoning about the outcome of completed events is considered to be easier and less sophisticated than generating predictions for events, as responding based on outcomes typically emerges at younger ages (Keen, 2003; Keil, 2006). Some researchers have even argued that responding based on event outcomes is evidence of perceptual discrimination and not conceptual reasoning (Hood, 2001). However, the present work shows that 10-month-old infants are capable of more than this when reasoning about object weight. Indeed, infants' differing attention to the test events in Experiment 2 is powerful evidence for conceptual reasoning and not perceptual discrimination, as neither event would appear surprising to the outside observer. In each event, one block compressed the platform and the other block did not; the only factor that varied between events

were infants' expectations for each block's weight. Altogether, the present work should quell doubts about infants' ability to reason about object weight as a causal factor in support events, as it demonstrates that infants both generate predictions and reason about the outcomes of these events, and that both their overt actions and visual attention are influenced by this understanding.

3.9.1 *Implications for developing a conceptual understanding of object weight*

Altogether, the present studies demonstrate that even infants invoke a concept of object weight when interpreting and predicting the outcomes of physical events. Curiously, research on the development of this understanding in infancy is scarce, though more studies have investigated children's understanding of object weight in physical events (Siegler, 1976; Smith et al., 1985). This is perhaps because early work suggested that infants were only capable of understanding object weight as it pertains to their own actions, such as modifying the amount of force when interacting with an object as a function of its weight (Mounoud & Bower, 1974), and that conceptual reasoning about object weight awaited later childhood (Inhelder & Piaget, 1958; Piaget, 1952; Piaget & Inhelder, 1974). Indeed, early work demonstrated that children as old as eight years of age did not understand seemingly basic aspects of object weight, such as understanding that an object maintains its weight across transformations (e.g., a kernel of popcorn versus a popped kernel) and that a ball of wax and a ball of clay weigh different amounts despite being the same size (Piaget & Inhelder, 1974). In addition, though children could eventually successfully balance weights on either side of a scale, they were unable to explain how they achieved this success (Karmiloff-Smith & Inhelder, 1975). However, later work found that in simpler tasks, even young children demonstrate an ability to conceptually reason about object weight (Smith et al., 1985; Povinelli et al., 2012).

For example, Smith et al. (1985) conducted an extensive study on children's understanding of object weight and their ability to differentiate concepts of size, weight, and density. They found that children as young as 3 years differentiate between size and weight (i.e., they can tell the difference between large objects and heavy objects). Most relevant to the present research, Smith and colleagues found that 3 year olds understand the effect of object weight in support events, in that they selectively choose heavy objects among objects of different weight in order to cause a foam bridge to collapse. More recent work has confirmed this conclusion, by demonstrating that 3-year olds can sort heavy and light objects based on visual cues, that is, without interacting with the objects and confirming their weight (Povinelli et al., 2012). In addition, 3 year olds choose to place heavy objects on top of rigid, rather than flimsy, surfaces when the goal is to keep the object supported on top (Povinelli et al., 2012). This demonstrates that even young children understand that weight is a separate property of an object, that exists independently of their own actions, and that they can conceptually reason about the causal effects of object weight in physical events when the problem is clear and density is left out of the equation. In interpreting their results, Smith et al. concluded that children's understanding of object weight is grounded in their sensorimotor experience with an object, a concept they termed 'felt weight' (Smith et al., 1985; see also Povinelli et al., 2012). Indeed, though these children understood that weight is an inherent property of an object, that exists and affects events independent of their own actions, they confidently asserted that exceedingly light objects, such as a grain of rice, have no weight, as the weight of a grain of rice is imperceptible when held.

This concept of 'felt weight' may suggest that infants are only able to reason about object weight after interacting with an object, and, until recently, it was unclear whether infants had anything more than a sensorimotor understanding of object weight that they use to guide their

actions (e.g., Mash, 2007; Palmer, 1989). However, the present work in conjunction with a prior study (Hauf et al., 2012) demonstrate that even infants conceptually reason about the effects of object weight and can interpret and predict the outcomes of support events involving objects of different weight. Moreover, the present work tempers the conclusion of the prior study that proposed that children's concept of object weight is grounded in their sensorimotor experiences with an object (Smith et al., 1985). Though sensorimotor experience is undoubtedly important, the results of Experiment 1 demonstrate that infants can reason about object weight based on experience interacting with a material, such as the soft compressible platform, in lieu of direct experience with the object. This suggests that infants and likely children have a more robust understanding of object weight than one that is strictly wed to sensorimotor experience.

In addition, the early competence of reasoning about object weight in support events is interesting in light of the later emerging competence of reasoning about object weight in balance events (Karmiloff-Smith & Inhelder, 1975; Messer, Pine, & Butler, 2008; Siegler, 1976). Though using a balance is in essence a support problem, as a heavy object is placed on one side of the balance which causes it to go down, this event is obviously more difficult for children. One possibility is that material information, such as that of the supporting surface, provides additional evidence that facilitates reasoning about the effect of object weight in support events. Another, non-mutually exclusive possibility, is that observing compression of a supporting surface is highly salient and provides ongoing information about the weight of an object. In contrast, observing one side of the balance go down is a fleeting event, and children may forget the underlying cause after it has occurred. This suggests that task demands, rather than an inability to conceptually reason about object weight, might limit children's performance in balance tasks

involving object weight, and that children may succeed earlier if an element of compression was incorporated (e.g., placing compressible material under each side of the balance).

Interestingly, comparative research with chimpanzees, one of our closest evolutionary relatives, suggests that chimpanzees can learn associations between object weight and the outcomes of physical events but that they do not generate expectations for the outcome of physical events involving object weight without prior experience (Vonk et al., 2012; Vonk, Reaux, & Povinelli, 2012). That is to say, chimpanzees do not seem to represent object weight as an explanatory causal factor when interpreting physical events or solving physical problems, which makes the early-emerging and flexible reasoning abilities of human infants all the more impressive. Indeed, studies with infants may help to elucidate the uniquely human developmental mechanisms underlying this ability.

3.9.2 *When might bodily factors, such as strength, influence cognition?*

Interestingly, strength was not associated with infants' performance in either experiment. This was somewhat unexpected, given prior work demonstrating that experience interacting with objects facilitates infants' understanding of object weight in support events (Hauf et al., 2012) and that strength influences infants' understanding of object weight during action perception (Upshaw et al., 2015). One possibility for this null finding is that our pull-force measure was an inaccurate measure of infants' strength. However, positive relations between pull-force, motor development, and body weight suggest that the pull-force assessment was an accurate measure of strength. Another possibility is that strength has a greater influence on the ability to reason about object weight when this ability is first emerging. If so, this would predict that younger infants' ability to reason about the effect of object weight in support events would be related to strength. Perhaps, by 10 months, this ability is more entrenched and less affected by other factors. A final

possibility, which we think is most likely, is that bodily factors like strength exert a greater influence on cognitive tasks with a more prominent role for action, such as tasks involving action perception. In other words, it is possible that strength does not have a broad influence on the understanding of object weight, but rather is more specifically and robustly related to processes pertaining to action.

To illustrate, prior work suggests that the influence of the body is greater in cognitive processes pertaining to action (Hauk & Tschentscher, 2013; Moseley, Kiefer, & Pulvermüller, 2016). Though the present tasks did contain an action component, the action demands were quite minimal, and, in Experiment 2, the critical test trials were simply observation. Perhaps more importantly, the content of the task, physical reasoning, is subserved by different neural regions than those that process human action (Blakemore et al., 2001; Martin & Weisberg, 2003; Upshaw et al., 2015). Thus, it is more likely that strength, which directly influences action production, would influence action perception due to their shared underlying neural system, whereas action production and physical reasoning have different neural substrates. All in all, we agree with the claim that the body plays an important role in cognition but caution that the influence of the body may vary depending on the prominence of action in the task.

3.9.3 *Conclusion*

Research on the development of infants' conceptual understanding of object weight is a pressing charge for developmental psychologists. The current studies contribute to this burgeoning effort by providing evidence that conceptual reasoning about object weight is present and relatively sophisticated by 10 months of age. Specifically, the present studies demonstrate that 10-month-old infants can apply experience interacting with a soft platform in order to infer object weight based on compression information and that they generate accurate predictions for

the role of object weight in support events. Though this work did not find an influence of strength on infants' performance, future work may continue to explore this possibility by investigating earlier points in the development of this understanding. Altogether, we hope that researchers continue to investigate infants' ability to reason about object weight as a causal factor in physical events, as the ability to explain the world by referring to unobservable factors, such as object weight, is part of what it means to be human.

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doi:10.1017/CBO9780511663284.008

FIGURE 3. Percentage of light block choices as a function of test trial pair and overall.

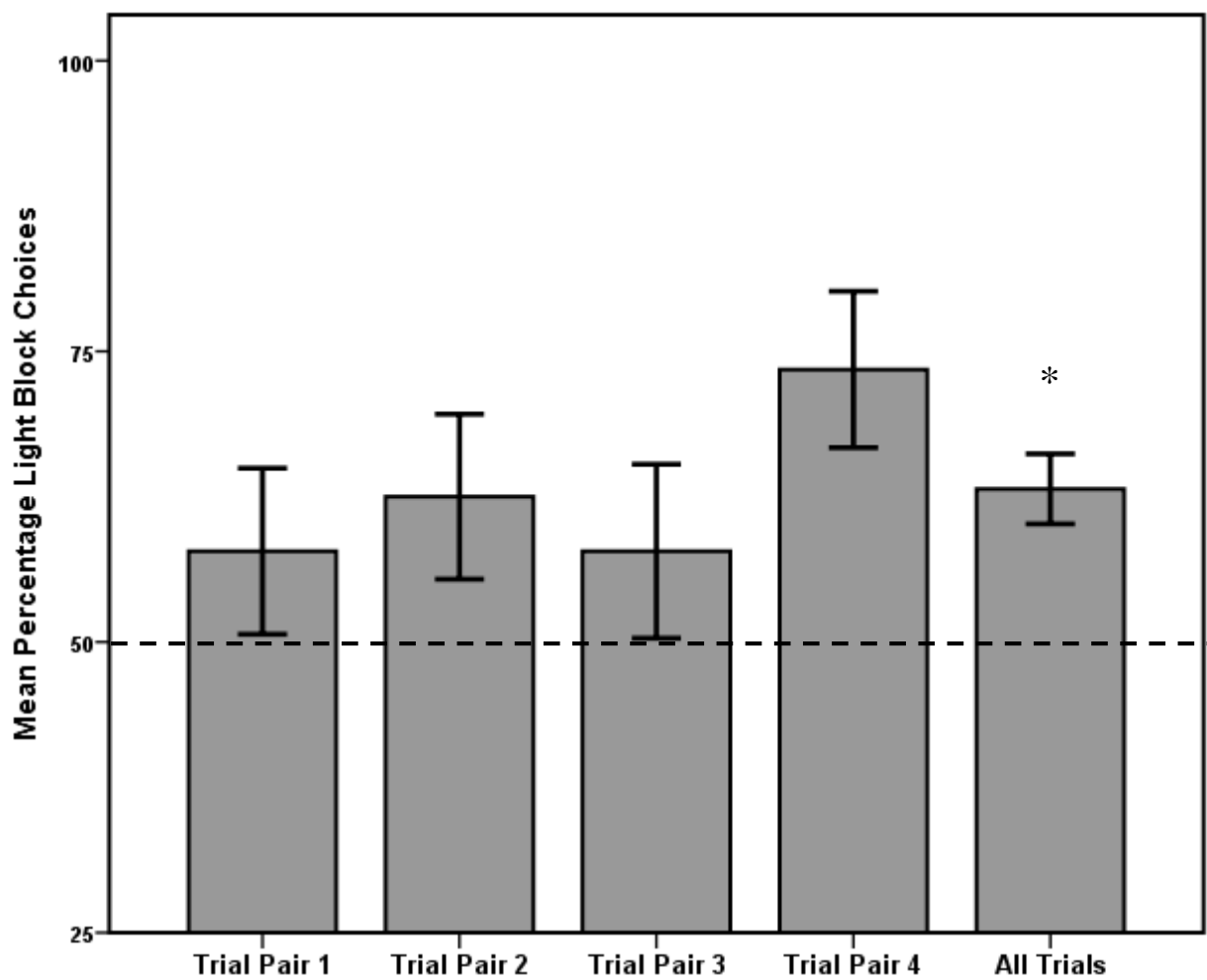


Figure 3. Mean percentage of light block choices as a function of test trial and overall. Error bars represent standard error. * $p = .01$.

FIGURE 4. Mean looking time during each test trial pair as a function of test event type.

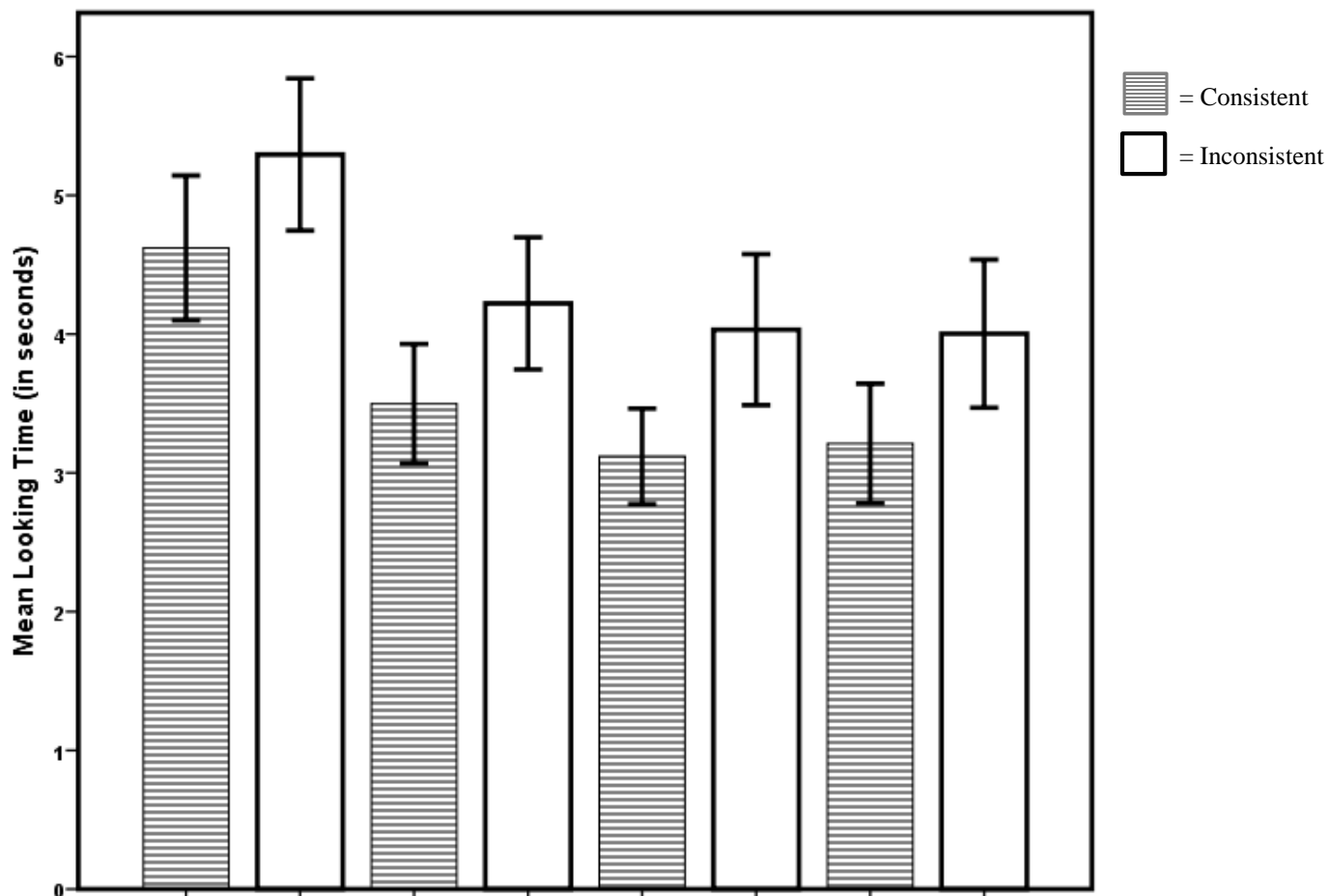


Figure 4. Mean looking (in seconds) during each test trial pair as a function of test event type. Error bars represent standard error.

Chapter 4. INFANTS' GRIP STRENGTH PREDICTS MU RHYTHM ATTENUATION DURING OBSERVATION OF LIFTING ACTIONS WITH WEIGHTED BLOCKS

Upshaw, M., Bernier, R., & Sommerville, J. (2015). *Developmental Science*.

4.1 ABSTRACT

Research has established that the body is fundamentally involved in perception: bodily experience influences activation of the shared neural system underlying action perception and production during action observation, and bodily characteristics influence perception of the spatial environment. However, whether bodily characteristics influence action perception and its underlying neural system is unknown, particularly in early ontogeny. We measured grip strength in 12-month-old infants and investigated relations with mu rhythm attenuation, an electroencephalographic correlate of the neural system underlying action perception, during observation of lifting actions performed with differently weighted blocks. We found that infants with higher grip strength exhibited significant mu attenuation during observation of lifting actions, whereas infants with lower grip strength did not. Moreover, a progressively strong relation between grip strength and mu attenuation during observation of lifts was found with increased block weight. We propose that this relation is attributable to differences in infants' ability to recognize the effort associated with lifting objects of different weights, as a consequence of their developing strength. Together, our results extend the body's role in perception by demonstrating that bodily characteristics influence action perception by shaping the activation of its underlying neural system.

4.2 INTRODUCTION

More than bodily movements through space, human actions convey important information about individuals and their surroundings. Interpretations of observed actions are not uniform across individuals, however, but vary according to the observer's bodily characteristics and experiences. For example, imagine two spectators at a weightlifting competition: a seasoned weightlifter and a novice weightlifter. Both observe a competitor approach, grasp, and heft a 300 lb. barbell into the air, before progressing to successfully lifting a 400 lb. barbell. For both spectators, it is clear that the barbells are heavy, and that the competitor's goal is to lift the barbells. However, whereas the novice is unable to recognize the increased effort exhibited by the competitor when lifting the 400 lb., relative to the 300 lb., barbell, the seasoned spectator marvels upon witnessing the second lift, in recognition of the increased effort associated with lifting the 400 lb. barbell. As this example illustrates, perceptions of others' actions vary according to the observer's prior experience and abilities.

4.2.1 *Bodily experience shapes action perception*

Given the centrality of action understanding to everyday functioning, a critical question concerns how this understanding is achieved. There is now a wealth of evidence demonstrating that bodily experience producing an action is linked to, and causally influences, action perception (e.g., Casile & Giese, 2006; Hommel, Müsseler, Aschersleben, & Prinz, 2001). This is particularly true in infancy: training infants to produce goal-directed actions enables them to detect the goal-structure of similar actions produced by others (Sommerville, Woodward, & Needham, 2005; Sommerville, Hildebrand, & Crane, 2008). Evidence suggests that this close alliance is established via a shared underlying neural system (Buccino et al., 2001; Iacoboni et al., 1999; Vanderwert, Fox, & Ferrari, 2013), the activation of which is shaped by one's

experience and expertise with the observed action, both in adults (Calvo-Merino, Glaser, Grèzes, Passingham, & Haggard, 2005; Cannon et al., 2014; Cross, Hamilton, & Grafton, 2006) and in infants (Paulus, Hunnius, van Elk, & Bekkering, 2012; van Elk, van Schie, Hunnius, Vesper, & Bekkering, 2008). Thus, bodily experience profoundly influences action perception by tuning the underlying neural system.

4.2.2 *Bodily characteristics shape spatial perception*

Work from a different line of inquiry suggests that the body is fundamentally involved in another perceptual arena: bodily states and characteristics influence perception of the spatial environment (Kretch, Franchak, & Adolph, 2014; Proffitt & Linkenauger, 2013). For example, Adolph and colleagues have demonstrated that infants' perception of their environment is heavily influenced by bodily characteristics, such as their posture: infants who primarily walk spend more time looking at distal and elevated surfaces than same-aged, primarily crawling infants who spend more time looking at the ground (Kretch et al., 2014). Similarly, infants who sit independently spend more time looking at the objects in their grasp than infants who cannot yet sit alone (Soska, Adolph, & Johnson, 2010). These perceptual differences that come as a consequence of infants' posture are in turn associated with unique cognitive achievements (Adolph et al., 2012; Campos et al., 2000; Soska et al., 2010). Relatedly, there is evidence that perception of the environment is influenced by bodily characteristics in adults: inclines are perceived to be steeper by adults wearing a heavy backpack relative to those who are unencumbered, by adults who are fatigued relative to those who are rested, and by the elderly relative to the young (Bhalla & Proffitt, 1999). Taken together, these findings raise the possibility that bodily characteristics may shape not only infants' perception of the spatial environment but also their perception of others' actions.

4.2.3 *Investigating the neural system underlying action perception in infancy*

Due to limitations with using functional neuroimaging techniques in infancy, researchers have relied on electroencephalography (EEG) to study the development of the neural system underlying action perception. Specifically, the mu rhythm, recorded between 8 – 13 Hz in adults and 6 – 9 Hz in infants (Marshall & Meltzoff, 2011; Southgate, Johnson, Karoui, & Csibra, 2010), has been tied to the shared neural system underlying action perception and production, due to its selective attenuation during action perception and production (Marshall, Young, & Meltzoff, 2011; Muthukumaraswamy, Johnson, & McNair, 2004), its prominence over the sensorimotor cortex (Pineda, 2005), and relations with other methods investigating this system (Keuken et al., 2011; Braadbaart, Williams, & Waiter, 2013). Thus, the mu rhythm is ideal for investigating the development and neural basis of action perception.

4.2.4 *Overview of the current study*

The question addressed in the current study concerns the impact of bodily characteristics on mu attenuation during action observation in infancy. Past work has demonstrated that bodily experience influences mu attenuation during action observation: for example, mu attenuation during observation of crawling is related to infants' crawling experience (van Elk et al., 2008). The novel question addressed in our experiment was whether bodily characteristics, particularly those that influence both the frequency and nature of motor experience, are associated with the degree of activation of the neural system underlying action perception and production during action observation. Infancy is an ideal time to investigate the effect of bodily characteristics on action perception and its underlying neural system, as there is wide variability in bodily characteristics (World Health Organization Child Growth Standards, 2006) and significant changes in action perception (Loucks & Sommerville, 2012b) during this developmental period.

Moreover, infants have fewer means than children and adults to mitigate bodily constraints in order to achieve their goals (e.g., grab a stool to increase height).

In the current experiment, EEG activity was recorded while infants took part in an action task during which they alternately lifted, and watched an experimenter lift, blocks of different weights; infants' grip strength was measured midway through the action task via a novel grip strength assessment. Prior work with adults has demonstrated that observing lifting actions performed with heavy objects, relative to lifting actions performed with light objects, results in increased activation of the shared neural system underlying action perception and production (Alaerts et al., 2010; Senot et al., 2011). One possible interpretation of this finding is that the action perception systems of adults are sensitive to differences in object weight *per se* (Cole, 2008; Flanagan & Beltzner, 2000). Another interpretation is that activation of the neural system underlying action perception and production is modulated by differences in the phenomenological experiences associated with lifting heavy versus light objects, such as differences in exerted force (Alaerts, Swinnen, Wenderoth, 2010; Mima, Simpkins, Oluwatimilehin, & Hallett, 1999) or expended effort. Indeed, some researchers have suggested that, in adults, perception is heavily shaped by bodily characteristics that increase or reduce the effort associated with producing a given action (Proffitt, 2006). This latter explanation may help to explain why a recent study with infants failed to find differences in mu attenuation as a function of object weight (Marshall, Saby, & Meltzoff, 2013). That is, given limitations and variability in infants' experience with lifting objects of different weights, infants may be unable to recognize differences in expended effort on the basis of object weight, or may be limited in their ability to do so.

In the present paper we investigated whether individual differences in infants' grip strength would predict mu attenuation during observation of lifting actions with weighted blocks. We hypothesized that infants' grip strength would predict mu attenuation during observation of lifting actions because grip strength gates both the nature and frequency of experience lifting objects of various weights, which in turn could influence infants' ability to recognize the differential effort associated with lifting objects of different weights. Because strength profoundly affects one's ability to lift objects, stronger infants have likely acquired more lifting experience with a broader, and more contrastive, range of object weights than weaker infants (see Wang & Baillargeon, 2008, for evidence that contrastive experience facilitates perceptual discrimination and learning). Thus, we predict that infants' grip strength will be associated with mu attenuation during observation of lifting actions with weighted blocks. Furthermore, as strength exerts a greater impact on infants' experience lifting heavy objects versus light objects, we predict that the association between infants' grip strength and mu attenuation will become stronger as the weight of the block being lifted by the experimenter increases.

4.3 METHOD

4.3.1 *Participants*

Thirty-four ($n = 17$ female), 12-month-old infants were recruited from a university-maintained database to participate in the study ($M = 12$ months, 7 days; range: 11 months, 22 days to 13 months, 1 day). Eleven infants were excluded due to technical problems ($n = 7$) or not providing sufficient usable EEG data (i.e., at least one artifact-free trial of each type; $n = 4$). Of the final sample of twenty-three infants ($n = 12$ female), the average age was 12 months and 10 days (range: 11 months, 22 days to 13 months, 1 day). Nineteen infants were Caucasian, and four infants were of mixed racial backgrounds.

4.3.2 *Stimuli*

Infants interacted with four plastic blocks (8.9 cm per side) that varied in color (i.e., red, yellow, orange, and green) and weight. For approximately half of the infants, two of the blocks were “light” (70 g) and two were “heavy” (470 g). For the remaining half, two of the blocks were “light” (70 g), one was “heavy” (470 g), and one was “super heavy” (720 g).⁷ The blocks were paired by contrasting weight (i.e., one light and one heavy, or one light and one super heavy) and color (e.g., red and yellow), and the color-weight pairings were counterbalanced across infants. A bucket (17.1 cm x 14.6 cm x 12.7 cm) and cardboard box (21.6 cm x 12.7 cm x 5.7 cm) were also used during the interaction. A set of 15 (21.6 cm x 27.9 cm) cardboard signs with different abstract patterns served as baseline images.

4.3.3 *Procedure*

4.3.3.1 **Action task**

Infants were seated in their parents’ lap, in front of a table, across from the experimenter. Infants were not familiarized with the blocks or other stimuli before the action task. During the task, infants received intermixed observation trials, action trials and baseline trials. During observation trials, the experimenter randomly selected one of three lifting actions to demonstrate for the infant: hopping a block across the table, lifting a block onto a platform, or lifting a block and dropping it into a bucket. The average duration of the experimenter’s demonstration was 5 seconds, during which approximately two exemplars of the lifting action were performed. Action trials began after the experimenter handed the block (and the bucket or platform, if those actions were demonstrated) to the infants. Action trials ended after infants performed an action with the

⁷ We administered 3 block weights to half the sample and 2 block weights to the other half (randomly assigned) in order to 1) ensure that all infants interacted with at least 2 block weights, as well as to 2) mitigate possible frustration and noncompliance that could be elicited when infants interact with heavy objects.

block or after 30 seconds elapsed with no block interaction. During action and observation trials, only the block being acted upon was visible to the infant.

For approximately half of the sample ($n = 13$), half of the action and observation trials were conducted with the 70 g block and half with the 470 g block. For the other half of the sample ($n = 10$), half of the action and observation trials were conducted with the 70 g block, one quarter with the 470 g block, and the remaining quarter with the 720 g block.

Baseline trials were administered after action and observation trials and consisted of the experimenter holding an image of an abstract pattern in front of her face for infants to view for approximately 3 seconds.

Breaks were taken as needed throughout the testing session. When breaks failed to re-engage infants, the action task was terminated.

4.3.3.2 Grip strength assessment

Infants' grip strength was recorded via a TruStability Silicon Pressure Sensor that was embedded inside a squeezable plastic toy. The embedded pressure sensor was connected to both a switch circuit and a laptop computer running *Processing*, an open source programming environment (<http://processing.org>). The purpose of the switch circuit was to activate the playing of the song "Old MacDonald." *Processing* served to: 1) record infants' grip strength values (in pounds per square inch, or psi) and 2) gate the activation of the switch circuit. By default, the switch circuit was incomplete (i.e., would not activate the song), but upon pressure, would complete, causing the song to play for 3 seconds. The switch circuit functioned such that, after infants' initial squeeze, the song would only play for squeezes that met or exceeded 90% of the force of their highest previous squeeze. By implementing this constraint, we hoped to elicit increasingly forceful squeezes on behalf of infants in order to play the song. Only squeezes that

succeeded in playing the song were recorded, and the maximum recorded grip strength value was analyzed as infants' grip strength score.

The grip strength assessment was administered midway through the action task. The experimenter first presented infants with the squeezable toy (containing the embedded pressure sensor), and, using an identical (but inert) toy, modeled forceful squeezes and encouraged infants to do the same. The grip strength assessment continued accordingly for as long as infants remained interested.

4.3.4 *EEG recording & analysis*

EEG activity was recorded via a 128-channel Geodesic Sensor Net at 250 samples/second (via EGI software; Net Station v4.1; Electrical Geodesics, Inc., Eugene, OR) and filtered online between .1 and 100 Hz. EEG activity was recorded with a vertex reference and re-referenced offline to a common average of all leads. Impedances were measured below 40 k Ω at the start of data acquisition.

EEG activity was segmented offline into 1000 ms epochs, extending from 0 ms, indicating the start of the lift, for action and observation trials (i.e., at the point of object contact immediately preceding the block being lifted from the table), or the initial presentation of the baseline image, for baseline trials, to 1000 ms afterward. EEG activity was continuously segmented into 1000 ms epochs until the end of the lift (i.e, when the object was placed back onto the table) or until removal of the baseline image. Epochs from observation and baseline trials in which the infant was not attending to the stimuli, or that were contaminated by infant movement, were identified from video and removed. Artifacts from remaining epochs were removed through NetStation's artifact detection algorithm which removed epochs that contained 18 or more leads that exceeded 200 μ V in raw amplitude, or 18 or more leads that exceeded 100

μ V in differential average amplitudes. Overall, this removed 37% of infant action epochs, 20% of infant observation epochs, and 35% of baseline epochs. The average number of artifact-free epochs of each trial type for each infant were: 20.91 action epochs ($SE = 3.49$), 29.87 observation epochs ($SE = 3.27$), and 7.52 baseline epochs ($SE = .83$).

Fast Fourier transforms (FFTs) were performed in Matlab (version 7.11.0.584, R2010b, Natick, MA). Power spectra were calculated based on the average amplitude within each trial type. Mu attenuation was calculated as the natural log of the ratio of power during action or observation trials over power during baseline trials, (i.e., [natural log (A / B)], where A is power during action or observation trials, and B is power during baseline trials). A ratio measure was used to account for individual variability in overall EEG power, and the log transformation accounts for the inherent non-normality of ratio data. Accordingly, values of zero indicate no change from baseline activity, negative values indicate mu attenuation relative to baseline, and positive values indicate mu augmentation relative to baseline.

In order to identify the location and frequency of maximal mu attenuation, we focused on oscillatory activity during infants' production of block lifts over central leads C3 and C4 within the 6 - 9 Hz frequency range. In line with proposed guidelines for investigating the mu rhythm (Cuevas, Cannon, Yoo, & Fox, 2014; Marshall & Meltzoff, 2011), the location and frequency of maximal mu attenuation during infants' production of block lifts was used in subsequent analyses on mu attenuation during observation of block lifts. Consistent with prior work on the infant mu rhythm (Marshall et al., 2011), we defined infants' mu rhythm band at the group level, rather than at the individual level, in order to statistically confirm the location and frequency of significant attenuation during infants' action production relative to baseline (an analysis precluded by power limitations when operationalized at the individual level).

Lastly, in order to confirm that our results accurately reflect mu rhythm activity (as opposed to measurement of the occipital alpha rhythm or widespread changes in neural activity), we investigated EEG activity during observation of block lifts at frontal (F3 or F4), parietal (P3 or P4), and occipital (O1 or O2) leads, in the frequency bin and hemisphere that was previously identified (i.e., based on maximal mu attenuation during infants' production of block lifts).

4.3.5 *Ancillary measures*

4.3.5.1 **Motor abilities checklist**

We assessed infants' overall level of gross motor development for two reasons: 1) to validate our novel grip strength measure, as we expected a significant positive relation between infants' motor development and grip strength scores (i.e., muscle strength increases with motor development; Woollacott, 1993) and 2) to ensure that relations between infants' mu attenuation and grip strength were not underwritten by differences in overall levels of motor development.

Prior to the experiment, parents completed a 24-item Motor Abilities Checklist (MAC; Loucks & Sommerville, 2013), adapted from the Bayley Scales of Motor Development (Bayley, 2006), which lists motor development milestones in order of increasing difficulty. We used the highest consecutive item that parents indicated that their infant could perform as infants' motor development score ($M = 13.50$, $SD = 6.06$; range: 4 - 24).

4.3.5.2 **Infant weight**

As body weight is correlated with grip strength in older children and adults (Wind, Takken, Helders, & Engelbert, 2010), we asked parents to report their infants' weight, taken at their 12-month doctor's appointment, in order to validate the grip strength measure. Infants' average weight was 9.85 kg ($SE = .25$; range: 7.75 – 12.80 kg).

4.3.5.3 Infants' in-task lifting experience

We coded the number of block lifts infants performed during the action task in order to ensure that any relations between infants' grip strength and mu attenuation were not explained by variability in infants' in-task lifting experience. Block lifts were operationalized as upward, manual actions that resulted in the infant fully supporting the block's weight. Infants performed an average of 9.61 ($SE = 1.16$, range: 0 - 23) light block lifts, 7.04 ($SE = 1.56$, range: 0 - 31) heavy block lifts, and 6.67 ($SE = 1.54$, range: 1 - 11) super heavy block lifts, for a grand average of 18.39 ($SE = 2.78$, range: 1 - 48) total lifts of all the blocks during the task. Overall, infants performed more one-handed lifts ($M = 7.00$, $SE = 1.09$) than bimanual lifts ($M = 2.61$, $SE = .61$) with the light blocks, $t(22) = 3.29$, $p = .003$, and more bimanual lifts ($M = 3.10$, $SE = 1.11$) than one-handed lifts ($M = .90$, $SE = .46$) with the super heavy blocks, $t(9) = -2.31$, $p = .05$. There was no difference in the number of one-handed ($M = 4.83$, $SE = 1.51$) versus bimanual lifts ($M = 2.22$, $SE = .53$) performed with the heavy blocks, $t(22) = 1.60$, $p = .13$. A second observer independently coded the number of lifts infants performed during the task for a randomly selected subset of infants. Inter-rater reliability (assessed via Pearson's correlations) was high, $r(7) = .98$, $p < .001$.

One possible concern for interpreting the results is that increased grip strength could enable infants to more accurately reproduce the experimenter's lifting action. Indeed, past work has shown that a greater similarity between produced actions and observed actions leads to greater activation of the shared neural system underlying action perception and production (Reid, Striano, & Iacoboni, 2011; Saby, Marshall, & Meltzoff, 2012). Accordingly, we coded the number of times, after observing the relevant demonstration, infants lifted the block onto a short platform and/or lifted the block and dropped it into a bucket (depending on which of the two actions were previously demonstrated). Faithful reproduction of the "lifting onto a platform

action” was operationalized as lifting a block and placing it completely and securely onto the platform. Faithful reproduction of the “lifting and dropping into a bucket” action was operationalized as lifting a block and dropping it into the bucket, without inverting the bucket. Infants faithfully reproduced the experimenter’s lifting action an average of 3.78 times ($SE = .95$; range: 0 - 16) during the task.

4.4 RESULTS

4.4.1 *Identification of mu rhythm: mu attenuation during infants’ production of block lifts*

To identify the location and frequency of maximal mu attenuation, we analyzed EEG activity during infants’ production of block lifts (collapsed over block weight) at sensor locations C3 and C4 from 6 - 9 Hz. As this required conducting eight, one sample t-tests (i.e., two leads and four frequencies), we employed the Bonferroni correction for this analysis and adopted a more stringent significance level of $p = .00625$. One sample t-tests revealed significant mu attenuation was only present in the 8 Hz frequency bin at C4, located in the right hemisphere, $t(22) = 3.92, p = .001, d = .82$ (see Figure 5). Thus, subsequent analyses on mu attenuation during observation of block lifts focused exclusively on EEG activity in the 8 Hz frequency bin at C4.

4.4.2 *Grip strength: descriptive statistics and relations with ancillary measures*

Infants’ maximum grip strength score was, on average, 2.31 psi ($SE = 1.86$; range: .89 – 3.73). Overall, infants recorded 3.61 squeezes on the grip strength device ($SE = .37$; range: 1 – 6; this number reflects infants’ initial squeeze and as many that met or exceeded 90% of the force of their previous highest squeeze). There were no differences in infants’ maximum grip strength

as a function of gender, $t(21) = .83, p = .4$. Infants' maximum grip strength was not associated with their frequency of faithful reproductions during the task, $r(23) = .13, p = .55$, but was marginally associated with the total number of block lifts performed during the task, $r(23) = .36, p = .09$, such that infants who performed more block lifts had higher maximum grip strength scores. Importantly, infants' maximum grip strength scores were positively correlated with their motor development scores, $r(22) = .54, p = .01$, (age-partialled, $r(19) = .55, p = .01$), such that infants who were more motorically advanced also had higher maximum grip strength scores. Additionally, infants' maximum grip strength scores were related to their body weight, $r(22) = .48, p = .02$, (age-partialled, $r(19) = .48, p = .03$), such that heavier infants had higher maximum grip strength scores. Together, these relations provide evidence that our novel paradigm accurately assessed infants' grip strength.

4.4.3 *Mu attenuation during observation of block lifts: relations to grip strength*

We hypothesized that mu attenuation during observation of block lifts would vary as a function of infants' grip strength, such that infants with higher maximum grip strength scores would exhibit greater mu attenuation during observation of block lifts than infants with lower maximum grip strength scores. We conducted a median-split analysis comparing mu attenuation during observation of lifts with all the blocks (i.e., collapsed across block weight) between infants who scored in the lower half on the grip strength assessment ($M = 1.52$ psi, $SE = 1.12$, range: .89 – 2.29) to infants who scored in the upper half ($M = 3.04$ psi, $SE = 1.42$, range: 2.39 – 3.73). This analysis revealed a significant difference in mu attenuation during observation of all block lifts as a function of grip strength group, $t(21) = 2.94, p = .01, d = 1.24$ (see Figure 6). One sample t-tests against zero confirm that mu attenuation during observation of all block lifts differed from baseline for the high grip strength group, $t(11) = 2.35, p = .04, d = .68$, but did not

for the low grip strength group, $t(10) = -1.90, p = .09$, (indeed, the low grip strength group showed marginal mu *augmentation*). These results demonstrate that infants in the high grip strength group exhibited mu attenuation during observation of all block lifts whereas infants in the low grip strength group did not.

Next, we investigated relations between individual differences in infants' grip strength and individual differences in mu attenuation during action observation. Because we hypothesized that the relation between mu attenuation and grip strength would become stronger as block weight increased (i.e., because grip strength exerts a greater impact when lifting heavy objects versus light objects), we performed Pearson's correlations between grip strength and mu attenuation during observation of all block lifts, as well as with mu attenuation during observation of lifts for each block weight independently. In these correlational analyses, we partialled-out infants' age, in-task lifting experience, and motor development scores, in order to examine the unique relation between grip strength and mu attenuation during action observation.

Paralleling the results of the median-split analysis, mu attenuation during observation of all block lifts was predicted by infants' maximum grip strength scores, $r(17) = -.56, p = .01$, such that higher maximum grip strength scores were associated with greater mu attenuation during observation of lifts. Furthermore, analyses investigating relations between infants' grip strength and mu attenuation during observation of lifts for each block weight independently demonstrated a progressively strong relation with increases in block weight: grip strength and mu attenuation during observation of light block lifts, $r(17) = -.31, p = .20$; grip strength and mu attenuation during observation of heavy block lifts, $r(16) = -.52, p = .03$; and grip strength and mu

attenuation during observation of super heavy block lifts, $r(3) = -.99, p = .002$ (see Figure 7)⁸.

The results of Steiger's Z-test (Steiger, 1980), which analyzes the difference between dependent correlations, confirm that there is a marginal difference in the correlation between mu attenuation during observation of light block lifts and grip strength, and the correlation between mu attenuation during observation of super heavy block lifts and grip strength, $z = 1.44, p = .08$, one-tailed (Lee & Preacher, 2013). The difference between the two correlations is compelling, as it was found with a small sample size (i.e., $n = 8$, as that is the number of infants who had artifact-free observation trials with the super heavy block), and demonstrating significant differences between dependent correlations requires considerable power (Kenny, 1987). As such, it is likely that with an increased sample size this difference would have reached conventional levels of significance.

Importantly, relations between infants' grip strength and mu attenuation during observation of block lifts were maintained after controlling for the frequency of infants' faithful reproductions (in addition to controlling for infants' age, in-task lifting experience, and motor development scores), which suggests that accurately reproducing the experimenter's actions did not account for these significant relations: grip strength and mu attenuation during observation of all block lifts, $r(16) = -.56, p = .02$; grip strength and mu attenuation during observation of light block lifts, $r(16) = -.29, p = .25$; grip strength and mu attenuation during observation of heavy block lifts, $r(15) = -.51, p = .04$; and grip strength and mu attenuation during observation of super heavy block lifts, $r(2) = -.99, p = .005$.

⁸ We conducted another set of Pearson's correlations between infants' grip strength and mu attenuation during observation of block lifts, controlling for the number of squeezes on the grip strength device, and significant relations with infants' grip strength were maintained: mu attenuation during observation of all block lifts ($r(16) = -.54, p = .02$); mu attenuation during observation of light block lifts ($r(16) = -.31, p = .22$); mu attenuation during observation of heavy block lifts ($r(15) = -.54, p = .03$); and mu attenuation during observation of super heavy block lifts ($r(2) = -.96, p = .04$).

Finally, we directly investigated whether infants' grip strength was the best predictor of variance in infants' mu attenuation. Accordingly, we conducted a multiple regression analysis with mu attenuation during observation of all block lifts as the dependent measure, and infants' age, motor development scores, in-task lifting experience, frequency of faithful reproductions, and grip strength as the predictor variables. The results of the multiple regression indicated that these five predictors explained 42.6% of the variance in mu attenuation, $F(5, 16) = 2.37, p = .09$. Critically, however, the multiple regression revealed that infants' grip strength was the only significant predictor of mu attenuation during observation of block lifts ($\beta = -.51, p = .02$) while the other four variables were non-significant (all p values $> .33$).

4.4.4 *Specificity of mu rhythm attenuation: examining EEG activity at frontal, parietal, and occipital leads*

In order to confirm that the reported mu attenuation was localized over the sensorimotor cortex, we investigated EEG activity during observation of block lifts in the 8 Hz bin at frontal, parietal, and occipital leads located in the right hemisphere (corresponding to 10-20 locations F4, P4, and O2, respectively). Critically, only over the sensorimotor cortex (i.e., C4) does attenuation differ significantly from baseline, and only for the high grip strength infants (see Figure 6; all remaining p values $> .10$). These findings are similar to that of previous studies on the mu rhythm in both infants (Marshall et al., 2011) and adults (Babiloni et al., 2002; Calmels, Hars, Jarry, & Stam, 2010; Marshall, Bouquet, Shipley, & Young, 2009)

In addition, we more closely investigated EEG activity at occipital lead, O2, in order to confirm that the reported mu attenuation was not reflective of the occipital alpha rhythm, a separate neural frequency also located in the 6 – 9 Hz range in infancy (Stroganova, Orekhova, & Posikera, 1999). Infants' grip strength scores, age, in-task lifting experience, frequency of

faithful reproductions, and motor development scores were all unrelated to EEG activity at O2 during observation of all block lifts, as well as unrelated to EEG activity at O2 during observation of block lifts for each block weight independently (all p values $> .34$). These findings demonstrate that the reported attenuation was specific to central leads overlaying the sensorimotor cortex, as attenuation was not found over matched frontal, parietal, or occipital leads, which confirms that our results specifically reflect attenuation of the mu rhythm frequency.

4.5 DISCUSSION

The aim of the present study was to investigate the influence of bodily characteristics on the shared neural system underlying action perception and production during action observation in infancy. To do so, we investigated the relation between grip strength and mu attenuation during observation of lifting actions with weighted blocks in 12-month-old infants, an age at which there is significant natural variability in infants' maximal grip strength. We found that infants with higher grip strength scores exhibited significant mu attenuation during observation of block lifts, whereas infants with lower grip strength scores did not. Furthermore, the relation between grip strength and mu attenuation varied as a function of block weight: grip strength more strongly predicted mu attenuation during observation of lifts with the heavy and super heavy blocks than with the light blocks. These relations were maintained after controlling for infants' age, in-task lifting experience, and motor development scores, which suggests that this relation was driven by differences in infants' grip strength, *per se*, and not other co-occurring factors.

Critically, our results confirm that differences in neural activity during observation of block lifts were found selectively at central leads, overlaying the sensorimotor cortex, and not

over matched frontal, parietal, or occipital leads. These findings, coupled with our use of a well-established method of identifying infants' mu rhythm band (i.e., based on the location and frequency of maximal mu attenuation during infants' production of block lifts; Cuevas et al., 2014; Marshall & Meltzoff, 2011), confirm that our results specifically reflect recruitment of the underlying neural assemblies indexed by the mu rhythm, and was not due to widespread changes in neural activity during the task (e.g., changes in visual attention as a function of task complexity; Herrmann, Sensowski, & Röttger, 2004).

More broadly, our results bear on issues regarding the development of the shared neural system underlying action perception and production. Specifically, scholars are actively debating whether we are equipped at birth with a neural system that links produced actions to observed actions, and whether experience is requisite versus facilitative towards this system's development (Cook, Bird, Catmur, Press, & Heyes, 2014; Gallese, Rochat, Cossu, & Sinigaglia, 2009). The present study contributes to this debate in two ways. First, mu attenuation during observation of block lifts was not exhibited by all infants in our sample; indeed, only the high grip strength infants exhibited significant mu attenuation during action observation. This finding, in itself, demonstrates that, irrespective of whether a shared neural system subserving action perception and production is present at birth, there are early emerging differences in activation of this system that are shaped by individual differences. Second, this study highlights the contribution of a previously unexplored factor that influences the development of this system, namely bodily characteristics. While previous work has evidenced the body's role in perception, broadly construed (Kretch et al., 2014; Proffitt, 2006; Soska et al., 2010), these results demonstrate that bodily characteristics also specifically influence action perception, and do so early in development.

A question that follows from these results is why grip strength was related to mu attenuation during observation of block lifts. One possible explanation is that grip strength and mu attenuation were related because grip strength alters the acquisition of lifting experience - serving to either facilitate or constrain its acquisition. This interpretation would align with prior work showing that activation of the shared neural system underlying action perception and production during action observation is shaped according to bodily experience (Cross et al., 2006; van Elk et al., 2008). Although our results cannot be attributed to in-task differences in lifting experience (as we measured and controlled for this factor in our analysis), it is possible that grip strength influenced infants' lifetime experience with lifting objects, particularly heavy objects. If this were the case in the present study, it would align with previous work that has found an effect of bodily experience on action perception, and extend it by demonstrating that acquiring experience that specifically corresponds to the actions being observed (in this case, lifting heavy objects) has a stronger influence on activation of the neural system underlying action perception than does generalized action experience (e.g., lifting any object). Moreover, if certain bodily characteristics (e.g., grip strength) prove to be an accurate proxy for aspects of infants' lifetime experience (e.g., lifting heavy objects), this would present a substantial methodological advance in studying the effects of bodily experience on action perception, by providing a quick, in-laboratory measure that captures infants' everyday action experience (i.e., grip strength assessment).

Another possible explanation for the relation between grip strength and mu attenuation during action observation is that grip strength may have affected infants' ability to accurately reproduce the observed lifting action, as past work has shown that a greater similarity between produced actions and observed actions leads to greater activation of the shared neural system

underlying action perception and production (Reid et al., 2011; Saby et al., 2012). However, if the similarity between the infants' and the experimenter's actions were driving the current results, we likely would have found relations between mu attenuation and infants' faithful reproductions of the experimenter's actions. As this was not the case, it seems unlikely that the degree of similarity between the infants' and experimenter's actions accounts for the current results.

Relatedly, given the inherent kinematic differences among object-directed actions as a function of their weight (even for skilled adult experimenters), as well as differences in the resulting physical outcomes (e.g., louder 'thumps' when dropping heavy blocks versus light), it is possible that infants' grip strength influences their sensitivity to these cues in others' actions. In this way, grip strength may have been associated with mu attenuation during observation of lifts because high grip strength infants were better at recognizing differences in the experimenter's actions as a function of block weight, as well as recognizing their associated physical outcomes, than were low grip strength infants.

A final possible explanation for the relation between grip strength and mu attenuation during action observation, and an interpretation that we favor, is that this relation may be driven by differences in infants' ability to recognize the differential effort associated with lifting objects of various weights. As strength necessarily influences one's ability to lift objects, it is likely that stronger infants have acquired more contrastive lifting experience (i.e., experience lifting a wider range of objects), which may help these infants recognize that object-directed actions require differing degrees of effort as a function of their weight (among other object properties). This would align with prior work that has demonstrated that experience observing contrastive outcomes allows for comparison between exemplars, which serves to accelerate infants' learning

(Wang & Baillargeon, 2008). Furthermore, weaker infants may allot more cognitive resources towards action production than do stronger infants, particularly when lifting heavy objects, which may come at the expense of attending to and encoding differences in their expended effort as a function of object weight. Thus, increased μ attenuation during action observation, as exhibited by the high grip strength infants in the current study, may reflect their recognition of the effort associated with the observed lifting action, and the progressively close relation between grip strength and μ attenuation with increased block weight may capture their understanding that effort increases with object weight.

Additional support for our interpretation is found in studies that have demonstrated greater activation of the shared neural system underlying action perception and production for individuals with experience and expertise with the witnessed action. Because action experience likely facilitates the ability to recognize the effort associated with a given action, it is possible that the results of prior studies reflect differences in the observers' ability to recognize expended effort for particular actions (Aglioti, Cesari, Romani, & Urgesi, 2008; Calvo-Merino et al., 2005; Cross et al., 2006). This novel interpretation of past results is also consistent with work by Proffitt and colleagues (Proffitt & Linkenauger, 2013) that has demonstrated that perception of the environment is scaled by the effort an individual anticipates expending during action production (e.g., perception of flat expanses is scaled by the anticipated effort to walk from point A to point B). Additionally, studies have found that observing actions performed with heavy versus light objects elicits increased activation of the neural system underlying action perception and production (Alaerts et al., 2010; Alaerts, de Beukelaar, Swinnen, & Wenderoth, 2012; Senot et al., 2011), which provides further support that perception of increased effort is associated with greater activation of this system. The present study builds on these findings by suggesting that

grip strength either constrains or facilitates the ability to recognize effort, such that weaker individuals may be unable to recognize and appreciate the effort expended by others, whereas stronger individuals can.

Our interpretation - that infants, as a consequence of their own developing strength, are differentially sensitive to effort - may also help to explain why a recent, similar study failed to find group level differences in mu attenuation during action observation as a function of object weight (Marshall et al., 2013). In that study, mu rhythm activity was recorded while 14-month-old infants observed an experimenter performing actions with objects of different weights. They found no difference in mu attenuation during action observation as a function of object weight, and, moreover, the reported mu attenuation was very subtle. As such, it is likely that infants in their study, as in the current experiment, varied in strength. However, because individual differences in grip strength were not measured and accounted for in their analysis, testing a heterogeneous sample in terms of strength may have served to obscure, rather than illuminate, differences in mu attenuation that would have been found as a function of object weight.

Nevertheless, it is always possible that infants' grip strength serves as a proxy for another, as-yet uncovered variable that better explains variability in mu attenuation during action observation. However, future work may provide a critical test of our hypothesis that grip strength leads infants to be differentially sensitive to others' expended effort. For example, given that individuals seek to minimize expended effort when possible (Proffitt, 2008), and given that infants preferentially select light over heavy objects (Hauf, Paulus, & Baillargeon, 2012), we would predict that, after seeing another individual act on objects of varying weight, and in the absence of direct experience, infants' tendency to select light over heavy objects should vary as a function of grip strength. Specifically, if grip strength gates the ability to recognize effort,

stronger infants should be more likely to choose lighter objects over heavier objects, while weaker infants should not differentiate their actions towards the objects. These findings would support the conclusion that stronger infants are better able to recognize the differential effort associated with lifting objects of different weights than are weaker infants.

Another unresolved and contested issue concerns the functional significance of neural activation of the shared system underlying action perception and production. Specifically, some researchers have argued that activation of this system during action observation is the by-product of domain general associative learning, and, as such, does not necessarily contribute to action understanding and could even be epiphenomenal (Cook et al., 2014; Heyes, 2010a; Hickok, 2009). Alternatively, other researchers have proposed that activation of this system facilitates one's ability to identify the goals and intentions underlying an observed action (Calvo-Merino, 2013; Iacoboni et al., 2005; Rizzolatti, Fogassi, & Gallese, 2001). Future work can begin to directly test these competing hypotheses. If the latter hypothesis is correct, it is possible that increased mu attenuation during action observation, as exhibited by high grip strength infants in our study, represents a heightened understanding of the goals underlying the experimenter's lifting actions (e.g., to place the block *on top of*, versus *beside*, a platform). Thus, future studies may seek to demonstrate that infants' ability to identify the experimenter's goal in this context is driven by their grip strength. For example, stronger infants should outperform weaker infants in visually anticipating the goal of the experimenter's lifting actions and in predicting her subsequent actions.

To conclude, the present experiment advances prior research by demonstrating that individual differences in bodily characteristics profoundly influence how infants perceive others' actions. Moreover, the impact of bodily characteristics on action perception emerges early in

development. Our findings suggest a potential novel role for the body in perception, by either enabling or constraining infants' ability to recognize the differential effort associated with various actions. Thus, the present study demonstrates that, beyond the acquisition of experience, the body in itself, its characteristics and capabilities, serve to uniquely shape our perceptions of the nearly ubiquitous actions of other people.

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FIGURE 5. Mu attenuation during infants' production of block lifts from 6 – 9 Hz at C4.

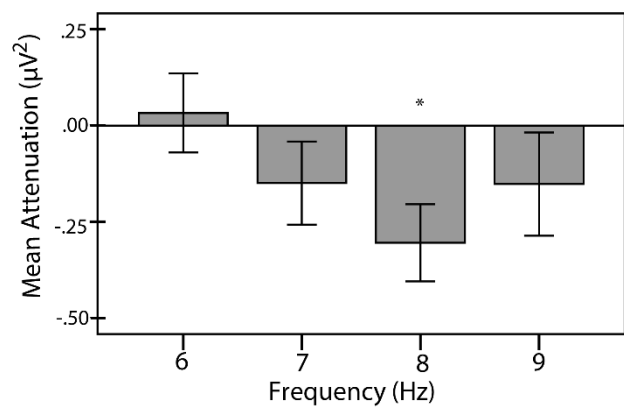


Figure 5. Mu attenuation during infants' production of block lifts from 6 – 9 Hz at C4. Mu attenuation differed significantly from baseline at 8 Hz only. Error bars represent standard error.

* $p = .001$.

FIGURE 6. EEG activity in the 8 Hz bin during observation of all block lifts as a function of grip strength group at four scalp locations.

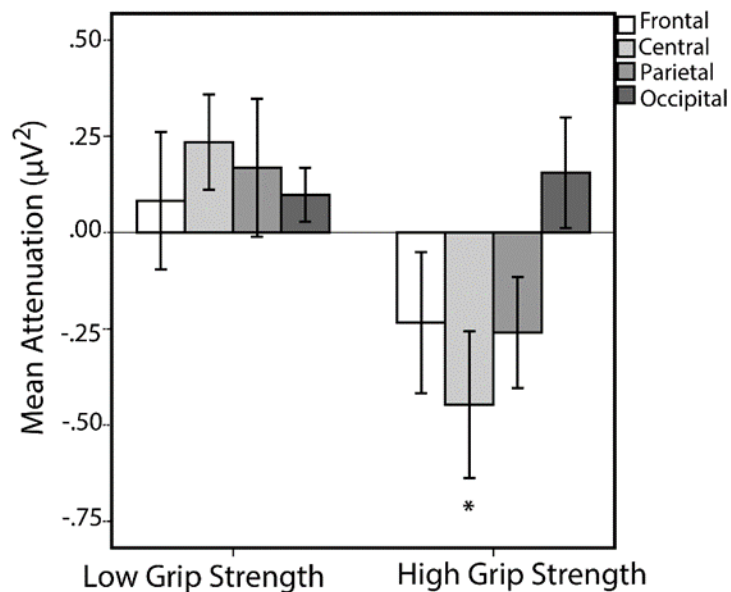


Figure 6. EEG activity in the 8 Hz bin during observation of all block lifts as a function of grip strength group at four scalp locations (F4, C4, P4, and O2). Significant attenuation relative to baseline was only found at the central lead, C4, for the high grip strength group of infants. Error bars represent standard error. * $p = .04$.

FIGURE 7. Pearson's correlations between infants' maximum grip strength and mu attenuation during observation of lifts.

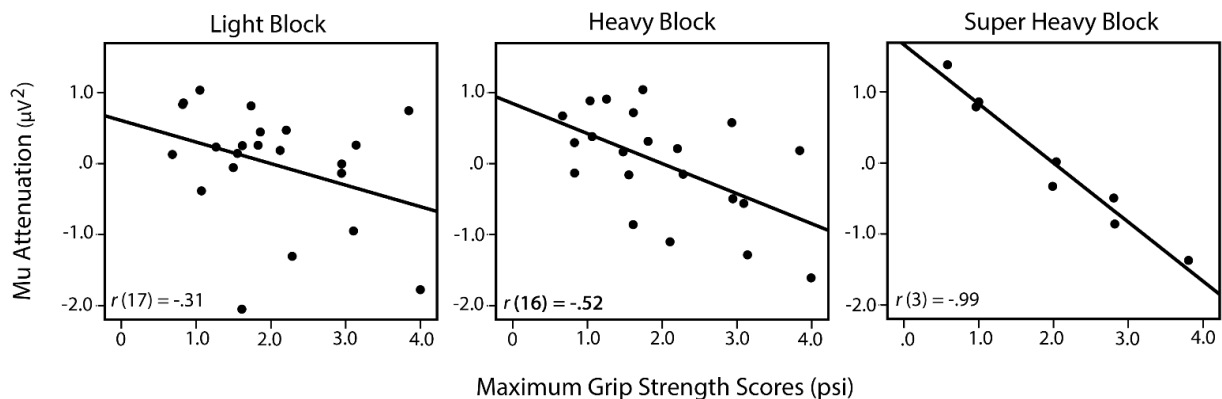


Figure 7. Pearson's correlations between infants' maximum grip strength (in psi) and mu attenuation during observation of lifts with the light block, heavy block, and super heavy block. Pearson's r values reflect the partial correlation (controlling for infants' age, in-task experience, and motor development scores) between grip strength and mu attenuation during action observation.

Chapter 5. DISCUSSION

This dissertation demonstrates that infants' understanding of object weight, and their ability to apply this understanding, is flexible and sophisticated by the end of the first year of life. In addition, I found that strength influences infants' understanding of object weight in some contexts (i.e., action perception) but not others (i.e., physical reasoning). Chapter 2 demonstrated that infants can apply object weight information acquired by lifting and pushing objects in order to guide their actions when retrieving those objects in a means-end task. Chapter 3 demonstrated that infants can infer an object's weight based on whether or not its supporting surface is compressed and that they generate accurate predictions regarding the outcome of support events involving heavy and light objects. Chapter 4 demonstrated that infants' understanding of object weight, and infants' strength, influence their recognition of another person's effort when lifting objects of different weight. Though past work demonstrated that infants can apply an understanding of object weight in order to guide action in familiar contexts (Itier et al., 2001; Mash, 2007; Molina & Jouen, 2003; Palmer, 1989), it was unclear whether infants could apply their understanding of object weight more broadly. This dissertation addressed this gap by demonstrating that, by the end of the first year of life, infants' understanding of object weight is already flexible (i.e., applied in areas outside of action production in familiar contexts) and sophisticated (i.e., used to reason abstractly about the outcome of physical events).

More specifically, prior work on infants' understanding of object weight demonstrated that over the first year of life, infants progress from adapting their actions toward objects as a function of weight (e.g., Palmer, 1989), to anticipating an object's weight after interacting with the object (Mash, 2007), to inferring an object's weight based on past interactions with visually similar objects (Gottwald & Gredebäck, 2015; Mash et al., 2014). Chapter 2 adds to this picture

by demonstrating that, after learning about an object's weight by lifting and pushing the object, infants can generate a novel action plan to retrieve the object in the absence of trial-and-error learning. This widens the scope of our early action production capabilities, which is important given that disruptions in the ability to plan and produce actions are implicated in several neurodevelopmental disorders (e.g., developmental coordination disorder; Bo & Lee, 2013). Thus, better understanding the typical trajectory of infants' action production capabilities may serve to identify early delays or abnormalities in development.

This dissertation also speaks to the nature of infants' conceptual representations, and, in particular, whether these representations are more accurately characterized as context-specific or abstract and generalizable. The present studies suggest that infants' representations of object weight are better characterized as abstract and generalizable rather than context-specific. Indeed, infants' representations of object weight were found to guide action in novel contexts (Chapter 2), aid in interpreting and predicting the outcome of a physical event (Chapter 3), and to shape the perception and understanding of another person's actions (Chapter 4). Thus, in all three studies infants had to go beyond the information that they acquired through acting on the objects in order to apply this information in novel and abstract ways. In conjunction with prior work (e.g., Hayne et al., 2000; Learmonth et al., 2004, 2005), this may suggest that the flexibility of infants' representations is partially determined by the breadth of their content. For example, infants' ability to remember and reproduce an observed action (e.g., shake a puppet to ring a hidden bell) is highly dependent on the context that the action was observed in and is hindered following contextual changes (e.g., a novel experimenter is present or a new puppet is used). This could be because actions are often defined by their context. For example, a novel person may not like or understand an action that was demonstrated by another, and an action is often

limited to its surroundings, such as cooking actions are specific to the kitchen. Infants may be sensitive to such distinctions (Learmonth et al., 2005), and, in particular, may rely on others' communicative cues when determining whether information is context-specific or generalizable (Egyed, Király, & Gergely, 2013). For example, imitation is more resilient to contextual changes when infants are explicitly addressed and implored to attend to the novel demonstration (Hanna & Meltzoff, 1993; Hayne et al., 2000) as compared to when the demonstration is simply performed in front of them (Learmonth et al., 2004, 2005). Thus, the flexibility of infants' representations may be shaped by the breadth of their content and the way in which information is communicated.

To illustrate, the present studies suggest that infants' representations of object weight are relatively abstract. This could be due in part because object weight is broadly applicable information with ramifications across contexts. That is to say, it is highly adaptive to generalize knowledge about object weight. For example, knowing that an object that requires more force to lift will also require more force to pull, and that an object that requires more of *my* force to lift will also require more of *your* force to lift, are helpful generalizations to make, as the same concept of object weight can be used to inform each situation. It is also likely that other people help to foster such abstract representations of object weight. For example, in the studies presented in Chapters 3 and 4, the experimenter purposefully drew infants' attention to her actions and the events involving objects of different weight, which may have emphasized the importance of object weight (e.g., saying "*Look at this!*" while pointing to an object that compressed the platform). This may correspond with infants' real life experience as well (e.g., a parent might say, "*Wow, that box is heavy. You sure have a lot of toys! Be careful, if the box topples over it could hurt you.*"). Thus, the adaptive benefit of generalizing object weight

information, and the possibility that other people emphasize object weight information, may explain how infants are able to leverage representations of object weight formed in one context to other contexts.

5.1 IMPLICATIONS FOR LEARNING FOLLOWING UNEXPECTED INFORMATION

The current findings also provide information regarding factors that facilitate early learning. Specifically, recent evidence suggests that encountering unexpected information facilitates learning (Gerken et al., 2015; Stahl & Feigenson, 2015), but it is unclear whether *any* type of unexpected information facilitates learning, or if this effect is unique for information that violates physical principles (Schulz, 2015). Chapter 2 addressed this issue by comparing infants who received consistent object weight information to infants who encountered an unexpected reversal of the objects' color-weight pairings between the familiar and novel contexts. This information was unexpected for infants only in light of their recent experience with the objects and not because it violated any physical laws. I found that infants who encountered unexpected object weight information were able to plan their actions according to these new representations of object weight in the novel context, which demonstrates rapid learning. In contrast, infants who encountered consistent object weight information did not improve when planning their actions in the novel context, despite having acquired more experience with the objects. This was borne out by the finding that infants who received consistent object weight information planned their actions in an equivalent way on both trials in the novel context, though their performance on the first trial was less than perfect and left room for improvement. Though it is conceivable that acquiring additional experience with the objects would have improved infants' ability to plan their actions according to object weight, it did not. Altogether, this suggests that encountering unexpected information, and not just information that violates physical laws, has a facilitative

effect on infants' learning, and that encountering additional, consistent information does not lead to noticeable in-task improvement. To be clear, this is not to suggest that acquiring more experience interacting with objects of different weight does not facilitate learning—of course such a claim would be untrue. However, during a brief experiment, acquiring incremental experience with the same objects of different weight does not appear to rapidly improve infants' understanding of object weight, while even brief experience with unexpected object weight information has a rapid and robust effect.

This finding of Chapter 2 is important because it serves to confirm an intuition that developmental psychologists have long held but have only recently validated. That is, though it is well known that infants exhibit heightened attention to events that violate their expectations (e.g., Baillargeon, Spelke, & Wasserman, 1985), it was not known whether these violations also served as learning opportunities over and above the fact that these events simply elicit increased attention (Schultz, 2015). By controlling for the amount of time infants had to explore the objects during the task, Chapter 2 confirms that encountering unexpected information leads to learning independent of the quantity of experience (Stahl & Feigenson, 2015).

5.2 THE CONTRIBUTION AND LIMITS OF BODILY FACTORS ON THE UNDERSTANDING OF OBJECT WEIGHT

The present studies also inform the debate regarding the role of the body in cognition by investigating the influence of strength on infants' understanding of object weight. Specifically, there is controversy over whether evidence that sensorimotor areas are active during cognitive tasks (Goldberg, Perfetti, & Schneider, 2006; Kiefer, Sim, Herrnberger, Grothe, & Hoenig, 2008; Martin, 2007) and that bodily states can both facilitate and interfere with cognitive performance (Ambrosini, Sinigaglia, & Constantini, 2012; Shebani & Pulvermüller, 2013) demonstrates a

causal role for the body in cognition or whether these relations are an epiphenomenal consequence of the oft-quoted axiom “cells that fire together, wire together.” On one side of the debate are traditional cognitive theorists (Fodor, 1983; Mahon & Caramazza, 2009) who argue that sensorimotor activity may enrich cognitive processes but that cognition is not dependent upon sensorimotor activity. On the other side of the debate are embodied cognition theorists (Barsalou, 2008; Gallese & Sinigaglia, 2011) who argue that the body plays a constitutive role in cognition. Increasingly, however, there is an emerging middle ground between the two sides (Hauk & Tschentscher, 2013; Moseley, Kiefer, & Pulvermüller, 2016) that advocates for an important role for the body in cognition while acknowledging that the degree to which the body is involved will differ depending on the cognitive process being investigated or the details of the task. To explain, support for a variable influence of the body is found in research demonstrating that the body has a greater influence on cognition whenever action, or the potential for action, is present (Costantini, Ambrosini, Tieri, Sinigaglia, & Committeri, 2010; Kirsch, Herbort, Butz, & Kunde, 2012; ter Horst, van Lier, & Steenbergen, 2011). For example, neural activity in motor areas is greater when reasoning about objects that are within versus beyond one’s reaching space (Cardellicchio, Sinigaglia, & Costantini, 2011; Culham, Gallivan, Cavina-Pratesi, & Quinlan, 2008; Gallivan, Cavina-Pratesi, & Culham, 2009) and when processing action-related words versus imagery-related words (e.g., kick, grasp, or bite versus snow, sun, or blond; Hauk, Davis, Kherif, Pulvermüller, 2008). Thus, these studies suggest that the body influences cognition more in some contexts than in others.

The present work supports this claim—that the body has a variable influence on cognition—by demonstrating that strength influences infants’ understanding of object weight in some contexts but not in others. In particular, strength did not influence infants’ ability to reason

about the effect of object weight in support events but did influence infants' perception and understanding of another person's lifting actions. These studies differed in two important ways: the prominence of action in the procedure and the importance of action to the research question.

Specifically, in Chapter 3, the action demands were quite minimal. Preferential reaching tasks, like the one used in Experiment 1 of Chapter 3, are often employed *because* of their minimal action demands: infants need only direct their reach toward one stimulus as opposed to another (Hauf et al., 2012; Hespos & Baillargeon, 2006). In addition, though infants were encouraged to interact with the objects after reaching toward one, they were not forced to do so, and the object was removed after infants lost interest. Furthermore, infants' actions with the objects did not influence their ability to infer object weight based on compression information, as there were no changes in infants' light block choices as they acquired more experience. Experiment 2 of Chapter 3 was even further removed from action, as it was a looking-time task. In addition, the objects in the critical test trials of Experiment 2 were presented well beyond infants' reach, so the possibility for action with the objects was eliminated. More important than the minimal action demands of the procedure, though, is the fact that physical reasoning is less likely to be influenced by action experience than is action understanding, the topic of Chapter 4. In support of this possibility is work demonstrating that physical reasoning and action processing are subserved by separate neural areas (e.g., Blakemore et al., 2001; Martin & Weisberg, 2003; Stosic, Brass, van Hoeck, Ma, & van Overwalle, 2014), which could reduce the influence of a bodily factor like strength on physical reasoning. In sum, action was not a central component of the procedure nor to the cognitive process being investigated in Chapter 3, either or both of which could have contributed to the null finding regarding strength.

In contrast, action was an essential element of Chapter 4. First, the procedure of the study in Chapter 4 was a highly active, turn-taking task, during which the infant and experimenter alternated between performing actions with differently weighted blocks. The actions that the experimenter and infant performed were also considerably more demanding than a simple reach, such as dropping a heavy block into a bucket or placing it on top of a platform, which require both strength and coordination. In addition to the importance of action to the procedure in Chapter 4, the cognitive processes under investigation were squarely action related: action perception and understanding. Thus, given that strength influences action *production*, it is perhaps more reasonable to predict that strength would also influence action *perception*, as the same neural structures that subserve action production subserve action perception (Marshall & Meltzoff, 2011; Rizzolatti & Craighero, 2004).

Future work should seek to verify the claim that the degree to which the body influences cognition differs according to the prominence of action—either via its role in the study procedures or via the cognitive process being investigated—by systematically stripping away these two components. For example, strength may be less associated with the perception of others' lifting actions if infants simply watched the experimenter performing the lifts, without acting on the objects themselves. It is possible the results of Chapter 4 would have been different if the objects were simply placed in the lap of each infant, so that they could perceive each object's weight without acting on them. Similarly, it would be interesting to investigate whether strength would influence cognitive processes that are far afield from action if the procedure incorporated a prominent action component. For example, it is possible that incorporating heavy objects into a manual search task would reveal that strength influences infants' numerical representations (e.g., Feigenson & Carey, 2003). Either of these hypothetical studies would be

informative for determining whether the role of bodily factors in cognition is stronger whenever action is prominent. Regardless, if the body's role in cognition is determined to be important yet variable, both traditional and embodied cognition theorists will need to move closer to this middle ground.

5.3 LIMITATIONS AND FUTURE DIRECTIONS

Though this dissertation was an earnest and thoughtful investigation into infants' understanding of object weight, these studies, like every scientific work, has its limitations. For one, a limitation of all three studies is that the infants under investigation were largely from educated, Caucasian families, based in the Pacific Northwest of the United States, and whom had the motivation and available resources (i.e., time and money) in order to travel to the lab and participate in developmental research. Indeed, evidence suggests that such socio-economic and cultural factors are associated with differences in cognitive processes (Henrich, Heine, & Norenzayan, 2010). Thus, the present results may represent the understanding of object weight for a slice of the overall infant population, rather than representing an early cognitive universal. Another limitation, that only pertains to the studies presented Chapters 3 and 4, is that though I sought to assess infants' strength—and can be relatively confident that infants' strength was assessed due to relations with motor development and body weight—it is nevertheless possible that the pull- and grip-force assessments were a better measurement of another, as-yet uncovered variable.

In addition, a limitation of the interpretation of Chapter 2 is in how far it extends infants' action production capabilities with respect to object weight. Though Chapter 2 demonstrates that infants can incorporate object weight information in order to guide novel actions, it is possible that infants' action production abilities are even more advanced. For example, a compelling

future direction would be to examine whether infants can additively apply separate experiences with objects of different weight in order to guide action when the objects are all together. Indeed, adults can swap seamlessly between performing actions on individual objects and combinations of objects (Davidson & Wolpert, 2004), and this ability is paramount to skilled and mature action production—producing too much force could damage the objects or oneself and producing too little force could lead to erratic or failed actions. However, it is unknown whether infants can skillfully act on novel combinations of objects. For example, a variant of the study presented in Chapter 2 could investigate whether, after interacting separately with two heavy objects, infants would apply more force when attempting to retrieve both objects relative to when attempting to retrieve a single object. If so, it would demonstrate even further sophistication in infants' action production capabilities and would indicate that adults' seemingly effortless ability to act on novel combinations of objects is actually underwritten by decades of practice.

In addition, the conclusion that infants' representations of object weight are relatively abstract must be considered alongside the fact that in each study infants were provided with some type of interactive experience with an object (either with the weighted objects themselves or the soft platform) that facilitated these generalizations. Thus, this dissertation is limited to suggesting that infants' representations of object weight are abstract *after* experience interacting with objects. As such, an interesting future direction would be to examine when infants' representations of object weight become sufficiently abstract in order to guide reasoning without interactive experience. For example, adults can infer an object's weight based simply on compression of a supporting surface and could likely infer an object's weight based solely on auditory information, such as hearing the sound of two objects crash to the ground after falling off of a support (i.e., a louder sound indicates a heavier object). However, during the first year of

life, infants seem to require some type of interactive experience, and it is unknown whether they could infer object weight based on auditory information. Determining when infants become capable of reasoning about object weight without interactive experience would signal a milestone in their conceptual understanding, as it would show that they truly represent object weight as an enduring property of an object that exists independent of their own actions.

Another limitation of the present work concerns the broad claim that bodily factors that influence action production, such as strength, have a downstream impact on action perception, as this dissertation only demonstrates that the bodily factor of strength has an influence on the perception of others' actions with differently weighted objects. Thus, an important next step would be to investigate whether *other* bodily factors have an influence on action perception. Indeed, if bodily factors that influence action production influence action perception and understanding, this effect should be found across a range of bodily factors and actions. One compelling bodily factor to investigate is the ability to maintain balance. For example, 16-month-old infants are able to traverse a narrow bridge with the aid of a handrail (Berger, Adolph, & Kavookjian, 2010), but there are individual differences in this ability between infants, and work with adults suggests that differences in the ability to maintain balance play a critical role in one's decision and ability to traverse a narrow expanse (Comalli, Franchak, Char, & Adolph, 2013). As such, it would be interesting to investigate if infants who are better able to maintain balance would exhibit heightened perception and understanding of another person's traversal actions, particularly as the width of the bridge gets narrower (e.g., a wide plank versus a tightrope). A relation between balancing ability and the perception of another person's traversal actions would support the claim that bodily factors that impact action production shape action perception and one's ability to recognize others' exerted effort.

5.4 CONCLUSION

Infants exhibit an impressive ability to apply their understanding of object weight across contexts. Not only are infants able to apply their understanding of object weight in order to guide action in familiar contexts, but they are able to leverage and abstract upon this experience in order to guide action in novel contexts, interpret and predict the outcome of physical events, and understand the actions of others. In addition, at least one bodily factor that impacts the acquisition of action experience, strength, plays an influential role in infants' action perception. Broadly, this dissertation demonstrates that infants' representations of object weight are flexible and sophisticated by the end of the first year of life, and that the role of the body in cognition is greater in contexts pertaining to action. Finally, though this dissertation explored the specific issue of infants' understanding of object weight, it should be viewed as being in service of a larger question: how are we, as humans, able to infer and reason about unobservable factors when predicting and explaining the world? This dissertation is my attempt to answer this question, with the hope of providing a little more clarity on a much bigger idea.

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APPENDIX A

Additional Variables: Experiment 1

Coding

A second dependent variable was the proportion of 2-handed reaches toward each block. Because infants had not yet received haptic feedback regarding the block's weight during their reach (i.e., prior to contacting the block), the number of hands infants used when reaching toward each block may reflect their ability to infer object weight from compression information. We reasoned that if infants can infer object weight from compression information, they would be more likely to reach toward the heavy block with two hands versus one.

Two additional variables were coded to ensure that infants differentiated their actions toward each block as a function of weight in their interactions with them during the test trials. This would confirm that infants accurately encoded each block's weight. These variables were: which action infants performed to retrieve the block off of the platform (i.e., lift, push/tip, or did not retrieve) and whether infants retrieved the block with one or two hands. We predicted that if infants differentiate their actions as a function of block weight, they would be more likely to retrieve the light block via lifting it (as pushing or tipping the light block may cause it to fall out of reach) and more likely to retrieve the heavy block via pushing or tipping it (as lifting the heavy block was more difficult).

Results

Proportion of 2-handed reaches toward each block. Separate proportion scores were created for the number of 2-handed reaches toward the light and heavy blocks over the total number of reaches toward each block. Paired samples t-tests were then conducted comparing the

proportion of 2-handed reaches toward the light and heavy blocks. This revealed no difference in the proportion of 2-handed reaches toward the blocks as a function of weight, $t(51) = 1.07$, $p = .29$, likely because infants predominantly reached toward the blocks with one hand (on $M = 89.8\%$ of all trials).

Action used to retrieve each block. Across the entire task, infants were more likely to retrieve the light block off of the platform by lifting it than they were to retrieve the heavy block via lifting ($M = 55.1\%$ vs. $M = 17.2\%$), as revealed by a paired samples t-test, $t(51) = 10.8$, $p < .001$, $d = 1.55$. Similarly, infants were more likely to retrieve the heavy block by pushing or tipping it off of the platform versus pushing or tipping the light block ($M = 58.7\%$ vs. $M = 34.9\%$), as confirmed by a paired samples t-test, $t(51) = 5.94$, $p < .001$, $d = .83$. Lastly, infants were more likely to refuse to retrieve the heavy block than they were to refuse to retrieve the light block ($M = 24.1\%$ vs. $M = 10\%$), as confirmed by a paired samples t-test, $t(51) = 4.5$, $p < .001$, $d = .69$.

Irrespective of the retrieval action performed, infants were more likely to use two hands when retrieving the heavy block than when retrieving the light block ($M = 36.1\%$ vs. $M = 21.9\%$), $t(50) = 3.86$, $p < .001$,⁹ $d = .54$. Note that retrieving the heavy block with two hands is distinct from reaching toward the block with two hands, as retrieval occurred *after* infants made contact with the block. These results demonstrate that infants differentiated their actions toward the blocks as a function of their weight.

⁹ One infant refused to retrieve the heavy block on all test trials and was excluded from this analysis.

VITA

Michaela was born and raised in Texas and is a proud alumna of Texas A&M University. She moved to Seattle in 2009 after graduating college and getting married to her husband, Sean.