# PRESCHOOL ENGINEERS: BUILDING BRIDGES TO SUPPORT AN ELEPHANT'S WALKING ACROSS A RIVER

by

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A dissertation submitted to the

School of Graduate Studies

Rutgers, The State University of New Jersey

In partial fulfillment of the requirements

For the degree of

Doctor of Philosophy

Graduate Program in Psychology

Written under the direction of

Rochel Gelman

And approved by

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New Brunswick, New Jersey

OCTOBER, 2018

ABSTRACT OF THE DISSERTATION

Preschool engineers: building bridges that can support an elephant's walking across a river

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Humans are creative artifact and tool makers. The first step in the manufacturing process is the selection of appropriate materials; yet, relatively little is known about children's understanding of the properties of different materials that make them suitable for creating particular artifacts. In the 3 studies presented here, we asked children from 3 to 5 years old if different kinds of materials can be used to build a bridge for an elephant to walk on. In Study 1, each material was presented individually to one group that was asked to touch it, and another group that was not, before deciding whether it could be used to make a bridge for an elephant to walk on. If so, the elephant could choose the short route across river, if not, the elephant should take the longer route around the forest. 5-year-old children, but not 3- and 4-year-old children, showed an ability to choose the correct route depending on the material in the Touching-Not-Required condition. Study 2 presented children with a simplified version of Study 1; children were asked to choose which of two materials would make a bridge walk-on-able for an elephant. Since the thickness of the material covaried with the rigidity, study 3 controlled the thickness of the pairs presented; children as young as 3 years old could reliably use the relative rigidity of the samples to select the appropriate material. Our findings suggest that a cognitive precursor for artifact-making behaviors emerges in early childhood.

*Acknowledgments*

I would like to thank my advisor, Rochel Gelman, for her encouragement to this adventure of the new areas, her tireless help and support, and insightful guidance. I am also grateful to our participants, their families and preschools, without whom the study would have been impossible. I also thank Mishal Khan and Danielle Sylvester for helping collect data, Tom Grace and Xiaotao Su for helping with the creation of some stimuli, Michelle Cheng and Christina Boyce-Jacino for doing the dubbing. Deep gratitude is due to Alan Leslie, Brian McLaughlin, Judith Hudson, Liqi Zhu, Randy Gallistel, and Susan Gelman for their helpful suggestions.

My special gratitude and appreciation also go to my parents, for their encouragement and unconditional support.

This research was supported in part by grants from the National Science Foundation REC 0529579 and Rutgers University.

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# *I. Introduction*

Humans are natural makers of tools and artifacts (Oakley, 1956; Risto, 2011). Even though humans can survive by using naturally occurring objects (e.g., living in caves, selecting tools from the environment, eating uncooked flesh) (Reich et al., 2010; Semaw et al., 1997; Susman, 1994), pre-existing artifacts are limited in their capability to meet human needs. For example, even though humans can take shelter in a cave, it is not as comfortable or safe as living in a man-made house. Likewise, even though we can use a leaf to hold water, a bowl is more efficient, and even though humans can survive on raw flesh, cooked meat is safer to eat. Without the invention of boats, planes, phones or computers, an American could never send a message to someone in China. Clearly, the making of tools and artifacts has improved the quality of human life.

The earliest artifact-making behavior can be traced back 2.5 million years (Ambrose, 2001). How humans started making tools and artifacts, however, has always been a mystery, and the underlying cognitive abilities remain largely unknown. This dissertation will focus on an essential cognitive precursor that prepares humans for artifact-making behaviors—specifically, how children understand a material's properties as constraints in making an artifact and serving its function.

In this chapter, I will first discuss humans' and animals' artifact-making behaviors. Even though one of the first steps in the manufacturing is the selection of appropriate materials, little attention has been paid to children's understanding of a substance's properties and whether it can be used to make an artifact in the field of cognitive development. To start to address this gap, I conducted three studies investigating children's reasoning about what kinds of materials can be used to build a bridge to support a certain weight. In Chapter 2, I examine what happens when 3- to 5-year-old children are explicitly asked whether a certain material can be used to make a bridge. Children were asked to decide which route an elephant should take. If the bridge is walk-on-able, then the elephant should cross; if not, then he should take the longer route around. Half of the children were required to touch each material, and half were not. I assessed how often children spontaneously touched the materials and whether required children to touch facilitate their performance in judging the correct route. In Chapter 3, I presented two studies that used a simplified task. In this task, children did not need to choose a route for the elephant; instead, 3- and 4-year-olds were only asked to choose the more appropriate of two materials. Of interest is whether they can use relative rigidity to help select the more appropriate material. In Chapter 4, I summarize the findings, discuss the implications of children's ability to consider the suitability of a material's properties for certain artifacts.

*Humans' and animals' artifact-making behaviors*

Humans make many different kinds of artifacts, including tools, shelters, vehicles, lamps, bridges, furniture and jewelry (Risto, 2011). The ability to manufacture requires many cognitive processes; the creator needs to keep the intended function in mind, to plan the building procedure, to acquire the necessary motor skills, to carry out the action, and to select or produce materials that have the right characteristics to support the functions of the intended artifacts (Hunt & Gray, 2004). For example, artifacts made from certain types of materials cannot serve the necessary function (e.g., a wooden bulb).

However, materials that can serve the intended function are usually not unique; for example, you can build houses out of wood but also stone, metal or even glass (Gelman, 1988; Kelemen & Carey, 2007). Thus, the key to selecting appropriate material is not finding “the” material; rather, it is finding a material that possesses suitable dispositional properties (e.g., rigidity).

Even though the tendency to look for and create materials develops as a function of education, many species including birds, chimpanzees, in addition to humans, select natural materials from the environment to manufacture artifacts (e.g., building shelters and modifying tools) (Aranguren et al., 2018; Boesch & Boesch, 1990; Collias & Collias, 1973; Franks, Wilby, Silverman, & Tofts, 1992; Shumaker, Walkup, & Beck, 2011).

Birds are known to be natural architects; they can construct complex nests that help them stay warm, reproduce and hide from predators (Collias & Collias, 1973; Hansell, 2000; Healy, Walsh, & Hansell, 2008) (See Figure 1). Also, they are able to modify materials to make artifacts. For example, a New Caledonian crow was observed to bend a wire in order to pull a bucket of food closer (Weir, Chappell, & Kacelnik, 2002). They can also rip a paper card to the appropriate size and insert it into a vending machine to access rewards (Jelbert, Hosking, Taylor, & Gray, 2018).

Figure 1. The nest of Baya weavers (made from Guinea grass, stripes of palm fronds, etc.) on the left. Retrieved from http://besgroup.blogspot.com/2006/05/baya-weavers.html. The nest of the crossbills on the right (made from pine twigs, grasses, moss, lichen, fine grass and feathers, etc.; from Healy, Walsh, & Hansell, 2008; Figure 1).

Similarly, chimpanzees can modify leafy twigs (e.g., remove leaves, modify the length, sharpen the tip) to make sticks serve a certain purpose (e.g., reach termites, honey, nuts) (C. Boesch & Boesch, 1990; Hopper, Tennie, Ross, & Lonsdorf, 2015; Sugiyama & Koman, 1979) (see Figure 2).

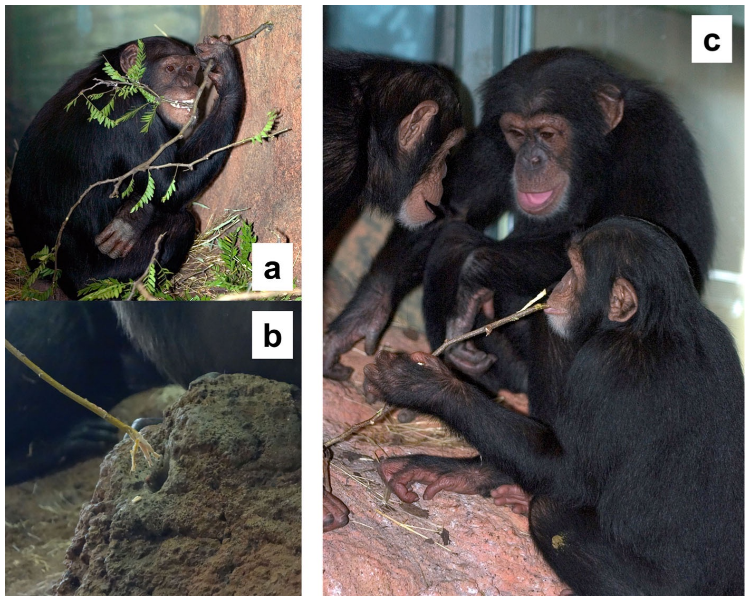



Figure 2. Chimpanzee modified a tool for later use in figure (a), and used the modified tool to dip fluid in figure (b) and (c) (from Hopper, Tennie, Ross & Lonsdorf, 2015; Figure 1).

Also, starting in preschool, children participate in creative activities where they build various things (Reindl, Apperly, Beck, & Tennie, 2017); they build towers with Legos™, create figures with Play-doh and make cookies with flour.

Previous studies have focused on when and how infants and children distinguish between objects and substances. Piaget (1952) studied children's understanding of the conservation of a given amount non-coherent materials like sand and water. Others investigated infants' ability to track the quantity of a substance (Gao, Levine, & Huttenlocher, 2000; Huntley-Fenner, Carey, & Solimando, 2002; Rosenberg & Carey, 2009; vanMarle & Wynn, 2011) as well as whether children can judge if smaller pieces share the same material composition as the object from which it came (Au, 1994; Dickinson, 1987).

Other studies have also demonstrated that children know that an artifact's shape is closely related to its function (Bloom, 1996; Landau, Smith, & Jones, 1998). Yet, children's ability to distinguish between different solid substances and understand their characteristics and possible functions has received considerably less attention. To our knowledge, no study has investigated young children's ability to decide whether solid materials can be used to make artifacts that serve a given function.

*Overview of dissertation research*

This dissertation examines the development of children's ability to assess how a material's properties will constrain the function of an artifact (i.e., a bridge that supports locomotion).

Chapter 2 first discusses the paradigm that researchers have used to test infants' ability to perceive the affordance of surfaces by measuring their gait adjustments. Since this ability has been considered as the interaction between perception and motion over time, it is unclear if children could reason it at the knowledge level.

Later, it introduces a prediction task and systematically study preschoolers' ability to predict how a material's composition will influence the capability of a bridge to support an elephant's weight. The experiment in Chapter 2 asks children and adults to select the best route for a moving agent to reach the other side of a river, depending on what material is used for the bridge. If the bridge is composed of rigid materials, participants should guide the agent directly across the bridge; if not, they should choose an alternative route. Of interest is their ability to choose the correct route based on the rigidity of the materials and the degree of relation between their exploratory behaviors and their judgment.

The experiments in Chapter 3 reduce the information processing demand of the first study. Instead of asking children to identify the correct route depending on whether the bridge is rigid or non-rigid, we presented children with a pair of materials and asked them to choose the more appropriate one. These studies also controlled for the thickness of the two materials and tested whether children use relative rigidity to help them determine the more appropriate material for building a bridge that would support a certain weight.

In Chapter 4, I summarize and discuss the findings in the context of affordance theory and artifact-making behaviors, then suggest directions for future research.

## *II. Which route to choose — bridge or grove?*

### Introduction

"We do not perceive stimuli or retinal images or sensations or even just things, what we perceive are things that we can eat, or write with, or sit down on, or talk to" (Gibson, 1982, p. 60). For example, an apple is edible, a pencil is write-able and a chair is sit-on-able. Perceiving the affordance of something, in other words, means perceiving the possibility of doing something with an entity (Adolph & Berger, 2006), or "what you can do with what".

Affordance usually changes when the perceiver changes (J. J. Gibson, 1979). A chair that is sit-on-able for a person may not be sit-on-able for an elephant, a bridge that is walk-on-able for a dog may not be walk-on-able for a human, a branch that is stand-on-able for a bird may not be stand-on-able for a dog.

One method that researchers use to measure the "affordance" of locomotion is to test how perceivers adjust their movement, given different surface layouts. In the "visual cliff" study, infants were placed in the middle of an apparatus of a certain height. There were two sides next to the infants, one is the shallow side, in which there is a patterned board just beneath the Plexiglas surface, creating a visual "solid" surface. Another side is the deep side, at the deep side, the patterned board was much lower than the Plexiglas surface, providing the visual impression of a "drop-off". Six months old infants refused to cross to the deep side, showing that they could already perceive visual drop-offs as unsuitable for walking, as can many precocial animals like lambs, kids, pigs and dogs (Gibson & Walk, 1960).

However, merely perceiving the danger of a visual drop-off is not sufficient. For example, even when a drop-off is covered with a flat, extended, horizontal surface, a rigid surface is necessary for safe locomotion (J. J. Gibson, 1979).

Later, researchers investigated how crawling and walking infants adapt their gaits when confronted with surfaces of different rigidity. When encouraging new walkers to cross either a wooden surface or a waterbed, the researchers found that infants test different surfaces before deciding whether to walk or crawl on them. If the surface moves, they get down and crawl instead of walking. When infants were provided a choice between a wooden surface and a waterbed, most preferred the wooden one (Gibson et al., 1987). Researchers also tested whether infants could perceive the affordances of external supports of various rigidities (Berger, Adolph, & Lobo, 2005; Berger, Chan, & Adolph, 2014). Infants of 16 months were provided handrails of different materials to cross a narrow bridge. They could distinguish between rigid and non-rigid handrails, and used the rigid one more often as an external support. These studies show that infants can detect the affordances of the rigid and non-rigid surfaces and handrails and adjust their gaits accordingly (see Figure 3).

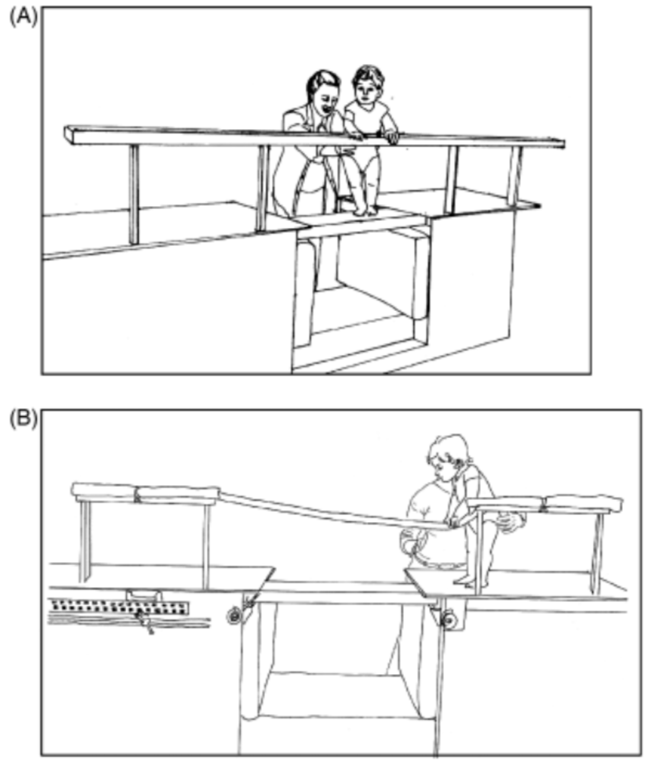



Figure 3. Stimuli used in Berger, Adolph, and Lobo (2005; Figure 1). The baby was asked to cross a narrow bridge with a rigid handrail in the figure A and a non-rigid handrail in the figure B.

Affordance theory has greatly influenced the field of perceptual and motor development (Kretch & Adolph, 2017). It describes the interaction between a perceiver and the environment, including how infants perceive the environment and adjust their behaviors (Adolph & Hoch; Franchak & Adolph, 2014; Gibson, 1982). James Gibson (1979) stated that the observer may or may not perceive the affordance; if he does, then he perceives the affordance directly. This indicates that perceiving the affordance does not involve any mediated inferences about the underlying constituent sensations other than direct perception (Fodor & Pylyshyn, 1981). By claiming the “direct perception” of affordance, Gibson also rejected the idea that knowledge is involved in perceiving the affordance.

As terrestrial animals, it is crucial for us to detect the safety of a surface (J. J. Gibson, 1979). However, we do not always have the chance to adjust our gait; for example, when humans encounter a bridge, they are unable to test the surface and adjust their locomotion. They need to predict the safety of the bridge and decide whether to proceed or not. Such prediction involves reasoning and conceptual understanding of whether a certain bridge can afford the moving agent or not.

The studies in this dissertation investigate whether children know that in order to support a heavy moving entity, a surface must be rigid enough to afford force. In other words, it asks whether they know that a material's composition will influence the support capability of its surface. The study in this chapter presented children with different kinds of solid materials, and asked if each could be used to make a bridge that would support an elephant's locomotion. This required children first to distinguish solid materials from objects, and then to perceive the rigidity of each material. Furthermore, children also had to understand that the sample came from the same material as the bridge-to-be. Lastly, they needed to understand that objects will create force on the surface, and only rigid materials were appropriate for the bridge construction. Below, we discuss infants' and children's abilities of each component we mentioned above.

*Distinctions between objects and solid substances*

Researchers have obtained divergent findings about children's ability to notice the composition of a solid entity. In a word learning task, when 3- and 4-year-olds were told a novel noun referring to a solid entity (e.g., this is my "blicket"), and then provided options with either a similarly shaped item made of a different material or differently shaped items of the same material, they did not map the new word onto the composition of the intact object; rather, they mapped it onto the shape (Landau et al., 1998; Landau, Smith, & Jones, 1988; Smith, Jones, & Landau, 1992). However, if children were shown familiar objects and told that the objects are made of a specific material with the correct label (e.g., sponge) rather than a novel noun (e.g., blicket), even 2.5-year-olds could apply the label to a differently shaped entity of the same material (Prasada, 1993).

Moreover, when 3-year-olds were asked whether a wooden pillow belonged in a living room or dining room, they categorized it according to its object kind (i.e., pillow). But when asked if it was soft or hard, they answered according to its material composition (i.e., wood). This suggests that children are capable of paying attention to either the object or the solid substance of a given entity (Kalish & Gelman, 1992).

*Distinguishing rigid from non-rigid objects*

Infants as young as 3 months can distinguish rigid from non-rigid objects with intermodal perception. In the previous studies, infants were first haptically habituated to either a rigid or non-rigid object. Later, they dishabituated to an object that shows a pattern opposite to that of its visual motion path (i.e., a rigid object in non-rigid motion, or a non-rigid object in rigid motion) (Gibson, Owsley, & Johnston, 1978; Gibson, Owsley, Walker, & Megaw-Nyce, 1979; Walker, Owsley, Megaw-Nyce, Gibson, & Bahrick, 1980). Moreover, at 12 months, infants can adjust their explorations based on the different substances of the objects. They stroked the seemingly haptic rigid (wood) object more than the elastic (spongy) object, whereas they squeezed the soft object more than the rigid one (Gibson & Walker, 1984). The studies above show that infants can tell the difference between objects of different rigidity and apply appropriate behaviors to them. Later in childhood, 3-year-olds can verbally tell whether objects made from some substances (e.g., wood, metal, cotton) are hard or soft (Kalish & Gelman, 1992).

*Understanding the relations between objects and solid substances*

Children's ability to distinguish between objects and solid substances depends highly on how the stimuli are presented. When children were only told that a certain machine grinds a wooden airplane, children younger than 9 years old did not know that the sawdust was still wood (Dickinson, 1987). However, if children observed large objects being ground into pieces, as young as 3 years old, they understood that the solid substance shared the same material composition as the objects (Au, 1994).

*Infants' knowledge about physical support and physical force*

At 3 months, when infants were presented with an object floating in the air that had no contact with another object, they watched it much longer than an object contacting another one. This suggests that infants understand that objects need contact with another entity in order to be supported. At 5.5 months, they understand not only that objects need to be in contact in order not to fall, but also that the contact has to support the objects vertically rather than horizontally. At 6.5 months, infants can understand that the amount of contact also influences the physical support. Moreover, Baillargeon's unpublished paper show that 13-month-old infants not only can take the amount of physical contact in to account, they also know that the amount of contact is not sufficient to decide whether an object will be supported, the center of the gravity should also be taken into account

(Baillargeon, 2002) (see Figure 4). The above-mentioned studies provide evidence that infants at an early age already possess rich knowledge about principles of physical support and that their reasoning about the physical support becomes increasingly sophisticated with age (Baillargeon, 2002).

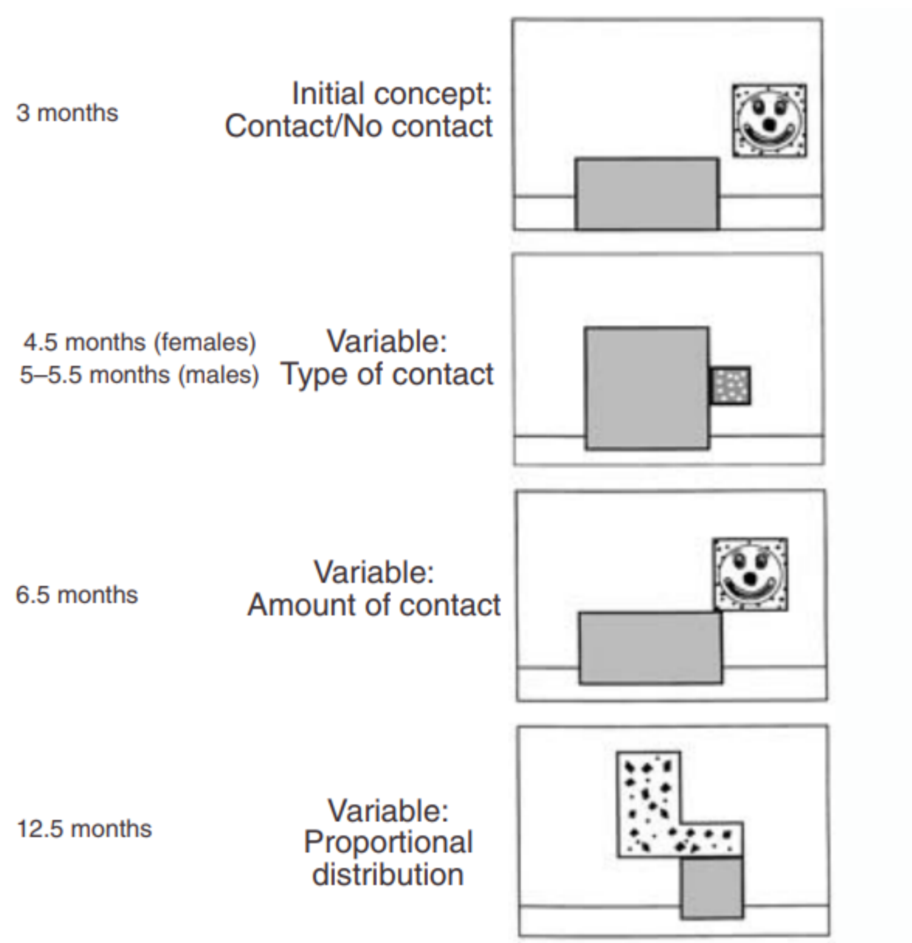



Figure 4. Stimuli used in Baillargeon (2002; Figure 3.3).

Moreover, not only do infants know that objects need to be fully supported in order not to fall, they also know that a moving object has momentum, and exerts force when it contacts another object. Studies have shown that when 6-month-olds watched a launching event (e.g., entity A moves towards entity B, and entity B moves immediately after), they were able to infer that a moving object could exert force on another object and initiate its movement (Leslie, 1984; Leslie & Keeble, 1987; Michotte, 1963). Moreover, 11-month-old infants also know that the larger the object is, the more force it will exert (Kotovsky & Baillargeon, 1994) (Figure 5) and that the force will also cause the compression of a soft surface (Hauf, Paulus, & Baillargeon, 2012).

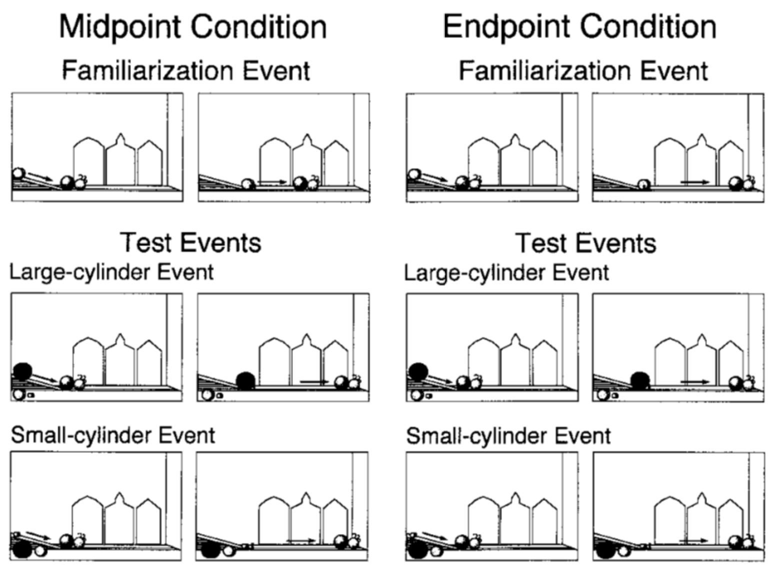



Figure 5. Stimuli used in Kotovsky and Baillargeon in 1998 (Figure 1).

*Rigidity as a relevant cue of affording force*

Lastly, there is evidence that young children understand that objects composed of certain materials are better able to afford force than others. When children were asked to choose between a rigid stick or a non-rigid string as a tool to get a Mickey Mouse toy beyond their reach (Brown, 1990), children at 24 months not only used rigidity to determine whether it could serve as an effective tool but also behaved as though rigidity was more important than length or the kind of head on the stick. Older children, from 3 to

4 years old, in the Fred-the-rabbit game (Bullock, Gelman, & Baillargeon, 1982), were capable of inferring that a rod made of soft, flexible material would not have enough force to knock down wooden blocks as compared to a rod made from rigid materials.

In the current study, children were shown an animation in which a man built a bridge out of different materials to help an elephant reach the far side of the river. Children were shown the different materials (rigid and non-rigid) that the bridgemaker would use. In the "walk on or around" task, they were asked to decide whether the elephant should walk on the bridge or take an alternative route, depending on which materials were used. Previous studies have shown that 3-year-olds already have the capability to pay attention to the material composition of objects, to distinguish a rigid from a non-rigid object, and to judge a rigid object as capable of affording force better than a non-rigid object. The current study combines all the components mentioned above, and tests 3- to 5-year-old children. We predicted that they would judge rigid samples as capable of supporting a young elephant, and non-rigid samples as not.

Haptic exploration, to some extent, offers information (like rigidity and friction) that vision alone cannot (Adolph, Joh, & Eppler, 2010; Joh & Adolph, 2006). This led us to vary whether or not young children were asked to touch the samples of different materials. Asking children and adults to touch the materials, we hypothesize, facilitates their selection of suitable materials because it ensures that they access relevant haptic information about the materials (i.e., rigidity).

Exploratory behaviors have been thought to be associated with the ability to adjust locomotion (Adolph, Bertenthal, Boker, Goldfield, & Gibson, 1997; Adolph et al., 2010; J. J. Gibson, 1966; J. J. Gibson, 1979). Infants gain perceptual information from their exploratory behaviors, including visual and haptic exploration, to guide the adjustment of their gait. Some studies have shown that infants explore surfaces haptically before locomotion (Gibson et al., 1987); moreover, the longer the exploratory behaviors, the better their gait adjustment (Adolph et al., 2010; Joh, Adolph, Narayanan, & Dietz, 2007). Other studies suggest that prolonged exploratory behaviors do not guarantee better adaptive locomotion (Kretch & Adolph, 2017). For experienced walking infants, even though they only explored the surface very little, they could make adaptive decisions; however, novices, even after exploring the unviable surface for a long time, still stepped onto it (Adolph et al., 1997). Given this, we tested that in the Touching-Not-Required condition, whether the spontaneous touchers would perform better than the non-spontaneous touchers.

## Study 1: "walk on or around"

*Design*

The study has 3 phases. In phase 1, participants were shown an animation. In phase 2, they were asked the memory questions of the animation. In phase 3, they were asked to judge whether the elephant should walk on the bridge or around the forest depending on the materials the bridgeman decides to use to make the bridge.

## Methods

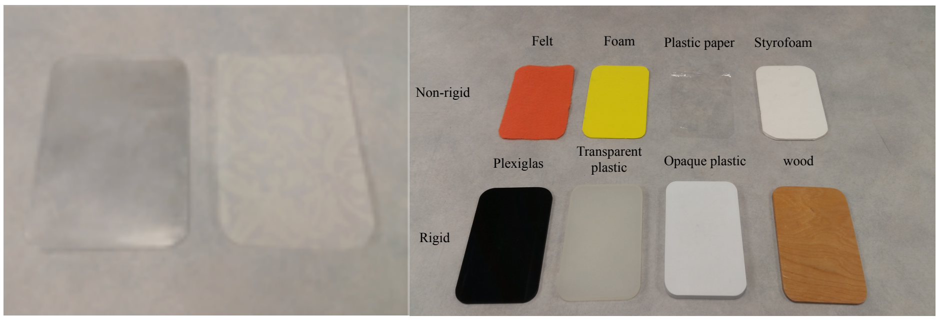
*Participants*

One hundred and thirty-six children were recruited from preschools in the central

New Jersey area, including 20 three-year-olds (13 female, ranging from 38 to 48 months, M = 43.39 months, SD = 2.57), 25 four-year-olds (9 female, ranging from 49 to 59 months, M = 53.95 months, SD = 3.54), 21 five-year-olds (9 female, ranging from 60 to 72 months, M = 62.56 months, SD = 3.35) in the Touching-Required (TR) condition and 22 three-year-olds (16 female, ranging from 37 to 48 months, M = 44.37 months, SD = 2.87), 26 four-year-olds (18 female, ranging from 49 to 59 months, M = 54.00 months, SD = 3.31) and 22 five-year-olds (13 female, ranging from 60 to 69 months, M = 63.77 months, SD = 2.11 ) in the Touching-Not-Required (TNR) condition. Nine additional children were excluded from the study, 7 children did not participate in the experimental test phase and 2 children were unable to finish the first round of the experimental phase. Children received a small sticker and a certificate for their participation, and each of the participating preschools were given a small gift. There were 22 adults (9 female and 13 male) in the TR condition and 23 adults (14 female and 9 male) in the TNR condition recruited from Rutgers University. Five additional participants were excluded due to experimenter errors or because they were younger than 18 years old. Adult participants were informed that this study was designed for preschoolers, and they were asked to help determine whether the procedure is clear or not. Each of them received 1 research participating credit for compensation.

*Materials*

The demonstration phase included two swatches of materials (paper and aluminum). The testing phase included eight swatches of materials (felt, foam, plastic paper, Styrofoam, black Plexiglas, transparent Plexiglas, white Plexiglas, wood). The size and shape of the samples were the same (10cm wide * 15.5 cm long, rectangular), but the thickness of the materials differed (Paper: 0.04cm, Aluminum: 0.15cm, Black Plexiglas: 0.4cm, White Plexiglas: 1.2cm, Transparent Plexiglas: 1cm, Wood: 0.5cm, Felt: 0.2cm, Styrofoam: 0.4cm, Plastic paper: 0.025cm, Foam: 0.2cm) (see Figure 6).




Good Not-good

(Aluminum) (Paper)

Figure 6. The different samples of the to-be-used material for the bridge.

*Design & Procedure*

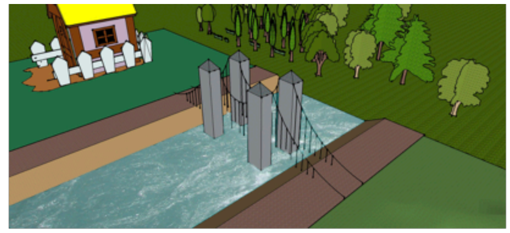
*Phase 1: demonstration phase*

Children were presented a computer animated story in which an elephant tried to get to the other side of a river. A bridge man had many different kinds of materials, and either used any of them to make a good or a not-good bridge. In the first example, the elephant walked across a bridge and did not fall when the bridge man used aluminum to make the bridge (a swatch of aluminum was shown to the children). In the second example, the elephant fell into the water when the bridge man used paper (a swatch of paper was shown to the children). The elephant was shown to walk through an alternative but longer route when the bridge was not safe (see Figure 7 for the full story).

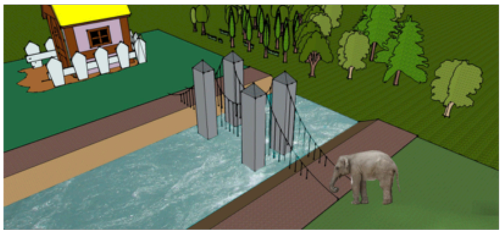
In the Touching-Required (TR) condition, the experimenter asked “here, hold it.

What does this feel like?" while handling the swatch of the material to the children. The animation in the Touching-Not-Required (TNR) condition was exactly the same as the one in the TR condition, except that the material was put on the table and the child was not asked: "here, hold it. What does this feel like?"

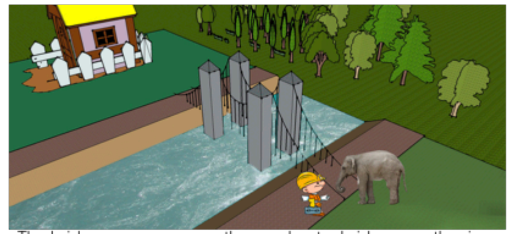
Look, there is a young elephant. The young elephant lives with his mother in the field.



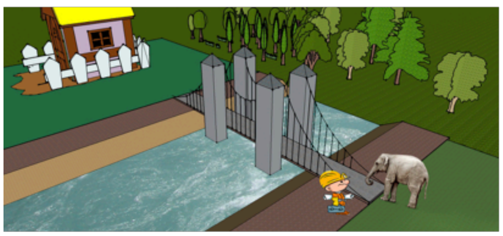
See, this is the elephant's house. The young elephant sleeps there at night.



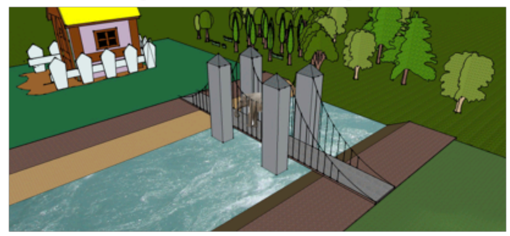
At night, it has to go to the other side of the river. He has two ways to do this. The young elephant can make a special sound. (The sound of the elephant)

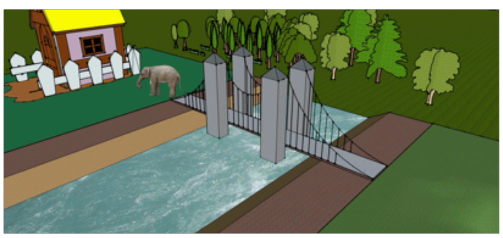


The bridge man can come then and put a bridge over the river. The bridge man makes lots of different bridges. Sometimes he uses good stuff to make a bridge. But sometimes he uses not good stuff to make the bridge.

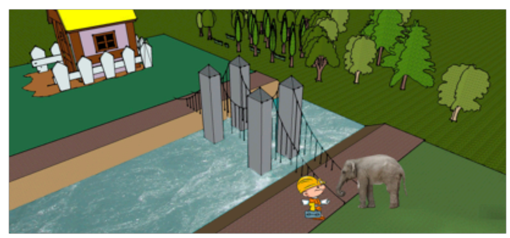


One good bridge was made out of this stuff. Let's see what happens when the young elephant walks on the bridge.

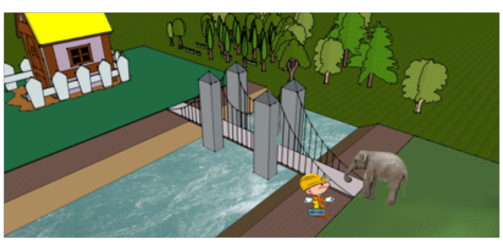




Look, the good bridge does not break, so the young elephant walks across the bridge safely.



One of the not good bridges was made out of this stuff.



Let's see what happens when the young elephant walks on the bridge.

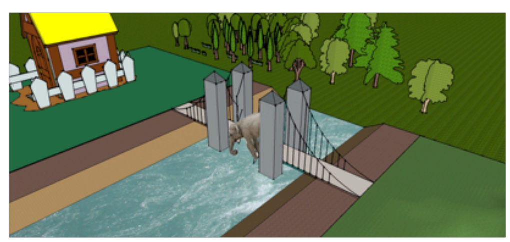



Figure 7. Animated story in the demonstration phase in the “walk on or around” study

*Phase 2: memory test phase*

Children were asked five memory questions after the demonstration phase. First, the experimenter put two demonstrated material swatches on the table. Then the children were asked: “Which stuff makes the good bridge? What happens when the elephant walks on the good bridge? Which stuff makes the not good bridge? What happens when the elephant walks on the not good bridge? Which way should the elephant go if the bridge is not good?” The position of the stimuli was counterbalanced. If children answered the first four memory questions wrong, then they were provided a chance to watch the video again. If they only answered the last question wrong[1], the experimenter

[1] In the pilot study, children got this question wrong frequently, so if they did not remember, the experimenter will prompt them.

first prompted them by saying “do you remember there is another way in the end of the story?” If they still were wrong, then they were asked to watch the video again, but not more than twice. If they already lost attention or rejected to watch again, then the experimenter simply proceeded to the experimental phase (15 three years olds, 8 four-year-olds, 2 five-year-olds).

*Phase 3: experimental phase*

In the experimental phase, the experimenter first presented children a material sample, and children were told that: “on this day, the bridge man uses this stuff to make the bridge”. In the TR condition, the experimenter said: “Here, hold it. What does this feel like?” and required children to touch the material samples. In the TNR condition, the sample was put on the table, and children’s spontaneous touching behavior was recorded. The experimenter then showed two pictures suggesting two different routes of either “walking on the bridge” or “walking around the forest”, and the children were asked: “should the elephant walk on the bridge to get to his house or walk around the forest to get to his house?” The sequence of the two options “walk on the bridge” and “walk around the forest” was counterbalanced. There were 8 different kinds of materials (4 rigid and 4 non-rigid), each one was presented once in 2 blocks in a random order with no more than 2 rigid or non-rigid samples shown consecutively. This led to a total of 16 trails in a total.

## Results

*Demonstration phase: participant's descriptions of "what does this feel like?" of the sample materials in the Touching-Required condition.*

In the demonstration phase of the TR condition, children were presented with paper and aluminum swatches and asked to describe "what does this feel like?". When children were asked to describe the material paper, 56.25% of the 3-year-old children could either used the correct label, describe it as non-rigid, or describe it under the correct superordinate category of non-rigid (e.g., non-rigid words or objects), but only 25% could do so when they were asked to describe the haptic perception of the aluminum[2]. There were 61.5% 4-year-old, 62.5% 5-year-old children and all adults who could either label the two samples correctly, describe them along the correct dimension of rigidity, or use the descriptions under the correct superordinate category of rigidity. The details of children and adult's description for each sample of materials are shown in the Appendix.

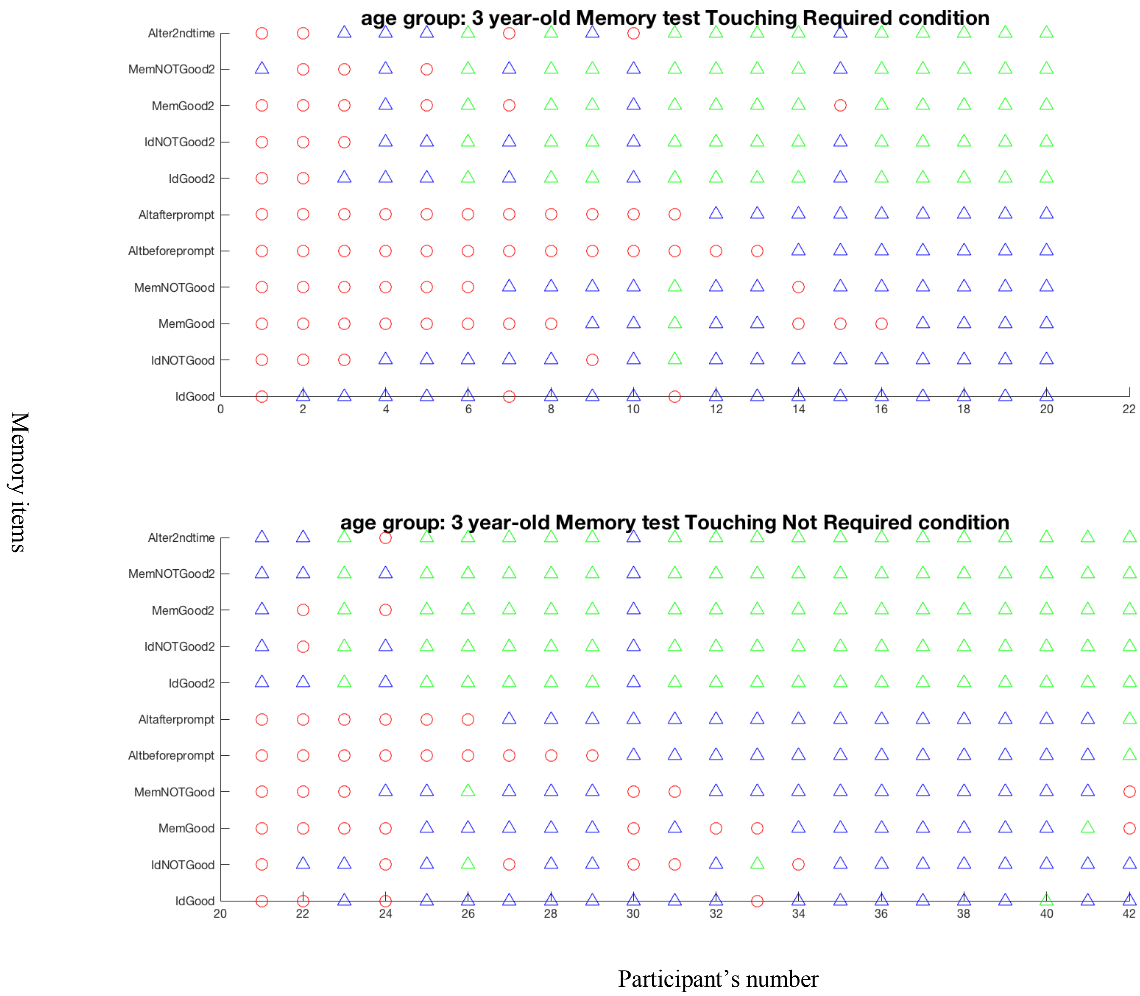
*Memory testing phase*

Table 1 shows children's and adults' performance to the five memory questions. If they got the answers wrong and watched it for a second time, their performance is shown in parenthesis. In the TR condition, 7 out of 18 3-year-olds, 19 out of 25 4-year-olds and 17 out of 21 5-year-olds passed the memory task after second time watching. In the TNR condition, 9 out of 22 3-year-olds, 22 out of 26 4-year-olds and 22 out of 22 5-year-olds passed the memory task (See Figure 8 to Figure 10).

[2] This is a very conservative results, children sometimes hesitated to respond or respond in a very vague way, they were all coded as not knowing. When coding the data, if the data was missing or unclear, it was coded as not knowing also.

Table 1. Proportion of children and adults' correct answers to the memory questions.

| | Identifying materials | | | | Events of two bridges | | | | Decision making | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | good | | Not good | | Good | | Not good | | Which way around? | | | |
| | TR | TNR | TR | TNR | TR | TNR | TR | TNR | TR | | TNR | |
| | | | | | | | | | Before prompt | After prompt | Before prompt | After prompt |
| 3YOs | 0.85 | 0.77 (0.91) | 0.75 | 0.67 (0.81) | 0.40 (0.45) | 0.59 (0.73) | 0.60 (0.70) | 0.68 (0.82) | 0.35 | 0.45 (0.65) | 0.55 | 0.68 (0.82) |
| 4YOs | 0.92 | 0.96 (1) | 0.92 | 0.96 (1) | 0.76 (0.8) | 0.81 (0.85) | 1 | 0.96 | 0.64 | 0.92 | 0.58 | 0.88 |
| 5YOs | 1.00 | 1.00 | 0.90 (1) | 1.00 | 0.95 | 1.00 | 1.00 | 1.00 | 0.57 | 0.86 | 0.59 | 1.00 |
| Adults | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.86 | 1.00 | 1 | 1.00 |

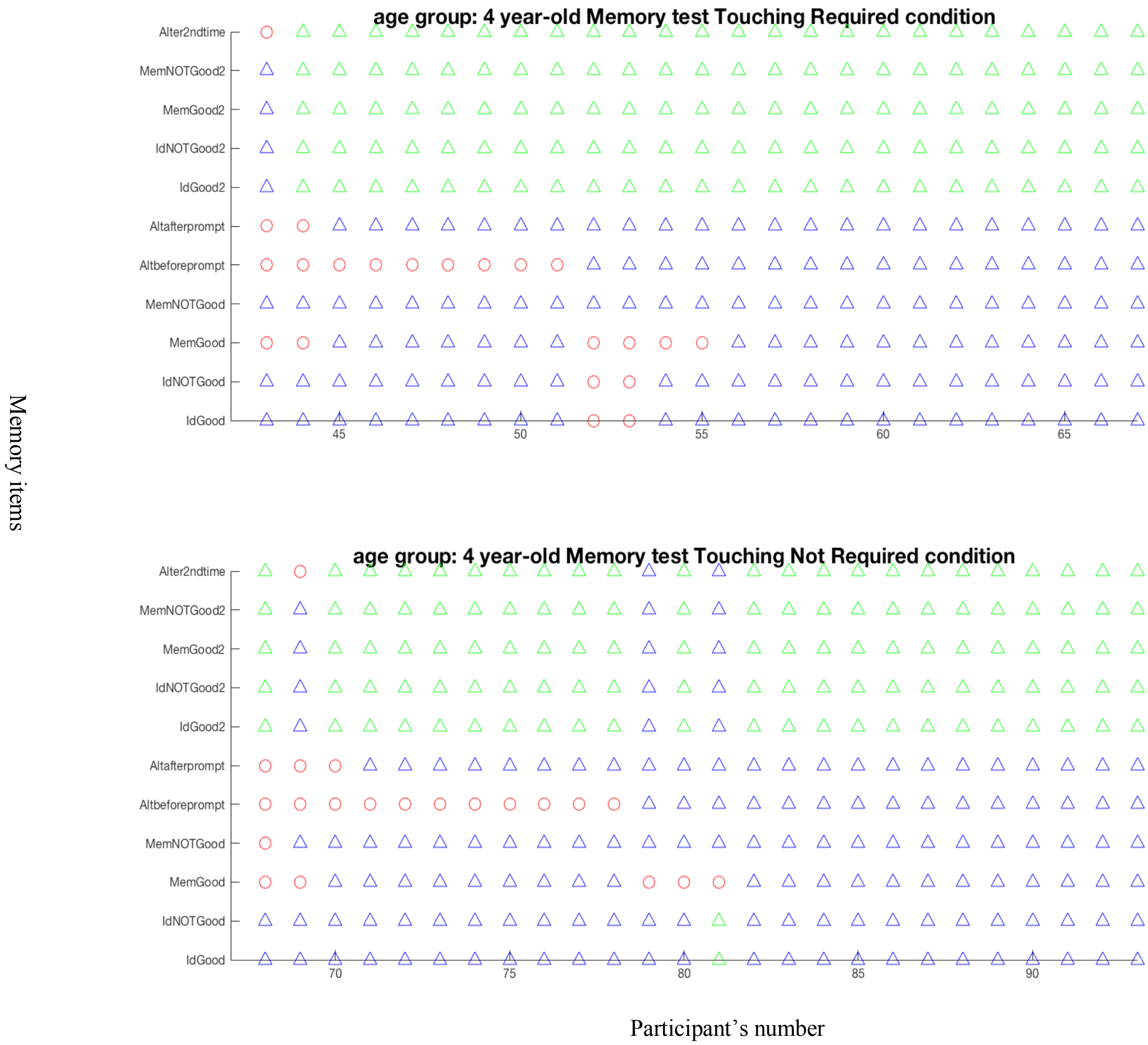



Note: △ indicates correct answer

○ indicates wrong answer

△ indicates no response or missing data

Figure 8. Three-year-old children's performance in the memory test in both touching conditions.

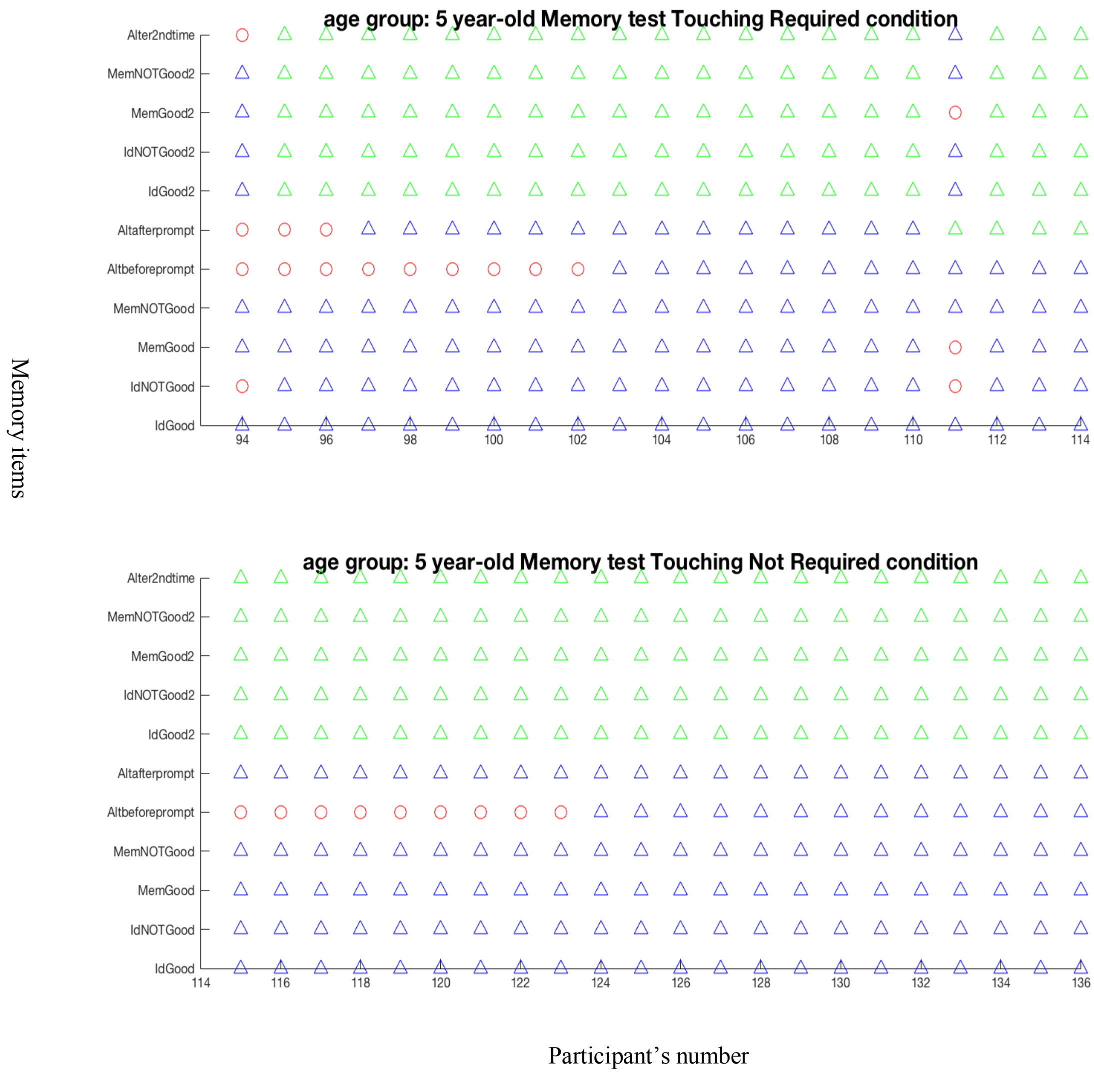



Note: △ indicates correct answer

○ indicates wrong answer

△ indicates no response or missing data

Figure 9. Four-year-old children's performance in the memory test in both touching conditions




Note: △ indicates correct answer

○ indicates wrong answer

△ indicates no response or missing data

Figure 10. Five-year-old children's performance in the memory test in both touching conditions

*Experimental phase – children and adult's performance in judging the correct route for the elephant in the TR and TNR conditions*

We graphed children's performance in judging whether the elephant should walk on the bridge in the both conditions (See Figure 11 – Figure 12). We used adult's judgment as the reference, in the TNR condition, as the rigidity of the material kinds increased, so did the probability of children's decisions that the elephant should walk on the bridge.

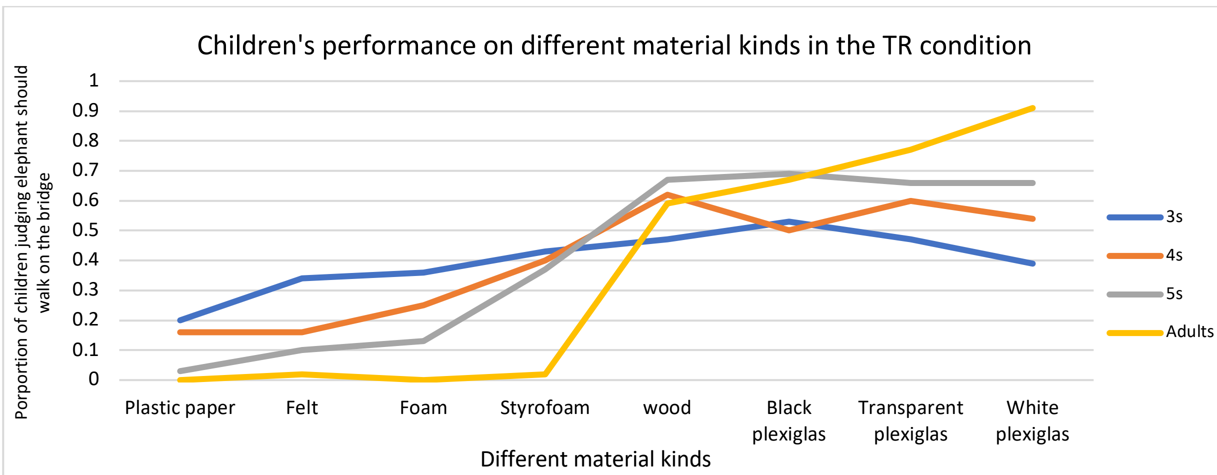



Figure 11. Proportion of participants judging "the elephant should walk on the bridge" by different kinds of materials in the Touching-Required condition

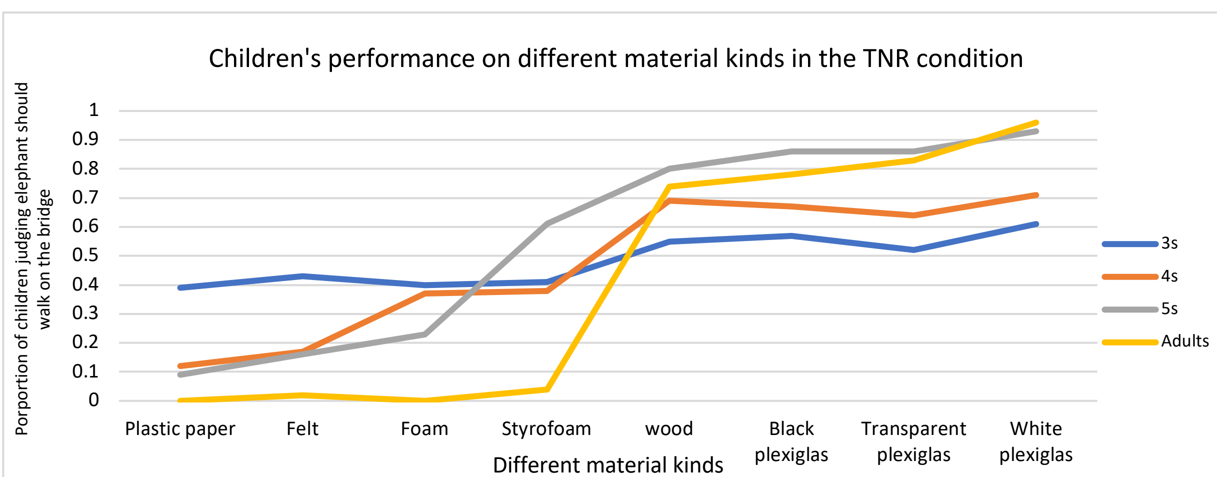



Figure 12. Proportion of participants judging "the elephant should walk on the bridge" by different kinds of materials in the Touching Not-Required condition

Later, we coded children's performance as correct or incorrect depending on their choices. When they chose walking around for non-rigid materials and walking on for rigid materials[3], it was scored 1, otherwise, it was scored 0. There were 4 rigid materials and 4 non-rigid materials. And each of them was presented twice. We compared the mean correct scores of two rigidity types to chance (4) for each age group and each touching condition (See Table 2). Since the data may not meet the normal distribution assumption of an ANOVA model. We also analyzed the data with respect to individual pattern. In order for them to pass each rigidity type, they have to answer 7 or more out of 8 questions correct (binomial test, 1/2, $p = .031$).

Table 2. The average scores of judging the route correctly by rigid and non-rigid material types in the TR and TNR conditions

| | Rigid materials | Non-rigid materials | Percentage of subjects passed the test | |
|---|---|---|---|---|
| Group | Score (SD) | Score (SD) | Rigid materials | Non-rigid materials |
| TR: | | | | |
| 3YOs | 3.30 (2.71) | 4.89 (1.88) | 4/20 | 3/20 |
| 4YOs | 4.52 (3.33) | 6.08* (2.48) | 10/25 | 14/20* |
| 5YOs | 5.20 (2.59) | 6.52* (1.89) | 9/21 | 14/20* |
| Adults | 5.82* (2.59) | 7.91* (0.29) | 11/22 | 22/22* |
| TNR: | | | | |
| 3YOs | 4.41 (2.89) | 4.73 (2.76) | 7/22 | 7/22 |
| 4YOs | 5.12 (2.86) | 5.58* (2.28) | 12/26 | 11/26 |
| 5YOs | 6.91* (2.22) | 5.82* (2.15) | 16/22* | 9/22 |
| Adults | 6.61* (2.43) | 7.87* (0.34) | 18/23* | 23/23* |

[3] It does not mean that these are the absolute correct answers. Some rigid materials may not able to support the weight neither, and this scoring is simply separated by rigid and non-rigid category.

Next, a Repeated Measures ANOVA was used, 3 (Age) * 2 (touching condition: TR or TNR) *2 (rigidity: rigid or non-rigid) with rigidity as within-subject variable. There was a main effect of age[4], *F* (2,127) = 14.38, *p* < .001. A post hoc LSD test found that 3-year-olds' overall performance (*M* = 8.59) was lower than 4- (*M* = 10.68, *p* = .002) and 5-year-old's (*M* = 12.21, *p* < 0.001), 4-year-old's performance was also lower than 5-year-old's (*p* = .02). A significant effect was found for the variable of rigidity, *F* (1,127) = 4.08, *p* = .05. Children's overall performance on the rigid items (*M* = 4.93) was worse than that of the non-rigid items (*M* = 5.62). There was no effect of condition, *F* (1,127) = 1.99, *p* = .16. Children did not perform differently between the TR and TNR condition. However, there was an interaction between condition and rigidity, *F* (1, 127) = 5.36, *p* = .02. Children did not perform differently on the non-rigid materials between the TR (*M* = 5.88) and TNR condition (*M* = 5.38) (*t* (132) = 1.22, *p* = .22), however, their performance on the rigid materials was significant lower in the TR condition (*M* = 4.35) than the TNR condition (*M* = 5.46), *t* (133) = -2.20, *p* = .03.

According to participant's performance of different material items, Styrofoam is an ambiguous item for children participants, but not for adult participants. Many children considered Styrofoam hard and be able to support an elephant's crossing over.

Plastic paper is the easiest item for all age groups, and even 3-year-old children judged that the elephant should walk around when the bridge was made out of plastic paper. Interestingly, adults judged material wood and black Plexiglas as not good to support the elephant's weight in the TR condition (See Table 3).

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[4] There were 5 children who were included in the data analysis, however, they did not finish the second round, so the final analysis of the overall performance excludes them.

Table 3. Proportion of judging the route correctly by each kind of materials in the TR and TNR conditions

| | 3YOs | | 4YOs | | 5YOs | | Adults | |
|---|---|---|---|---|---|---|---|---|
| | TR | TNR | TR | TNR | TR | TNR | TR | TNR |
| Felt | 0.61 | 0.57 | 0.83* | 0.79* | 0.85* | 0.84* | 1* | 1* |
| Foam | 0.58 | 0.59 | 0.75* | 0.60 | 0.88* | 0.77* | 0.98* | 0.98* |
| Plastic paper | 0.71* | 0.61 | 0.83* | 0.81* | 0.93* | 0.91* | 1* | 1* |
| Styrofoam | 0.55 | 0.59 | 0.63 | 0.60 | 0.56 | 0.39 | 0.98* | 0.96* |
| Black Plexiglas | 0.45 | 0.57 | 0.52 | 0.65 | 0.68 | 0.86* | 0.67 | 0.78* |
| White Plexiglas | 0.34 | 0.61 | 0.54 | 0.69* | 0.65 | 0.93* | 0.91* | 0.96* |
| Transparent Plexiglas | 0.37 | 0.50 | 0.60 | 0.56 | 0.68 | 0.86* | 0.77* | 0.83* |
| Wood | 0.37 | 0.52 | 0.63 | 0.65 | 0.60 | 0.80* | 0.59 | 0.74* |

*Participant's spontaneous touching behaviors in the Touching-Not-Required condition*

A number of children in all three age groups touched (made contact with) the materials spontaneously (see Figure 13). The percentage of participants who touched differed in different kinds of materials (see Figure 14). The graph shows that there is a tendency that adults touch the rigid materials and Styrofoam more than the non-rigid materials.

However, within the TNR condition, the children who spontaneously touched the materials did not perform better than the children who did not, $t\ (64) = -0.90$, $p = .37$.

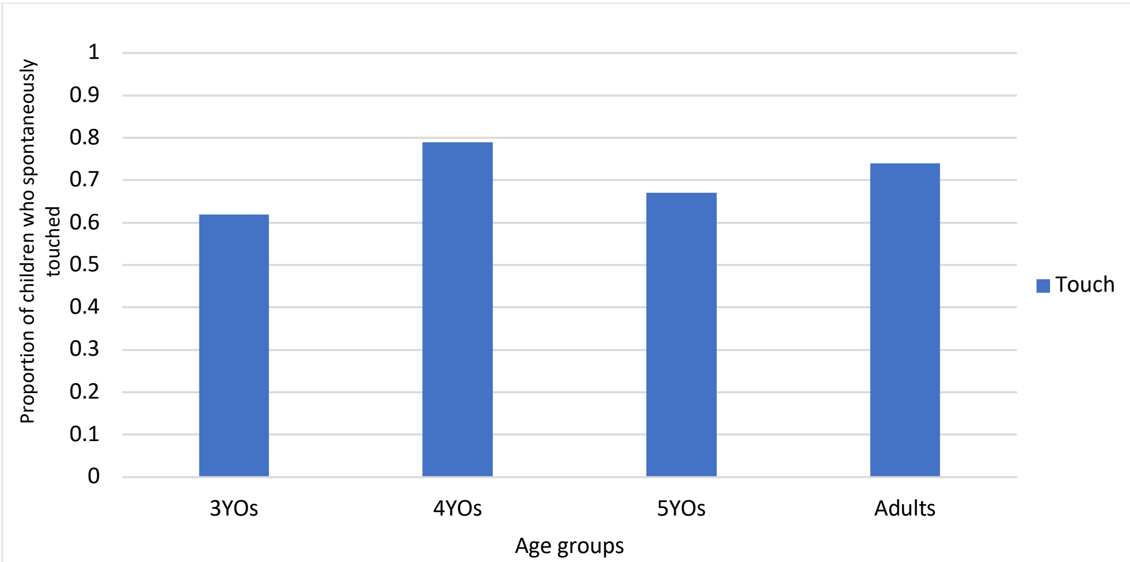



Figure 13. Proportion of children and adults who spontaneously touched the materials in the TNR condition[5]

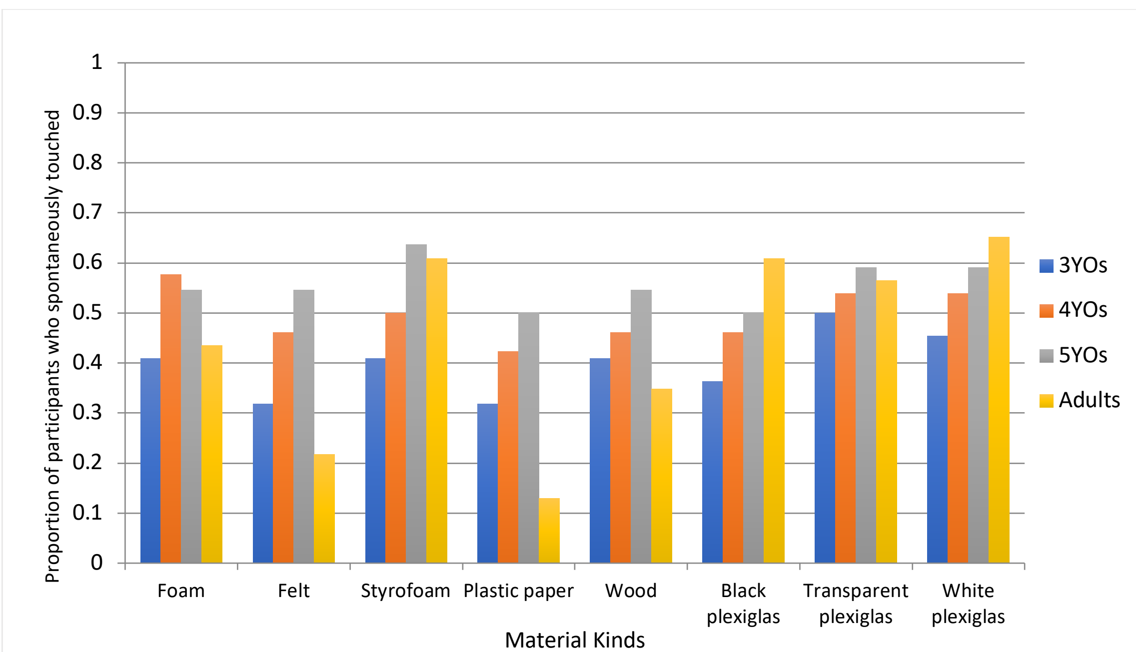



Figure 14. Proportion of children and adults who spontaneously touched the material by different kinds in the TNR condition

[5] If children only touch once among the 16 trials, it was considered touch

*Participant's specific exploratory behaviors in the Touching-Not-Required condition*

The above graphs use 'touching' to mean making contact with the materials; furthermore, we analyzed children's touching behaviors of different materials in details. Children made contact with the materials in many different ways; they held, knocked, bent, rubbed, tapped, waved the materials, etc. We collapsed children's exploratory behaviors into five categories, depending on the manner. If they did not touch, it was coded as 'no touching;' if they only touched, rubbed, or waved the material, it was coded as 'touch;' if they held, it was coded as 'hold;' if knocked, tapped, or stroked the material, it was coded as 'tap;' and if they bent or folded the material, it was coded as 'bend' (see Figure 15 to Figure 20). Interestingly, we found that although children who spontaneously touched the materials did not perform better than the children who did not ($t$ (64) = -0.90, $p$ = .37), children who explored beyond simply touching (hold, bend, tap) performed better than the children who did not touch. But only in judging the rigid materials ($t$ (34.62) = -1.98, $p$ = .056, marginal significance), but not the non-rigid materials ($t$ (38) = 0.65, $p$ = .65).

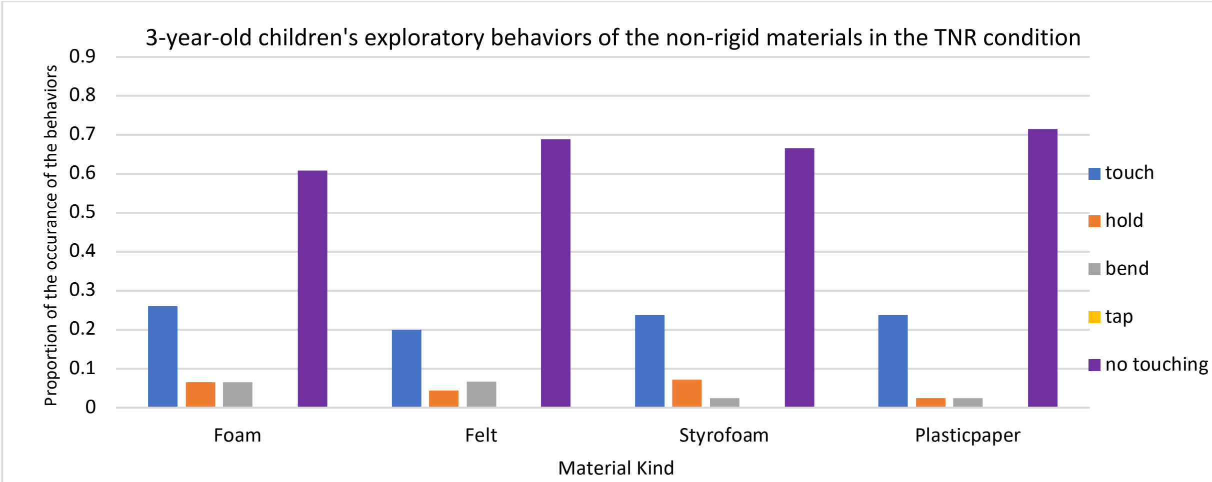



Figure 15. Three-year-old children's exploratory behaviors of the non-rigid materials in the TNR condition.

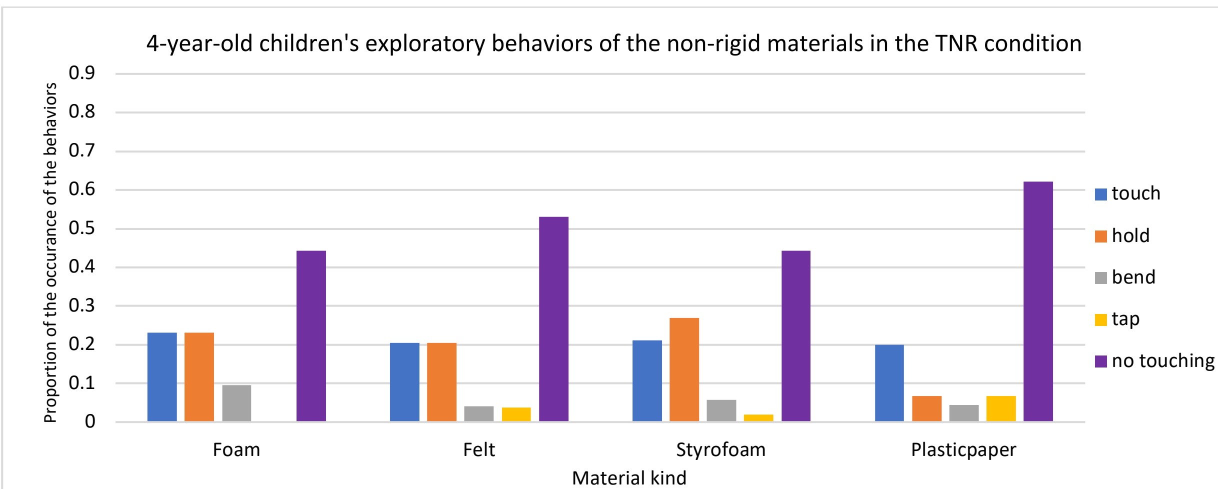



Figure 16. Four-year-old children's exploratory behaviors of the non-rigid materials in the TNR condition.

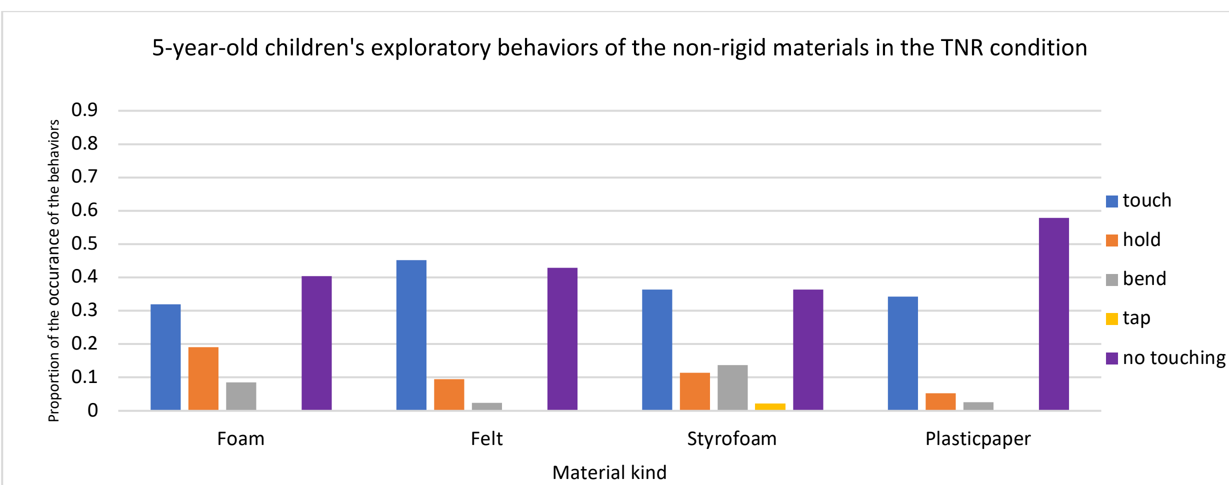



Figure 17. Five-year-old children's exploratory behaviors of the non-rigid materials in the TNR condition.

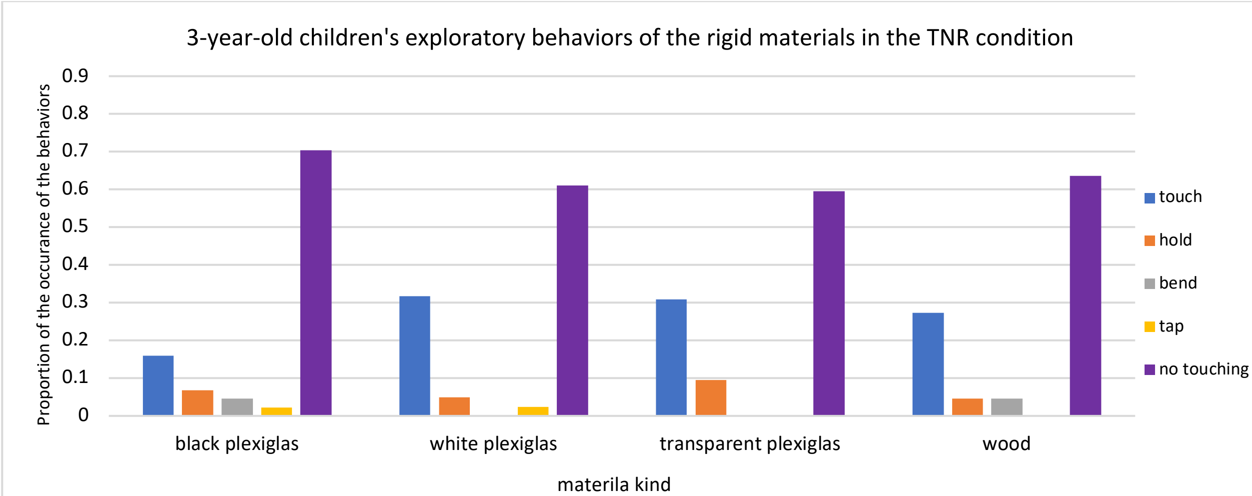



Figure 18. Three-year-old children's exploratory behaviors of the rigid materials in the TNR condition.

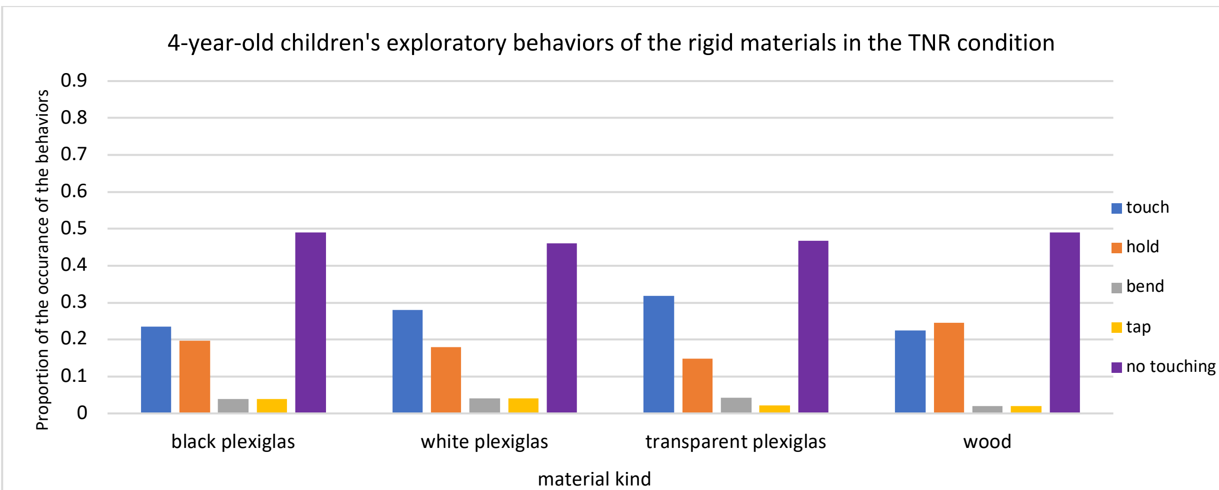



Figure 19. Four-year-old children's exploratory behaviors of the rigid materials in the TNR condition.

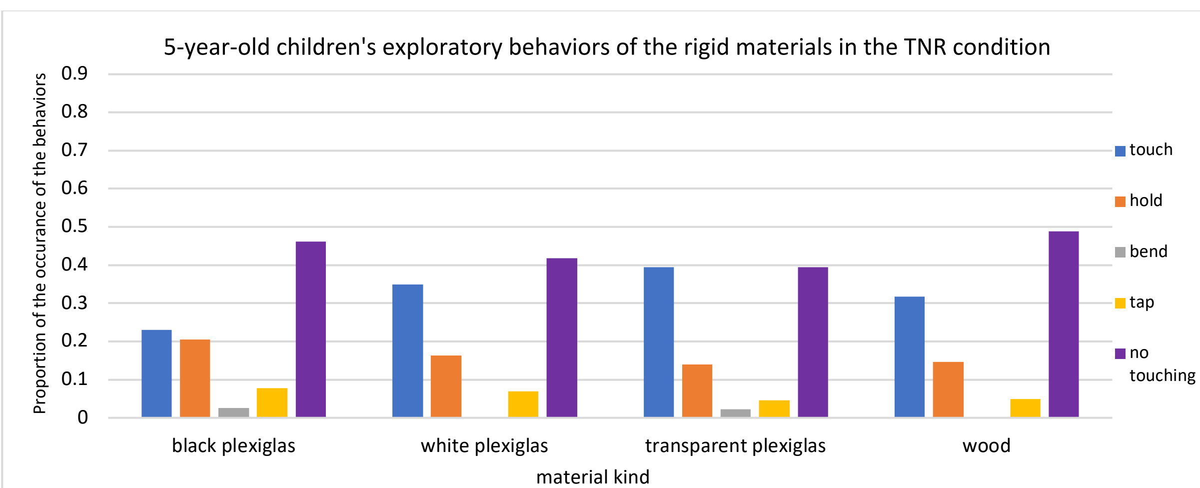



Figure 20. Five-year-old children's exploratory behaviors of the rigid materials in the TNR condition.

*Participant's descriptions of "what does this feel like" of the eight different material kinds in the Touching-Required condition*

Children and adult's descriptions of eight material kinds in the TR condition were coded. Wood and Plastic-paper were the most recognizable and well-labeled materials. Children described the materials in their own idiosyncratic way (see Appendix), resulting in a wide range of descriptions. In order to compare different types of material, we coded children's descriptions into several categories. The first we called the 'correct superordinate' category; if children used a word like "soft" when presented with a non-rigid material, then we put them in the 'correct superordinate' category. If they used a word like "hard" for objects that were hard to describe, then we put them in the 'wrong superordinate' category. If they described the object as cold or heavy, then we put them in the 'irrelevant perception' category. If they used task-relevant words like "in the river" or "elephant," we put them under 'task-relevant answer.' Other answers that were uncodable or missing were put into the remaining categories (See Figure 21 to Figure 28).

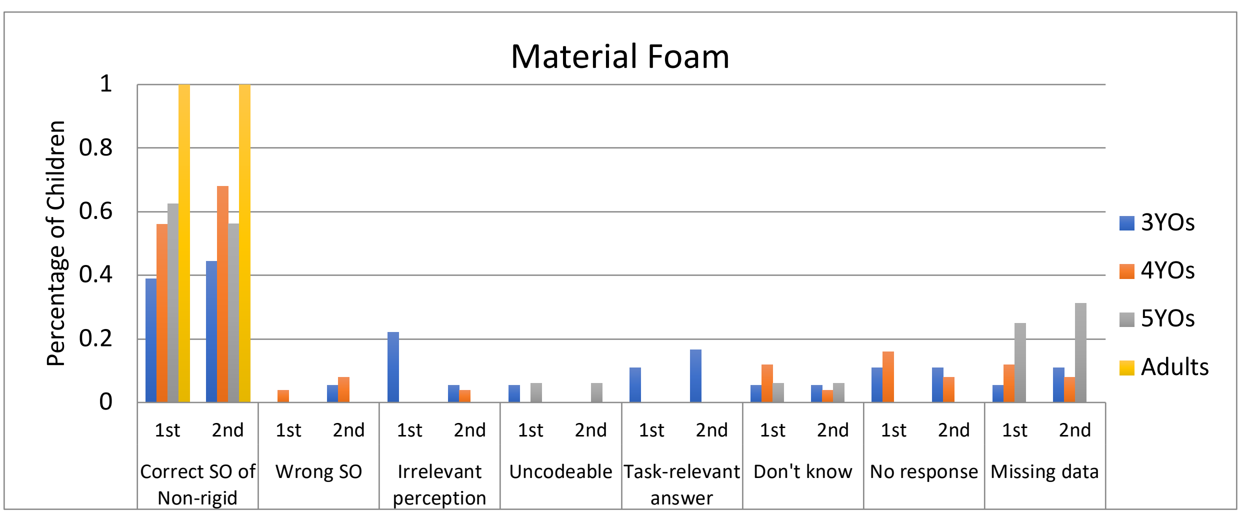



Figure 21. Children and adult's collapsed descriptions of "what does this feel like" of the material Foam

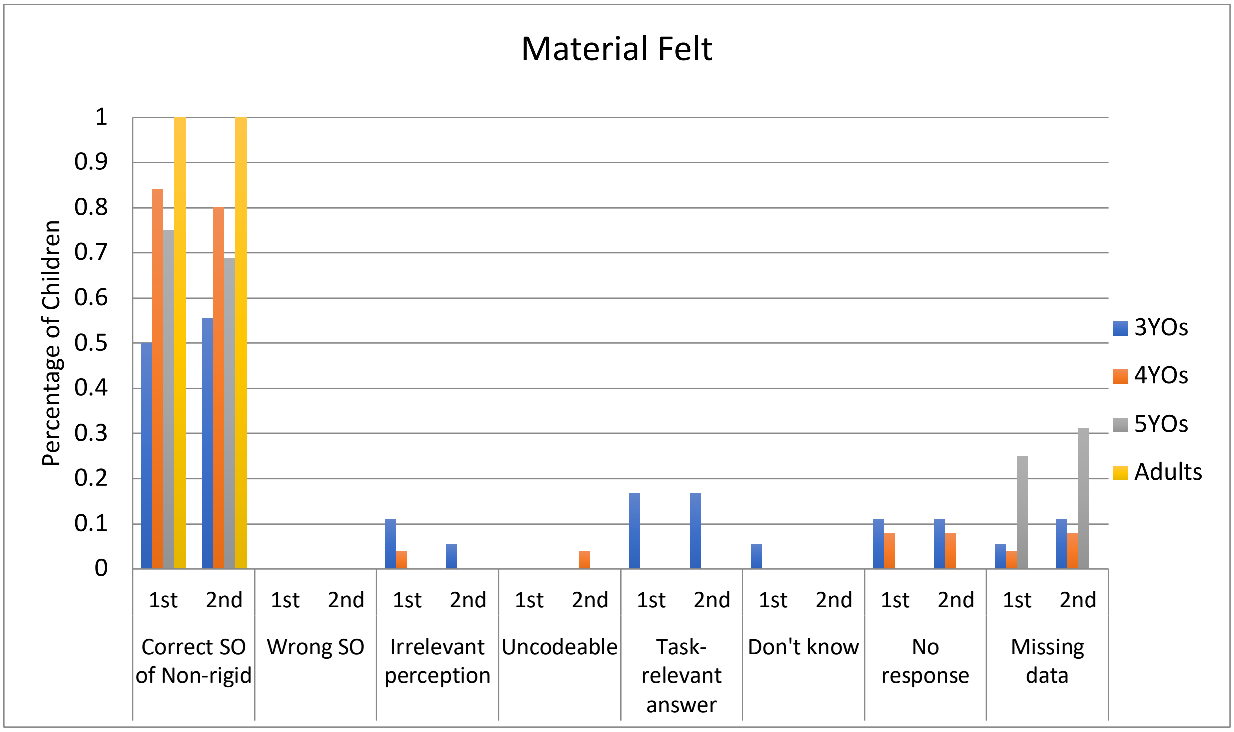



Figure 22. Children and adult's collapsed descriptions of "what does this feel like" of the material Felt

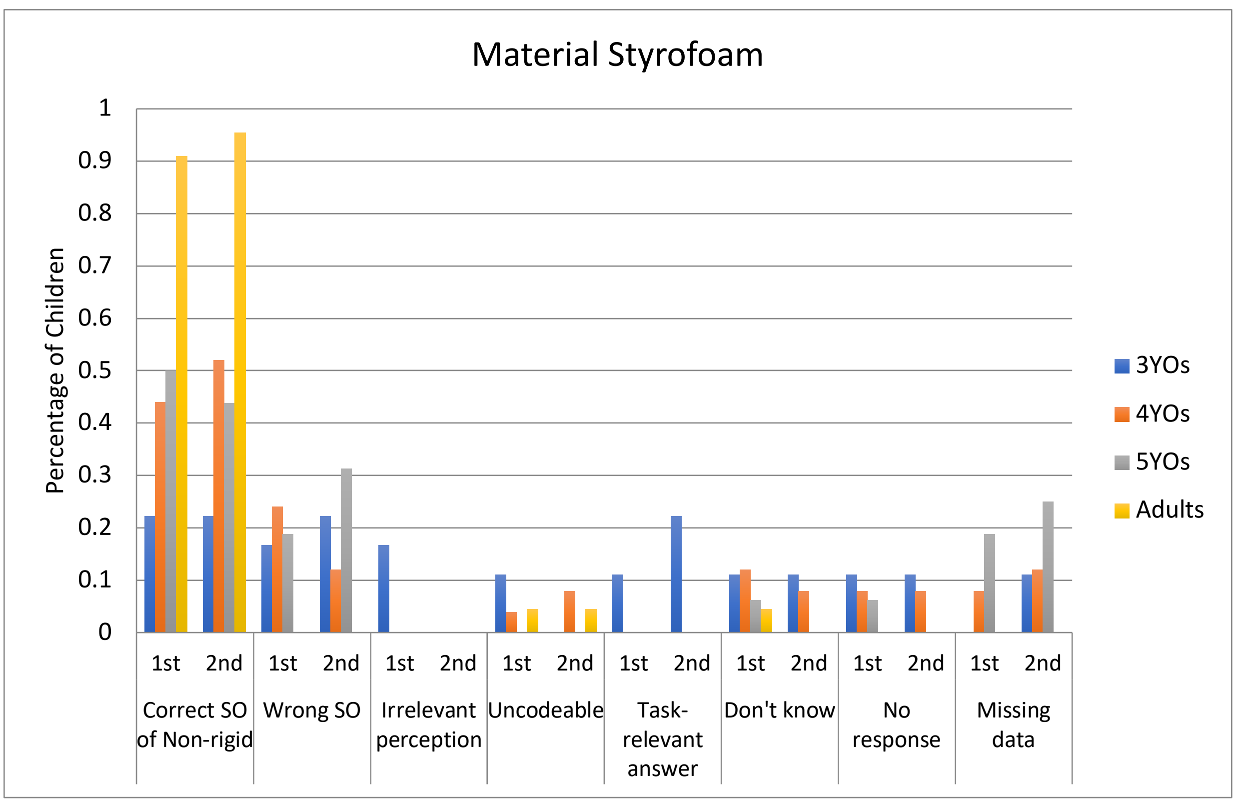



Figure 23. Children and adult's collapsed descriptions of "what does this feel like" of the material Styrofoam

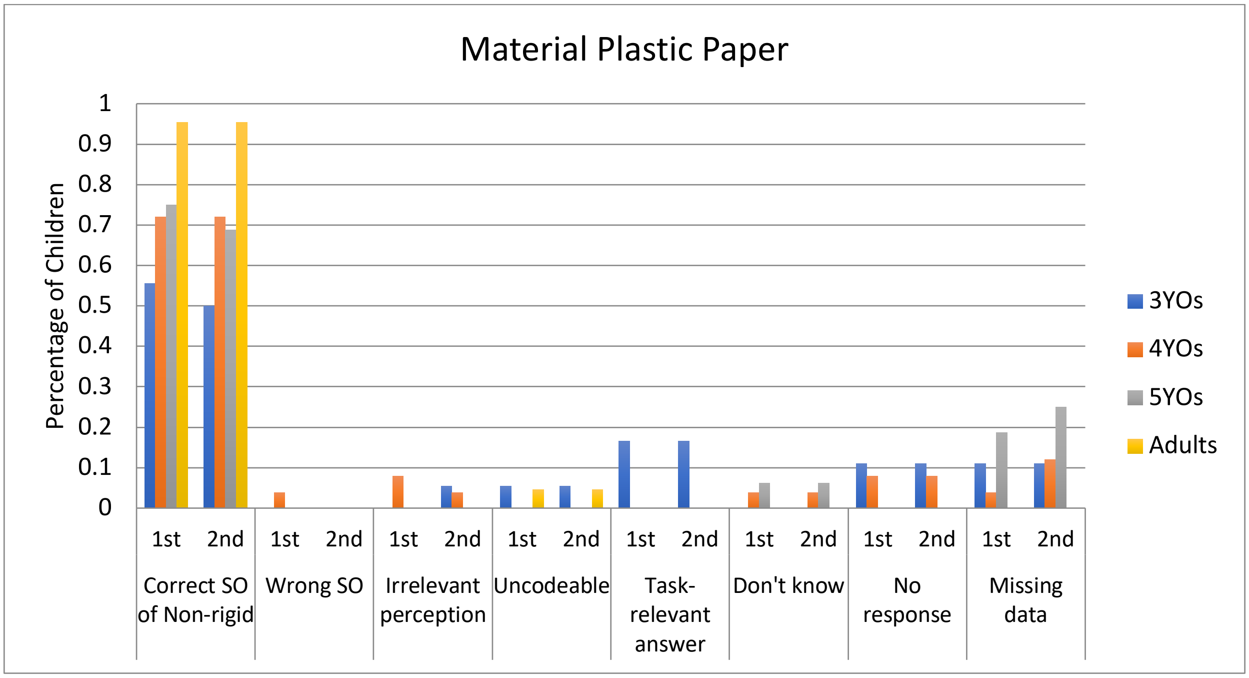



Figure 24. Children and adult's collapsed descriptions of "what does this feel like" of the material Plastic paper

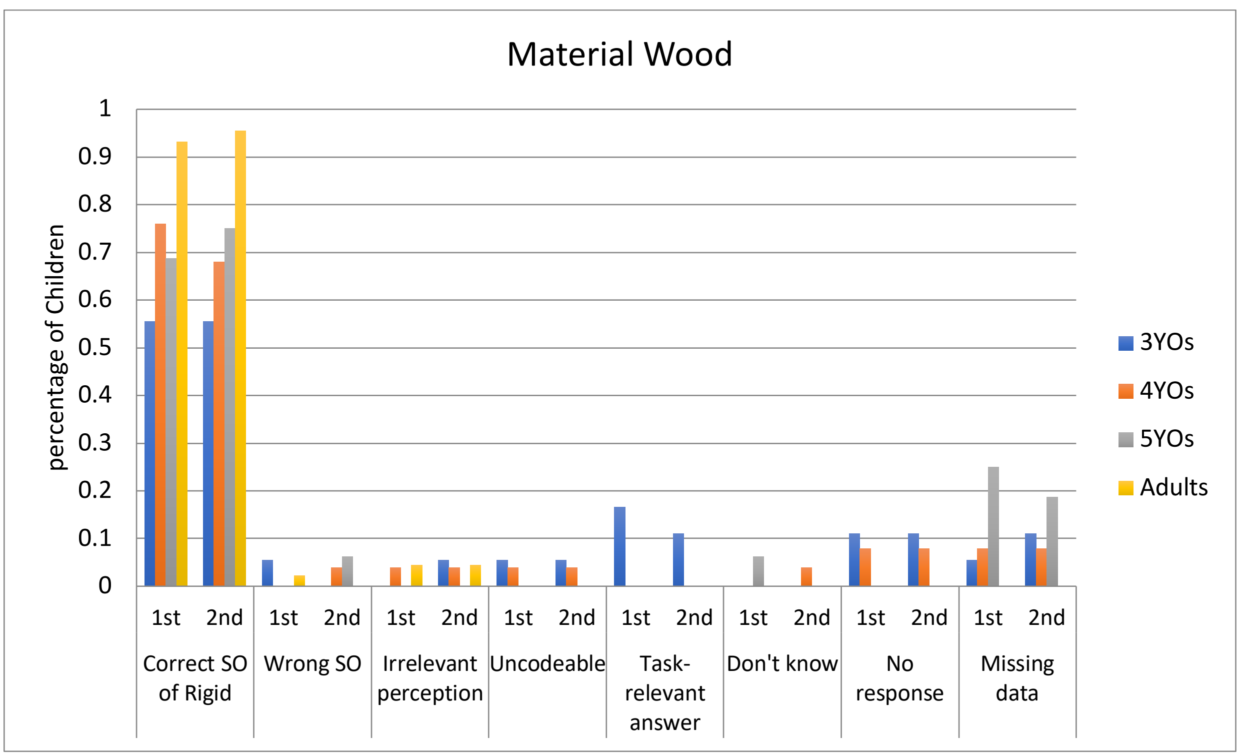



Figure 25. Children and adult's collapsed descriptions of "what does this feel like" of the material Wood

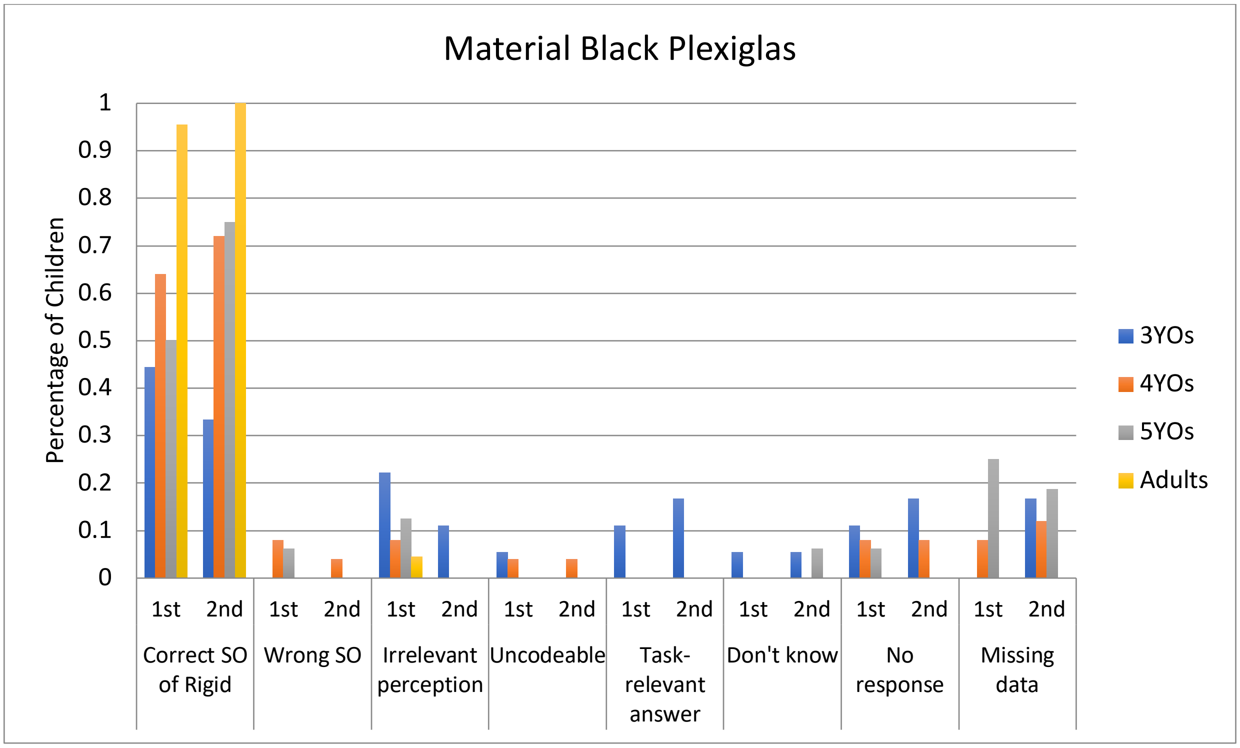



Figure 26. Children and adult's collapsed descriptions of "what does this feel like" of the material Black Plexiglas

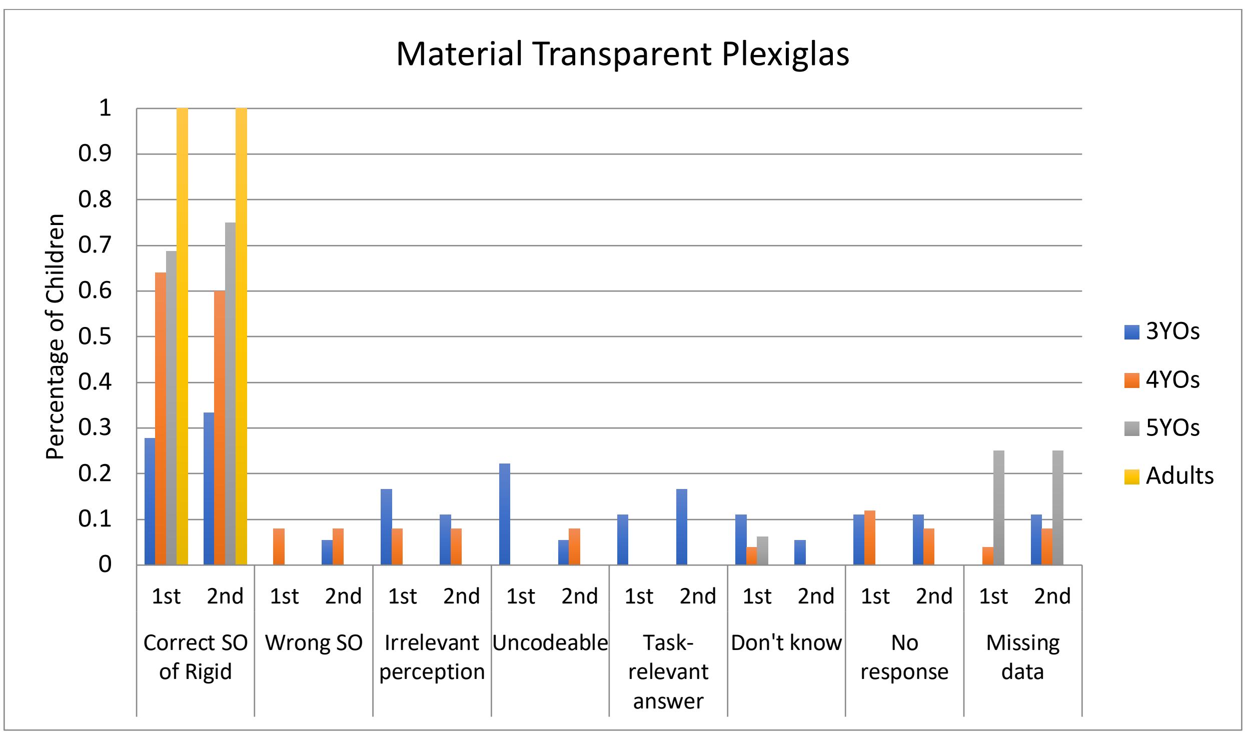



Figure 27. Children and adult's collapsed descriptions of "what does this feel like" of the material Transparent Plexiglas

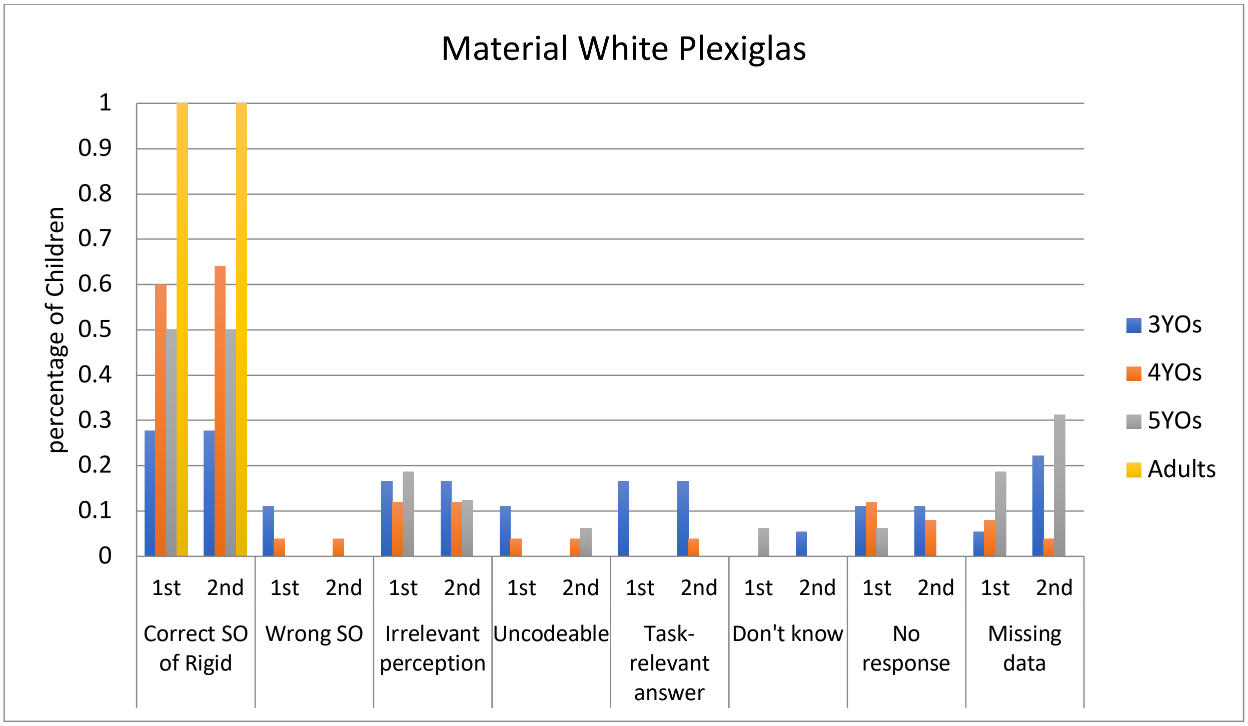



Figure 28. Children and adult's collapsed descriptions of "what does this feel like" of the material White Plexiglas

## Discussion

Study 1 showed that in the Touching-Not-Required condition, children at 5 years old decided that the elephant should take the alternative route when the bridge was non-rigid, and walk on the bridge when it was rigid; however, after they were required to touch, they preferred that the elephant avoid the bridge regardless of its rigidity. This indicates that children were more likely to avoid the risk of the elephant falling after being required to touch. This result is surprising. We predicted that required contact with the materials would improve participants' performance, but children in the Touching-Required condition performed no better than those in the Touching-Not-Required condition.

One possible reason for this could be that when asked to touch the material swatches, they were implicitly informed that the haptic information was relevant to the task and their attention was drawn to the tactile information of the material swatch. This could have made them think harder about whether the thin rigid material could indeed make a bridge strong enough to support an elephant's weight. As a result, they may have become more conservative and less likely to have the elephant step on the bridge. In the Touching-Not-Required condition, participants were not told to pay special attention to the haptic information of the materials. Even though they still could touch if needed, they were less attentive to the strength of the material. They might just consider that as long as it is hard, it could make a walk-on-able bridge for the elephant.

In the Touching-Not-Required condition, children who touched performed as well as the non-spontaneous touchers. But children who extensively explored the rigid materials performed better than the non-spontaneous touchers. The result is telling. Simply touching does not directly link to children's understanding of the material properties and how it influences the support capability of the surface. Children touched for different reasons, among the spontaneous touchers, some touched to glean more information about the rigidity, but some may have touched for other purposes, such as fun or curiosity (Adolph et al., 2010; Joh & Adolph, 2006). Only extensively exploration indicates their intended acquisition of the information of the rigidity, therefore, reflect their better understanding of the material's properties and how they constrain the support capability of the bridge (Joh, Adolph, Narayanan, & Dietz, 2007). However, this difference did not happen on the non-rigid materials. One possible reason is that it may be easy to tell a certain material as non-rigid from visual or acoustic information. It will require more tactile information to tell a material kind as rigid (Adolph et al., 2010; Joh & Adolph, 2006).

Our hypothesis that 3-year-old children could pass the current task was rejected. In the current study, 3- and 4-year-old children could not judge the correct route for the elephant depending on the material composition of the bridge.

Their failure in the "walk on or around" study could be due to the complexity of the design and the extra cognitive demand generated by the task.

First, the study may have unwittingly introduced a decision task, one that requires children to know that it is better to take a shorter route—that is, crossing the bridge rather than going all the way around. Even though 3- and 4-year-olds can think hypothetically, their ability is highly constrained by information processing demands (Beck, Robinson, Carroll, & Apperly, 2006; German & Nichols, 2003).

In Study 1, children first had to understand that one route was faster but could be safe or unsafe, whereas another route was longer but was always safe. To make the optimal choice, participants must always consider the safe and faster route first; only if the faster route was unsafe should they consider the longer one. The multiple layers of the task placed high information processing demands on the younger children. Not only did they need to judge whether the rigid or non-rigid bridge was safe, they also had to understand the trade-off between safety and speed, and then hold two possibilities in mind.

A second consideration is that the material swatches were shown to participants one at a time. This originally aimed to test their ability to assess whether a surface that they might encounter in the natural environment could be stepped on. However, we found that this approach increases the ambiguity of the task and has no correct answer. Even adults felt uncertain and did not always judge the rigid (i.e., black Plexiglas, wood) materials as good enough to support an elephant. When presenting some rigid materials (e.g., wood), one 5-year-olds explained: “the elephant can break trees, so he should walk around.” Moreover, it is known that young children are better able to attend to the relevant features or dimensions of an item when paired with another similar item (Gentner & Markman, 1997; Markman & Gentner, 1993).

Lastly, this study tested children on the same materials twice, which may have bored them with repeated questions. Also, the verbal descriptions of the tactile information were too demanding for the younger children.

The study 2 and 3 lowers the demand of the present study in three ways: 1) by not requiring the children to predict the elephant’s action, 2) by implementing a forced choice paradigm where they only need to decide which material can construct a “good” bridge between two materials, and 3) shorten the task by taking out the ambiguous items for even 5-year-olds, and not requiring children to touch and describe the texture feeling of the materials.

## *III. Preschool Engineers: building the bridges to support an elephant's walking across a river*

In Chapter 3, we presented two following "bridge-making" studies. In the simplified version of the studies, children first saw an animation of a bridge-maker-man constructing bridges made from either rigid or non-rigid materials. The bridge was meant to help an elephant cross the river safely. In the experimental testing phase, for each novel pair of materials (one rigid and one non-rigid), children decided which material will serve as a good bridge to support the elephant. We assumed that, after reducing the demand, preschool children could decide the more appropriate materials to make a bridge that will support the safe crossing of a young elephant. We hypothesized that younger children can successfully select the rigid materials over the non-rigid to construct a bridge.

### Study 2 and 3

### "Good or Not-good bridges" studies

*Design*

The first two phases in the current studies are similar as Study 1. In the third phase, children were directly asked to select the more appropriate material kind. Study 2 tested pairs of materials that differed in thickness. Study 3 tested by controlling the thickness variable and also took off the sounds that the elephant made on the bridge.

## Study 2

## Methods

*Participants*

We recruited 59 participants from local preschools in New Jersey. The children were mainly from middle-class white families at the New Jersey area. Six children were dropped because one participated in a similar study before, one did not want to participate, two did not finish the protocol and two because of experimenter errors. There were 25 3-year-olds (17 female, ranges from 37 to 48 months, M = 43.84 months, SD = 2.59) and 28 4-year-olds (15 female, ranges from 49 to 59 months, M = 54.75 months, SD = 3.00) that were included in the final analysis. As planned, participants received 2 small stickers and the school received a small gift for participating the experiment.

*Materials*

*Animation*

A short video was created from Sketch-up, Photoshop and MATLAB (see Figure 29). The video was presented on a 15-inch Macbook-Pro laptop situated at the children's level. Throughout the experiment, a puppet with a hidden speaker asked the relevant questions.

*Demonstration and memory test items*

Two rectangular (10 cm wide * 15.5 cm long) samples of materials with thickness differed (Paper: 0.04 cm, Aluminum: 0.15 cm).

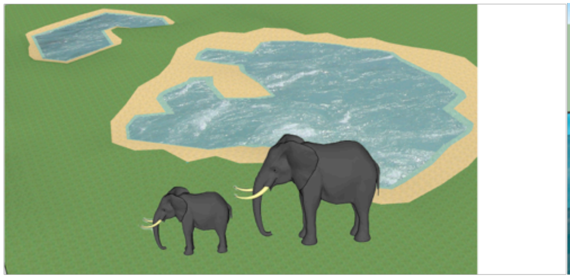
*Prediction items*

Four different rectangular (10 cm wide * 15.5 cm long) samples of materials with two rigid (wood (0.5 cm), plexiglass (1.2 cm) and two non-rigid materials (plastic paper (0.025 cm), felt (0.15 cm) (see Figure 30).

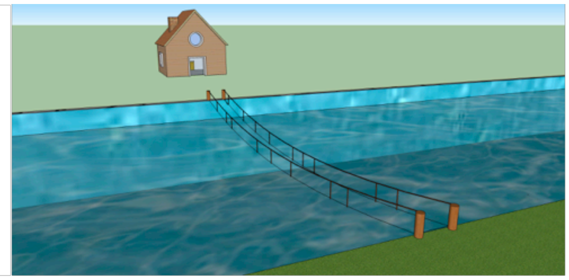
*Design & Procedure*

*Demonstration Phase*

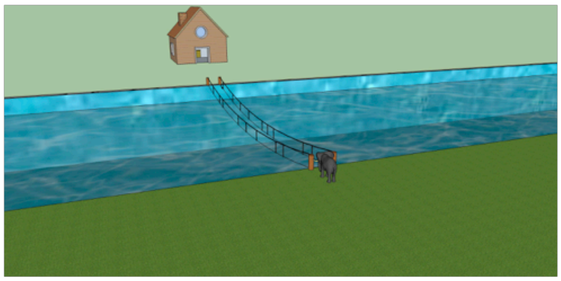
Children watched an animated story (see Figure 29) in which an elephant tried to get to the other side of a river. A bridge man helped the elephant make bridges by using different kinds of materials. In the first example, the elephant walked across a bridge when the bridge man used aluminum to make the bridge. A swatch of the aluminum material was shown to the children. In the second example, the elephant fell into the water when the bridge man used paper and a swatch of the paper material was shown to the children.



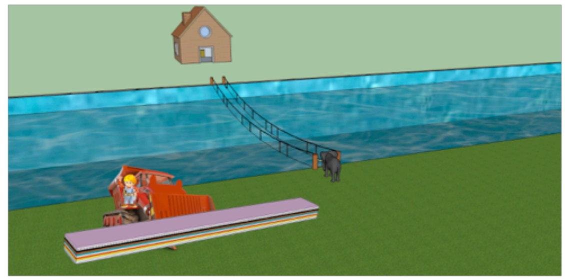
Look, there is a young elephant. The young elephant lives with his mother in the field.



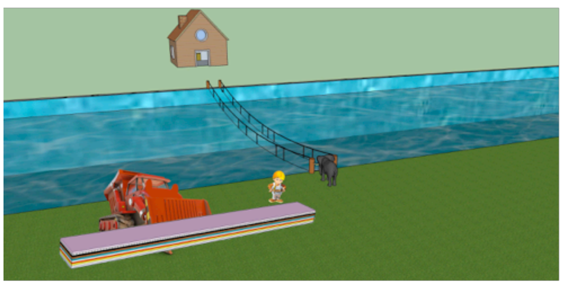
See, this is the elephant's house. The young elephant sleeps there at night.



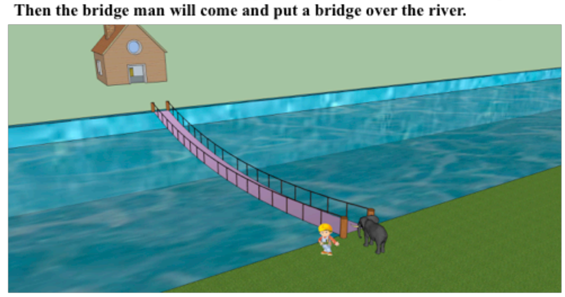
But, the house is across the river. So, he needs help.



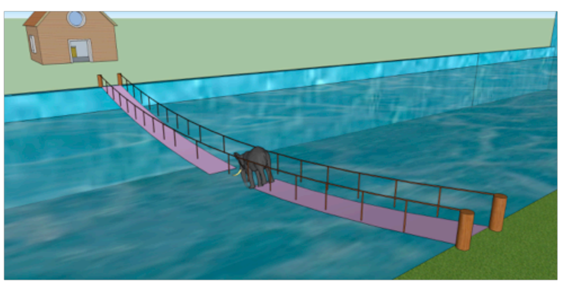
The young elephant can make a special sound (The sound of the elephant). Then the bridge man will come and put a bridge over the river.

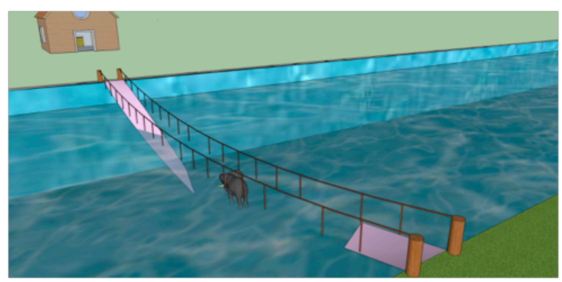


The bridge man has lots of stuff. Some stuff is good for making a bridge and some stuff is not good. He is still learning about good and not-good stuff. He does not always know which stuff is good and which stuff is not. Let me show you.



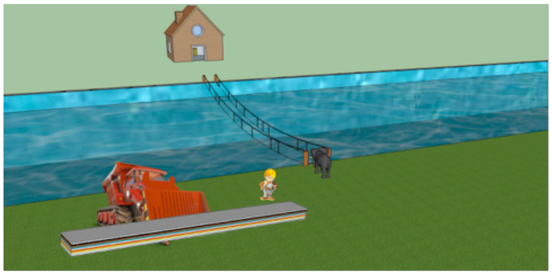
First he tries this kind of stuff to make the bridge. I brought a small piece of this stuff to show you. Here, feel it. Let's see what happens when the elephant walks on the bridge.



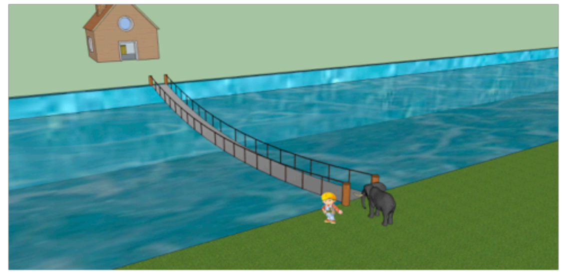


(Sound of breaking the paper and falling into the water).

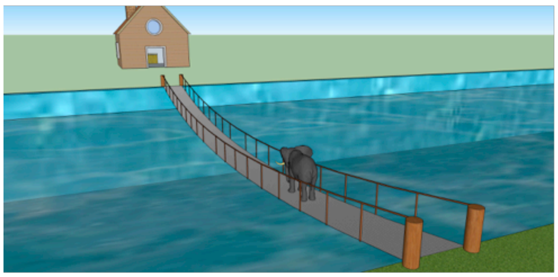
Oh, no! The elephant falls into the water. Not a good bridge!



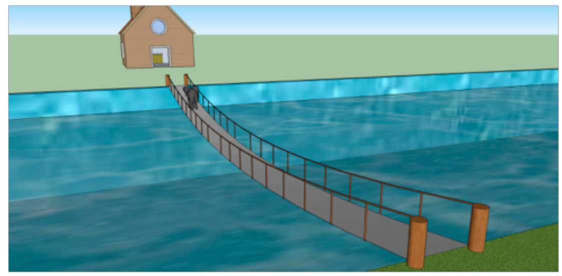
**The bridge man tries again.**



**This time he uses a different kind of stuff. I brought another small piece to show you. Watch what happens when the elephant walks on the bridge.**

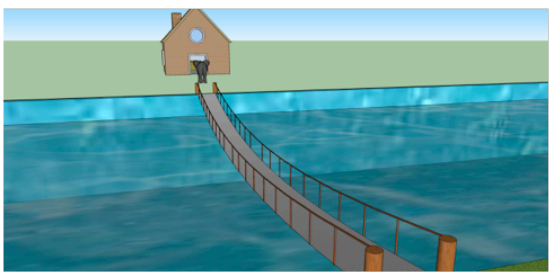


**(Sound of walking on the bridge)**



**(Sound of walking on the bridge)**

**The elephant walks across the bridge safely. A good bridge!**



**(Sound of walking on the bridge)**

Figure 29. Animated story shown in the demonstration phase in study 2

*Memory test phase*

Children were asked four memory questions after the demonstration phase. These served to select subjects who understood our phrases of “good stuff” and “not-good stuff.” The test involved showing children a pair of demonstration materials on two separate rounds. They were asked “which one is the good stuff? What happened when the elephant walked on the good bridge?” Which one is the not-good stuff? What happened when the elephant walked on the not-good bridge?” If the children provided no answer after the questions, the experimenter would prompt them and ask the questions again.

After the first memory round, the experimenter put the items away. In order to make sure the children did remember what happened in the story rather than randomly pointed to the correct one, the experimenter asked the memory questions for a second time by saying: “Oh, I made a mistake. I forgot the puppet. The puppet was not watching!” Then the experimenter put the puppet in front of the child and the puppet with a hidden speaker would say: “Oh, I missed the story! I also want to know what happened in the story” (We decided to use the puppet because children often change their answer when they are asked the same question twice. They may think the experimenter indicate their answer as incorrect by asking the same question twice). Then the experimenter changed the position of the two stimuli, put them back on the table and said to the children: “please tell the puppet, which one is the good stuff? What happened when the elephant walked on the good bridge. Which one is the not-good stuff? What happened when the elephant walked on the not-good bridge? If the children answered any of the two times wrong, the experimenter said: “let’s see what the puppet says.” The puppet (speaker inside) said: “Oh, I still don’t remember! I want to watch the video, too!” Then the experimenter asked the children to watch the video with the puppet together. After the second video demonstration, the puppet would say: “Ah, I remember now. How about you? Do you remember?” Then the children were asked for the third time of the memory questions. If they still did not get the memory questions right, the study ended here, otherwise, experimental phase begun.

*Prediction phase*

In the prediction phase, children were told by the experimenter: "Oh, let's play a new game, the bridge man has lots of stuff, but he does not always know which stuff is good and which stuff is not good. He wants you to tell him which one is the good stuff and which one is the not-good stuff. I bet you can do it." Because we took out the ambiguous items from the study 1, and there were fewer test items in the current study. For a total of 4 trials, two samples of materials were presented in front of the children at the same time (one rigid and one non-rigid). The experimenter then asked the children "Which one is the good stuff? Which one is the not-good stuff?" The sequence was random. The position of items was counterbalanced.

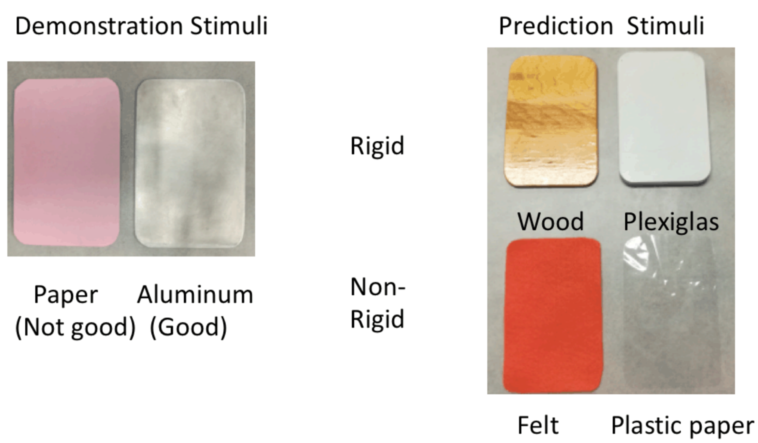



Figure 30. Material swatches used in the demonstration and experimental prediction phase in study 2

## Results

*Memory test*

Since the distribution for the responses violates the normal distribution, a non-parametric test was conducted to test 3- and 4-year-old children's performance. For the first memory round, both 3- and 4-year-old children performed better than chance in identifying both good and not-good stuff (chance level = .5) ($\chi^2$ (1, N = 25) = 4.84, $p$ = .028; $\chi^2$ (1, N = 28) = 20.57, $p < .001$, respectively). Eighteen out of 25 3-year-old and 27 out of 28 4-year-old children could correctly identify both materials. Nineteen out of 25 3-year-old and 26 out of 28 4-year-old children gave appropriate answers of the event after the elephant walked on the good (e.g., didn't fall, didn't break, went home, etc.) and not-good bridge (e.g., fell into the water, broke, etc.). For the second memory round, 20 3-year-old and 28 4-year-old children could correctly identify both materials and 19 out of 25 3-year-old and 27 out of 28 4-year-old children correctly answered the event questions.

Overall, for children's initial two memory rounds, 18 out of 25 3-year-old (72%) and 26 out of 28 4-year-old (93%) correctly answered 4 out of 4 questions twice. Four-year-old children performed better than 3-year-old children ($\chi^2$ (1, N = 53) = 4.08, $p$ = .044, two-tailed).

One 3-year-old child passed after testing for a third time. In the end, 19 3-year-old and 26 4-year-old children participated in the prediction test.

*Prediction test*

Among the children who passed the memory test, both 3- ($M$ = 3.79, $SD$ = 0.54) and 4-year-old ($M$ = 3.85, $SD$ = 0.78) children performed better than chance level (p = .5) ($\chi^2$ (4, N = 19) = 197.56, $p < .001$, two-tailed; $\chi^2$ (4, N = 26) = 329.23, $p < .001$, respectively). By conducting Two-Sample Kolmogorov-Smirnov test, there was no difference between 3- and 4-year-old children's performance on the prediction test ($p = .998$).

## Discussion

Given the children who remembered the story, both 3- and 4-year-old children did well in choosing the one from the two materials that would make a good bridge. It is possible that children did not use the relative rigidity of the materials to decide the appropriateness of the materials. Instead they may have used the thickness or the acoustic information (i.e., the sound of elephant walking on the bridge) to help them decide. In study 3, we eliminated the acoustic information in the demonstration and controlled the thickness of the materials for the pair. In addition, study 3 changed the shape from rectangle to square as testing the irrelevance of the shape. Moreover, study 2 did not test the children who failed the memory task, and study 3 included them in the test phase.

## Study 3

## Methods

*Participants*

We recruited 57 children from the central New Jersey area, and 9 children were dropped from the analysis (two experimenter errors, one did not reach 3-year-old, two participated the first study, and 4 children did not finish the protocol). In the end, there were 21 3-year-olds (10 female, ranges from 37 to 47 months, $M = 43.57$ months, $SD = 3.00$) and 28 4-year-olds (16 female, ranges from 49 to 60 months, $M = 53.61$ months, $SD = 3.13$) were included in the data analysis. As planned, participants received two small stickers for participating the experiment and the school received a small gift for participating the experiment.

*Materials & Procedure*

*Animation*

The same video as in study 2 except that the sound of elephant breaking the paper and walking on the bridge were eliminated. Also, there was no puppet in study 3.

*Demonstration and memory test items*

Two square (10 cm wide * 10 cm long) samples of materials with thickness differed (Paper: 0.04 cm, White Plexiglas: 1.2 cm).

*Prediction items*

Six square pairs in a total. There were two pairs of materials (Foam (0.2 cm) VS. Wood (0.2 cm), Felt (0.15 cm) VS. Metal (0.15 cm) that are incongruent (rigidity cannot be discerned from the thickness), two pairs of materials that are congruent (rigidity can be discerned from the thickness) (Plastic paper (0.025cm) VS. Wood (0.5cm), Plastic paper (0.025cm) VS. Metal (0.15cm)), and two pairs of materials that are mixed (Felt (0.15 cm) VS. Wood (0.2 cm), Foam (0.2 cm) VS. Metal (0.15 cm)) (See Figure 31).

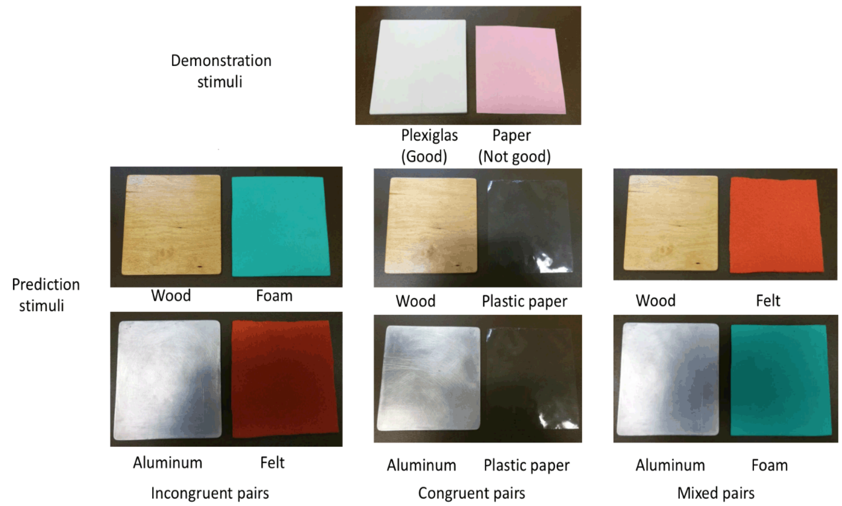



Figure 31. Material swatches used in the demonstration and experimental prediction phase in study 3

*Design & Procedure*

The procedure was the same from study 2 except that children were only asked for memory questions for one round. If they answered the memory questions wrong, they were shown the video again. The sequence of the items was random and the position was counterbalanced between each two pairs.

## Results

*Memory test*

For the initial response, both 3- and 4-year-old children performed better than chance in identifying the materials ($\chi^2$ (1, N = 21) = 10.71, $p$ = .001; $\chi^2$ (1, N = 28) = 17.29, $p$ < .001, two-tailed, respectively). There were three 3-year-old and three 4-year-old children who can only identify one or none item correctly. Six 3-year-old and six 4-year-old children could not articulate the events after the elephant walked on the bridges correctly.

Overall, 15 out of 21 3-year-old children (71%) and 22 out of 28 4-year-old (79%) children answered 4 out of 4 memory questions correct. There was no significant difference between 3- and 4-year-old children's overall performance ($\chi^2$ (1, N = 49) = 0.33, $p$ = .56, two-tailed).

Three more children completely passed the memory test after second time watching (two 3-year-old children and one 4-year-old child). In the end, 17 out of 21 3-year-old children (81%) and 23 out of 28 4-year-old (82%) children completely passed the memory test (4 out of 4 trials correct).

*Prediction test*

Given the children who passed the memory test, both 3- (M = 1.47, SD = 0.80) and 4-year-old (M = 1.68, SD = 0.69) children performed better than chance ($p$ = .5) in the incongruent pairs ($\chi^2$ (2, N = 17) = 18.06, $p < .001$; $\chi^2$ (2, N = 23) = 35.26, $p < .001$, respectively, see Figure 32). A Friedman test revealed that there was no effect for the different thickness conditions ($p$ = .576, two-tailed). Three- and 4-year-old children did not perform differently overall ($p$ =.993, by Two-Samples Kolmogorov-Smirnov test, two-tailed).

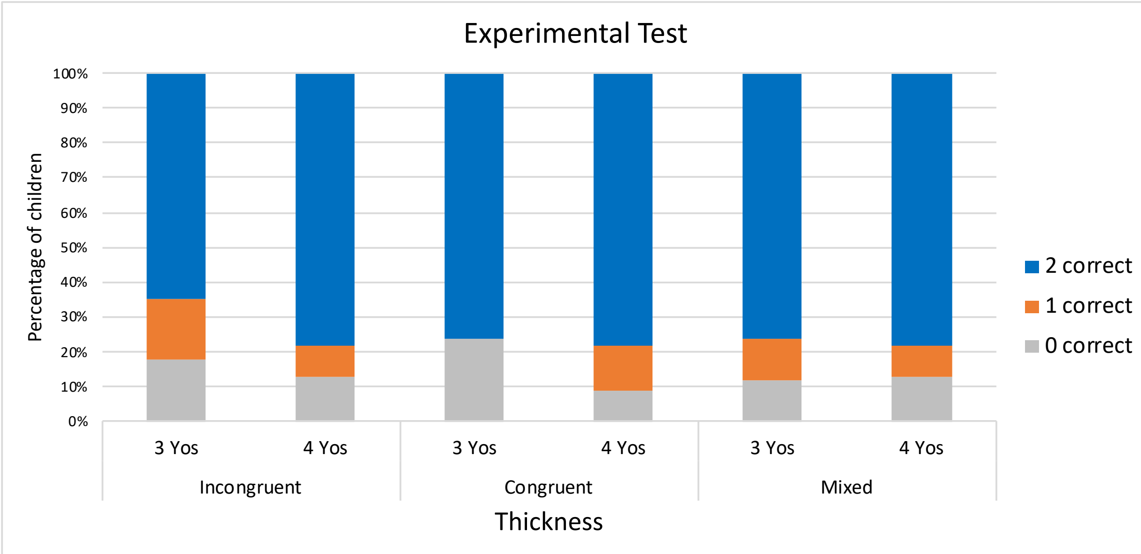



Figure 32. Children's performance in the experimental prediction test in study 3.

## Discussion

After reducing the cognitive demand of the first study, both 3- and 4-year-old children could use the relative rigidity to judge whether a bridge can support a certain weight.

To our knowledge, this are the first studies to demonstrate that children as young as 3 could explicitly assess the rigidity of a sample substance to judge whether it can be used to make an intended artifact (i.e., bridge). Previous studies have asked children to judge whether a tool, or the essential part of a tool, that differed in material composition could serve its intended function (Baillargeon, Gelman, & Meck, 1981; Brown, 1990; Klatzky, Lederman, & Mankinen, 2005). In our studies, children were asked whether a sample material could be used to construct the intended artifact. When animals and humans are making tools and building shelters, they need the capability to judge whether particular raw materials can be used to make the intended artifacts. This ability is crucial in the engineering process and can be an early precursor of human's ability to create plans for making objects.

We propose that children's capability to select suitable materials for making artifacts is rooted in their implicit understanding of physical objects and principles (Baillargeon, 1994, 1995, 2002, 2004; Luo, Kaufman, & Baillargeon, 2009; Spelke, 1994, 2000; Spelke & Kinzler, 2007). Their success may be due to the fact that infants already possess rich knowledge about physical support and experiences of locomoting (Baillargeon, Needham, & DeVos, 1992; Gibson, 1988; Gibson et al., 1987; Needham & Baillargeon, 1993). They know that heavy/large/moving objects will create force onto another object (Hauf et al., 2012; Kotovsky & Baillargeon, 1994, 1998; Leslie & Keeble, 1987). Nonetheless, they need to infer that in order to support the weight of these objects, the surfaces should be able to resist the force and thus need to be rigid.[2] This ability to select the raw materials before the artifacts are even made differs from understanding physical objects (i.e., distinguishing objects from substances) and mechanisms (e.g., the causal physical interactions between entities, how to create force). It requires one to know that a given material constrains the function of an artifact and specifically what property is needed to serve the intended function.

The studies also add to the current literature about children's knowledge of an artifact's function (Kelemen, 1999; Kelemen & Carey, 2007; Matan & Carey, 2001). Children at age 3 can ignore shape, size and degree of thickness and pay attention to material composition in considering whether an artifact's function will be supported.

# *IV. General Discussion*

This dissertation reveals an essential cognitive precursor that prepares humans for artifact-making behaviors. It provides evidence that the ability of selecting appropriate materials in thinking of making an artifact emerges in early childhood and may not require formal education.

In Chapter 1, I outlined a fundamental problem faced by artifact makers: how do we select appropriate materials to make the intended artifacts? The studies presented in this dissertation shed light on the cognitive ability underlying the building behaviors by asking when preschoolers develop the ability to explicitly take material properties into consideration.

In Chapter 2, I asked 3- to 5-year-olds and adults what kind of materials can be used to make a bridge to support a certain weight. Children and adults watched an animation in which a man used different (rigid/non-rigid) materials to build a bridge for an elephant. Participants were asked to decide whether the elephant should step on the bridge or take the longer route, depending on what material was chosen. Three- and 4-year-olds had some trouble deciding the correct route for the elephant based on different bridge conditions. At 5 years of age, children began to display this ability. The results suggest that 5-year-olds not only understand that bridges need to be rigid in order to support locomotion, but also that they can consider the trade-off between distance and safety. In Chapter 2, I also discussed how the touching behavior influenced children's performance and how the high information processing demand might hinder younger children's performance.

In Chapter 3, I simplified Study 1 and asked if, with a lower demand, 3- and 4-year-olds could decide which of two materials was more appropriate. Also, could they still succeed after the rigidity cannot be discerned from the thickness? Results show that both 3- and 4-year-olds could choose the more appropriate material based on its relative rigidity.

The results of the experiments in Chapters 2 and 3 are summarized in Table 4. From Table 4, it is easy to see the developmental function of children's growing abilities. In an explicit prediction task, when children need to hypothetically predict what would happen in two different scenarios—namely, consider both safety and distance—and make the optimal choice, only 5-year-olds were able to identify the correct route based on the absolute rigidity of a material swatch when they were not required to touch. When they were asked to touch, however, they were more likely to avoid risk regardless of material type. Three- and 4-year-olds were unable to pass this task independent of the touching condition.

Table 4. Summary of the results of the experiments from Chapter 2-3.

| | | 3-year-olds | 4-year-olds | 5-year-olds | Adults |
|---|---|---|---|---|---|
| Judging the route based on one material kind at a time | Required to touch | × | × | × | √ |
| | Required not to touch | × | × | √ | √ |
| Selecting the appropriate material from a pair | Rigidity covaried with thickness | √ | √ | | |
| | Rigidity not covaried with thickness | √ | √ | | |

The experiment in Chapter 2 provides critical evidence that children at 5 years of age can reason and judge whether a bridge can afford an agent's locomotion based on its rigidity.

Even though the study shows that 5-year-old children have the ability to choose the material to make a walk-on-able bridge, we do not conclude that they can judge how much weight a bridge can exactly afford. Even adults felt uncertain to consider using some rigid material kinds to make a bridge to support an elephant. In Gibson's theory, affordance is a relational property—it changes when the perceiver changes (J. J. Gibson, 1979); a chair that is sit-on-able for a person may not be sit-on-able for an elephant, a bridge that is walk-on-able for a dog may not be walk-on-able for a human. Because it is relational, it is unclear what "rigid" means here or the degree which it indicates.

The results from the adults' performance indicate that it is not easy to perceive accurately whether a rigid bridge is walk-on-able; we may have an estimate, however, it is far from accurate. One may argue that adult's uncertainty was due to the task difference and the lack of sufficient information (e.g., weight of elephant, thickness of bridge, etc.). If adults were standing in front of a bridge and judging whether they should cross, they might be able to judge more accurately; however, other evidence also supported the notion that judging the affordance of a single surface is challenging. Berger et al. (2014) showed that when infants were provided a handrail that is either rigid or non-rigid to cross over a narrow bridge, even though infants attempted to cross more with the rigid handrail compared to the non-rigid handrail, many infants failed to notice the unreliability of the wobbly handrail and attempted to cross with it. Also, in another study, adults sometimes failed to detect the affordance of a foam surface in the middle of a rigid surface and stumbled on it (Joh & Adolph, 2006). These studies suggest that without a clear reference of how much weight a surface or handrail can support, the affordance of a single surface is not obvious to perceivers. If a wooden bridge becomes increasingly thin, it is difficult to accurately identify the point at which it stops supporting weight. Judging this accurately or even making a safe bridge is a job for engineers or experienced builders, and they need to have enough experience and conduct precise calculations to ensure that the bridge will support a certain weight. We seldom step onto a breakable surface or go over a drop-off, but it is not because we accurately perceive the affordance. Rather, it is because bridges are made by engineers who perform calculations to ensure that they can afford at least a certain weight. If we use perception alone, it is unlikely that we will accurately assess a surface's safety.

A point worth noting is that in Chapter 2, the benefit of haptic exploratory behaviors is only evident in children when the exploration has a clear aim and driven by the clear goal of gathering relevant information of rigidity.

One limitation of the study in Chapter 2 is that the high cognitive demand posed in the task lower younger children's performance. When children were tested in a less demanding version in Chapter 3, children as young as 3 could select the more appropriate material from a pair. These results indicate that in early childhood, humans are cognitively ready to select appropriate materials for making the intended artifacts.

The results from Chapter 3 are informative. First, children were able to consider solid objects as solid substances when they were told that this solid entity would serve as the purpose of constructing another intended object. Second, many studies have discussed how humans transfer material culture through social learning, such as imitation and language (Christophe Boesch & Tomasello, 1998; Dean, Kendal, Schapiro, Thierry, & Laland, 2012; Tennie, Call, & Tomasello, 2009; Tomasello, 2009; Van Schaik et al., 2003). This study offers a different perspective and shows that, with the exception of learning from others, humans may already have the cognitive ability to select the correct materials for building artifacts. Third, this study showed that even though children were able consider different materials as appropriate for making artifacts, they can identify the ones that have the correct dispositional property.

*Conclusion and directions for future research*

This dissertation provides critical evidence for children's understanding of solid materials and the functions they can serve in making an artifact. Even 3-year-olds can use relative rigidity to choose a suitable material for building a bridge, showing that one cognitive precursor of the artifact making behavior emerges in early childhood.

This dissertation reveals a small portion of the cognitive abilities underlying humans' artifact-making behaviors; yet, many questions remain unanswered. In the current studies, the information-processing demands were still high. As a noticeable number of 3- and 4-year-olds were unable to pass the memory test, future research should reduce the memory load by asking children to identify the correct answers instead of recalling the events and then test if their performance improves.

One direction for future research would be to investigate which perceptual information children use to help them choose an appropriate material. Studies could provide children with visual, haptic and acoustic information of the materials and test which perceptual modality dominants children's judgment.

Another possibility would be to change the agent of the task and investigate children's consideration of the relativity of the affordance. For example, if a bridge could not afford an elephant, could it afford a rabbit? If it could afford a rabbit, could it afford an ant?

One research goal could be to understand the nature of the selection of materials. Specifically, do children only understand materials as constraints of making a bridge? Or do they also understand materials as constraints in making artifacts in general? Does this depend on the kind of artifact and the children's prior knowledge? For example, do they know that even though hard materials are better for making the bridge, soft materials are better for making artifacts like clothes or toys?

Another direction for future research would be to test animals like birds and ants to see if they can select the appropriate material for a certain manufacturing process and provide comparative evidence for the cognitive precursor of animals' building behaviors.

Answers to these questions could shed light on the nature of artifact-making behaviors, including how we acquire information to select materials, how we consider different kinds of materials when making things for different purposes, and how other living beings understand the manufacturing process.

# APPENDIX

## Analyses

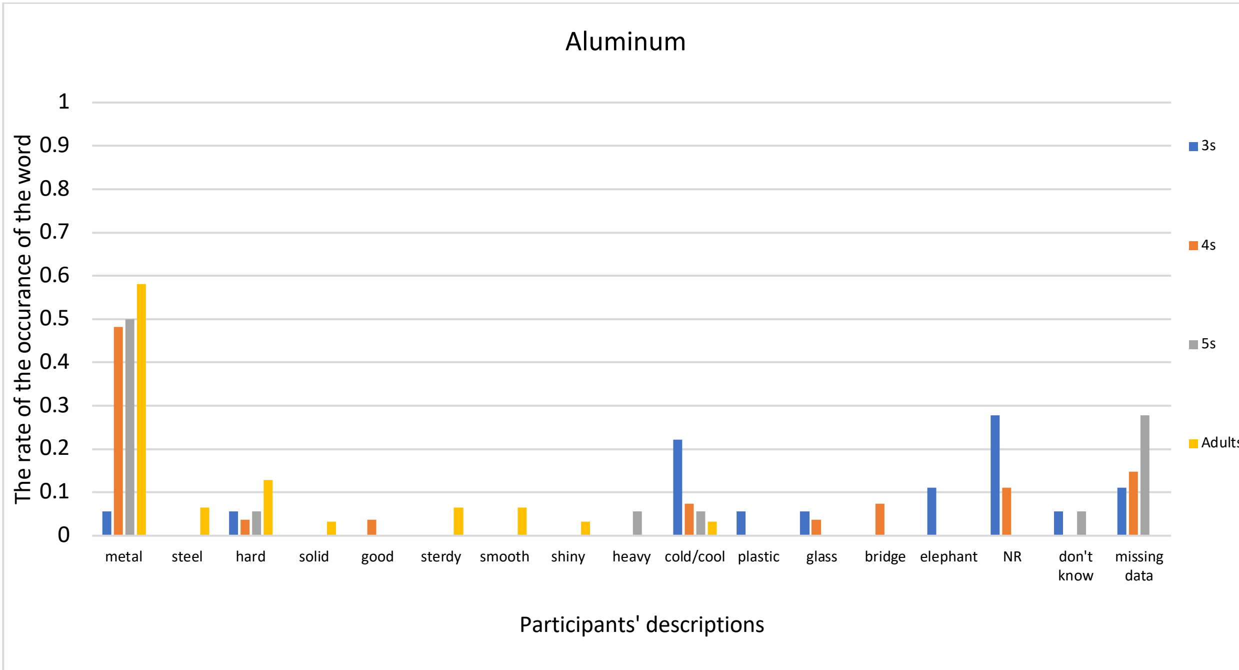



Figure A.1. Participants' specific descriptions of "what does this feel like" of the material aluminum in the demonstration phase in the Touching-Required condition

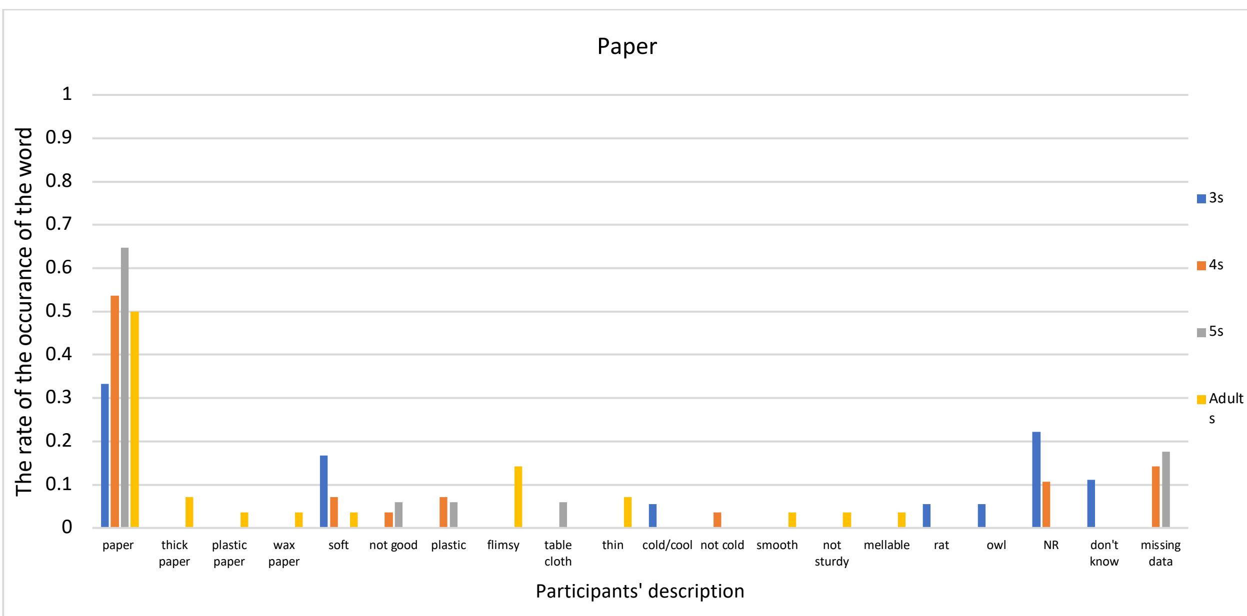



Figure A.2. Participants' specific descriptions of "what does this feel like" of the material paper in the demonstration phase in the Touching-Required condition

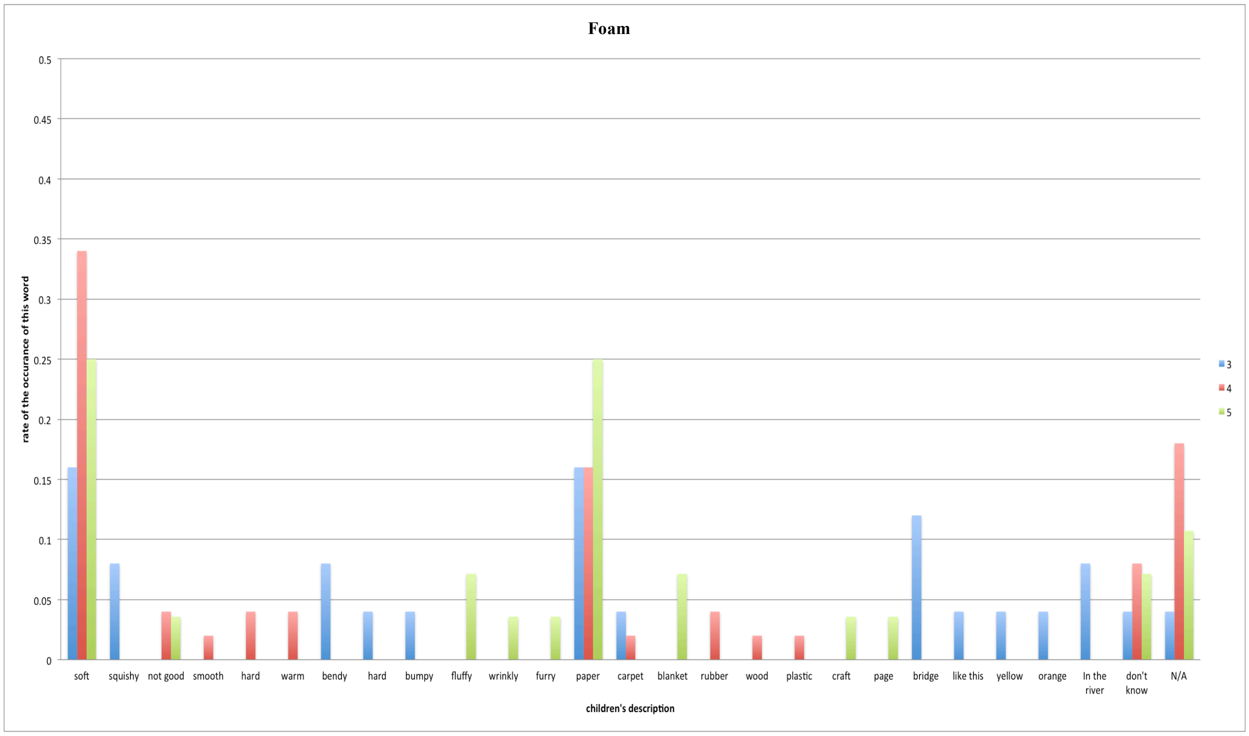



Figure A.3. Children's specific descriptions of "what does this feel like" of material Foam by different age groups

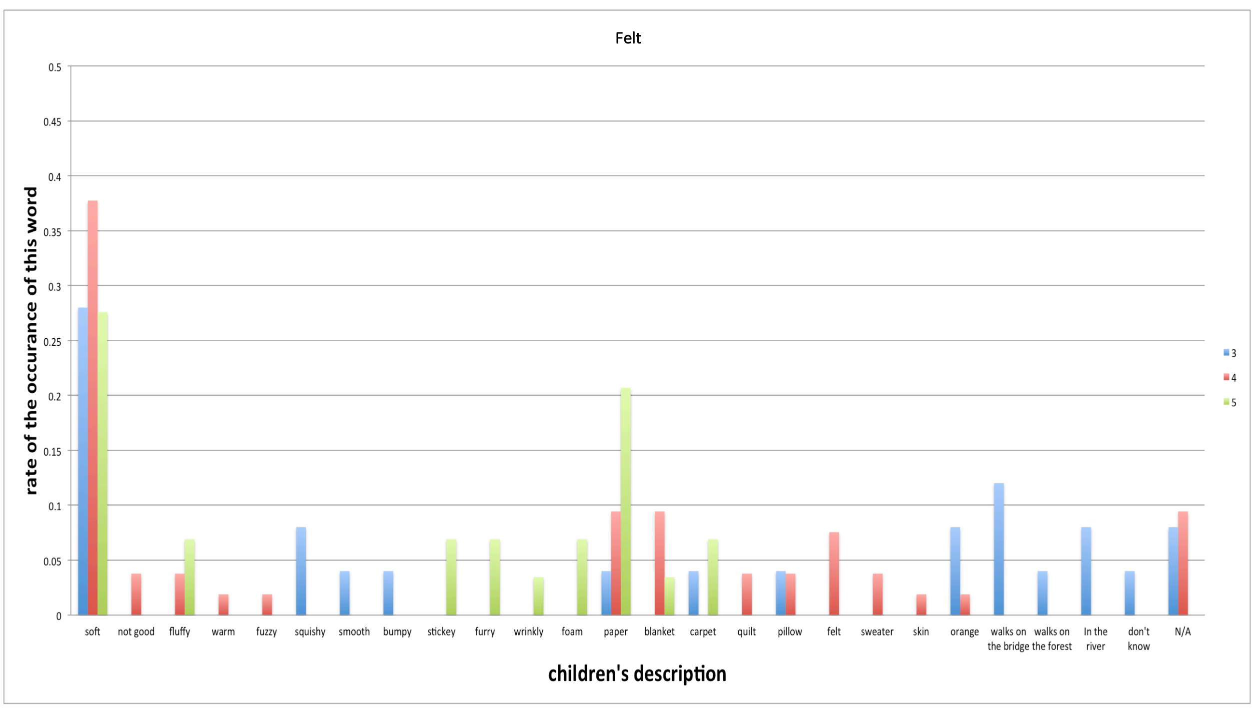



Figure A.4. Children's specific descriptions of "what does this feel like" of material Felt by different age groups

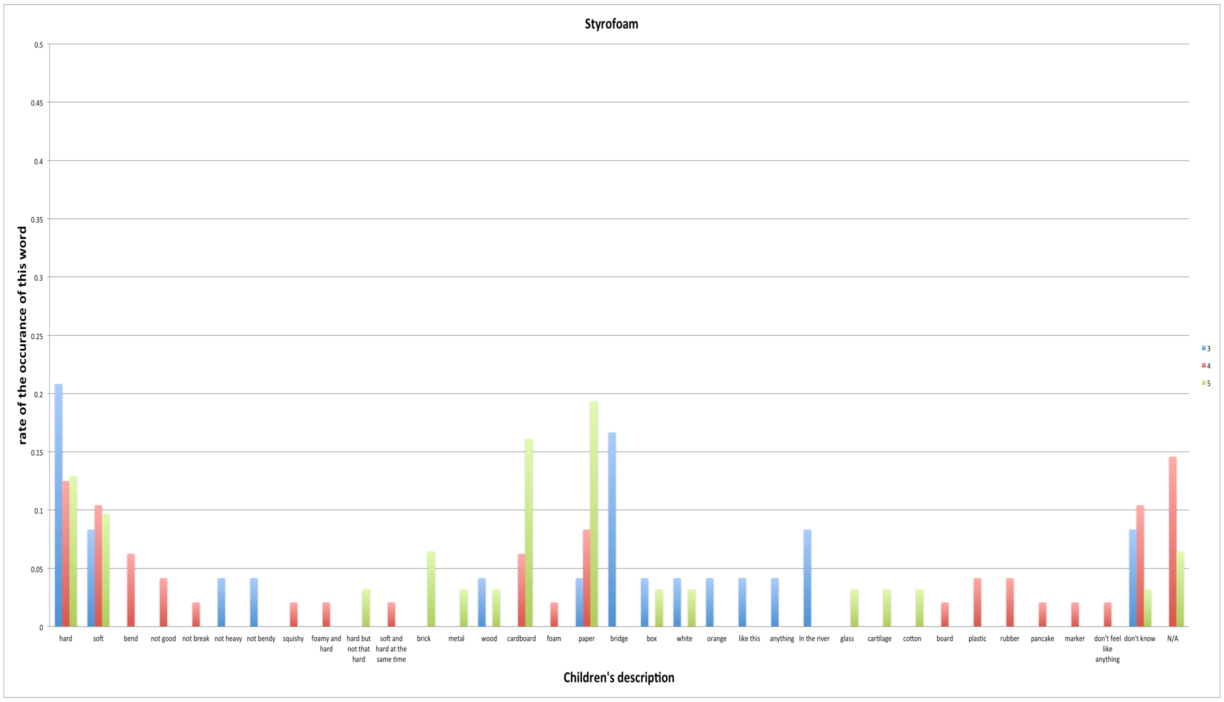



Figure A.5. Children’s specific descriptions of “what does this feel like” of material Styrofoam by different age groups

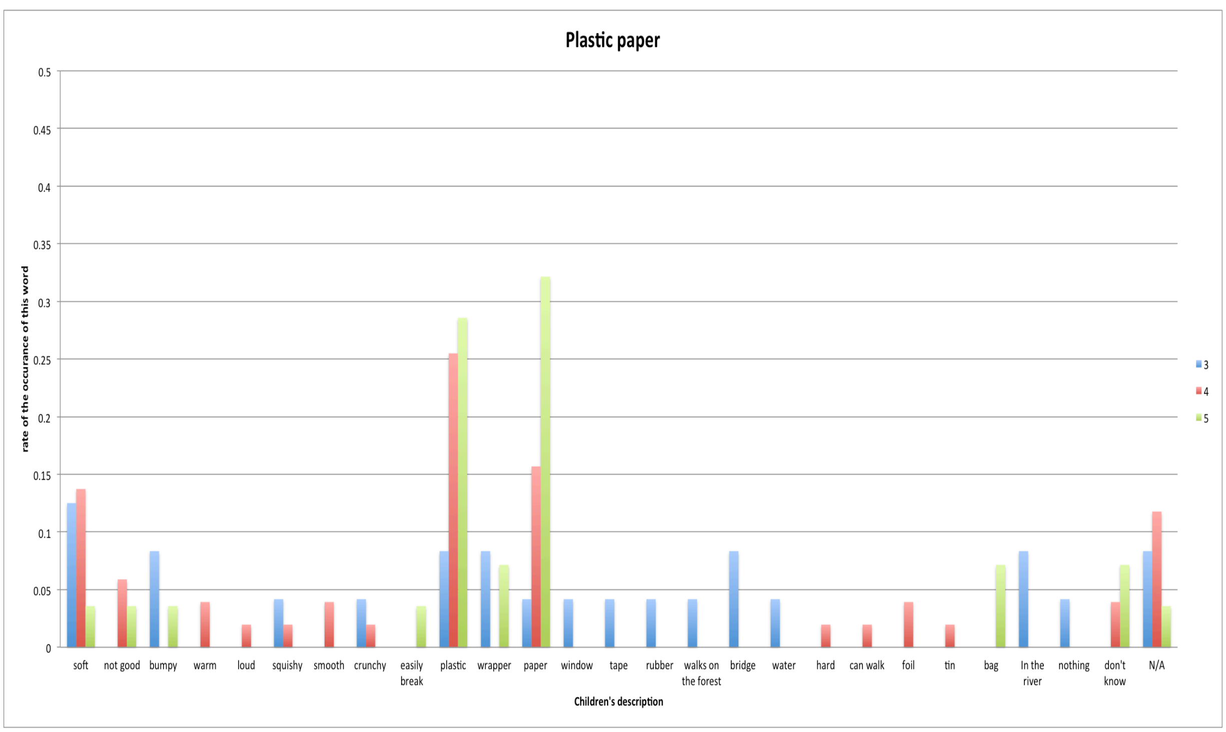



Figure A.6. Children’s specific descriptions of “what does this feel like” of material Plastic paper by different age groups

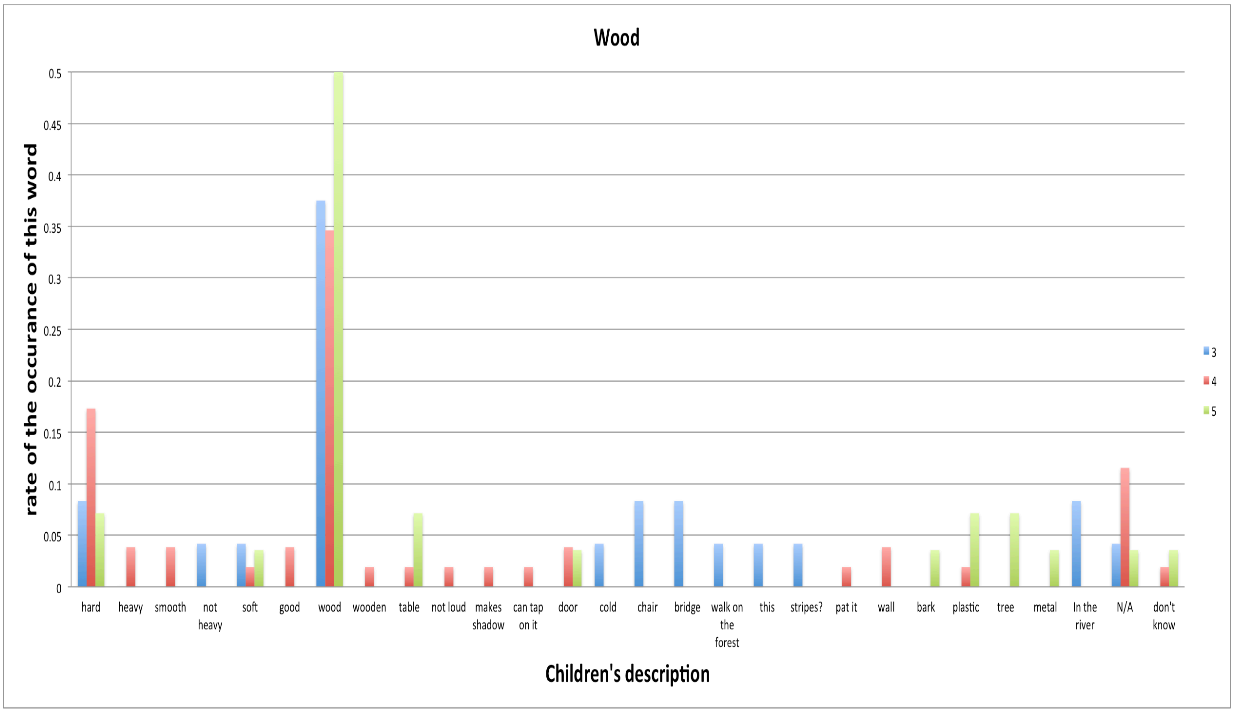



Figure A.7. Children's specific descriptions of "what does this feel like" of material Wood by different age groups

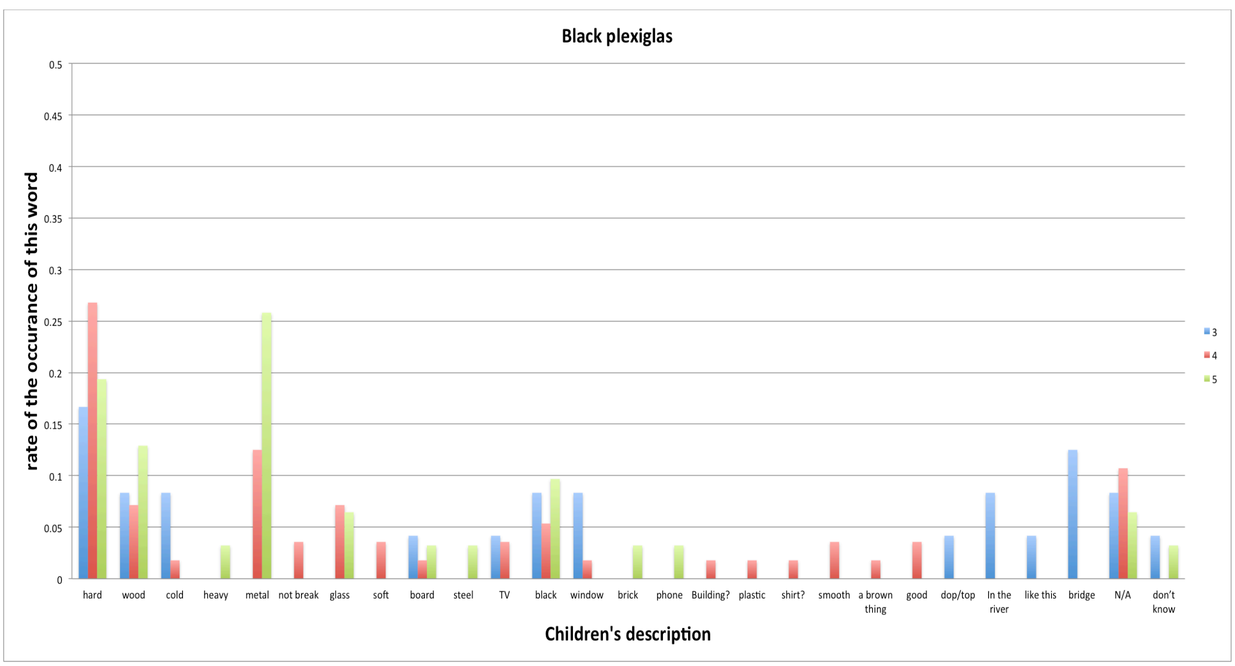



Figure A.8. Children's specific descriptions of "what does this feel like" of material Black Plexiglas by different age groups

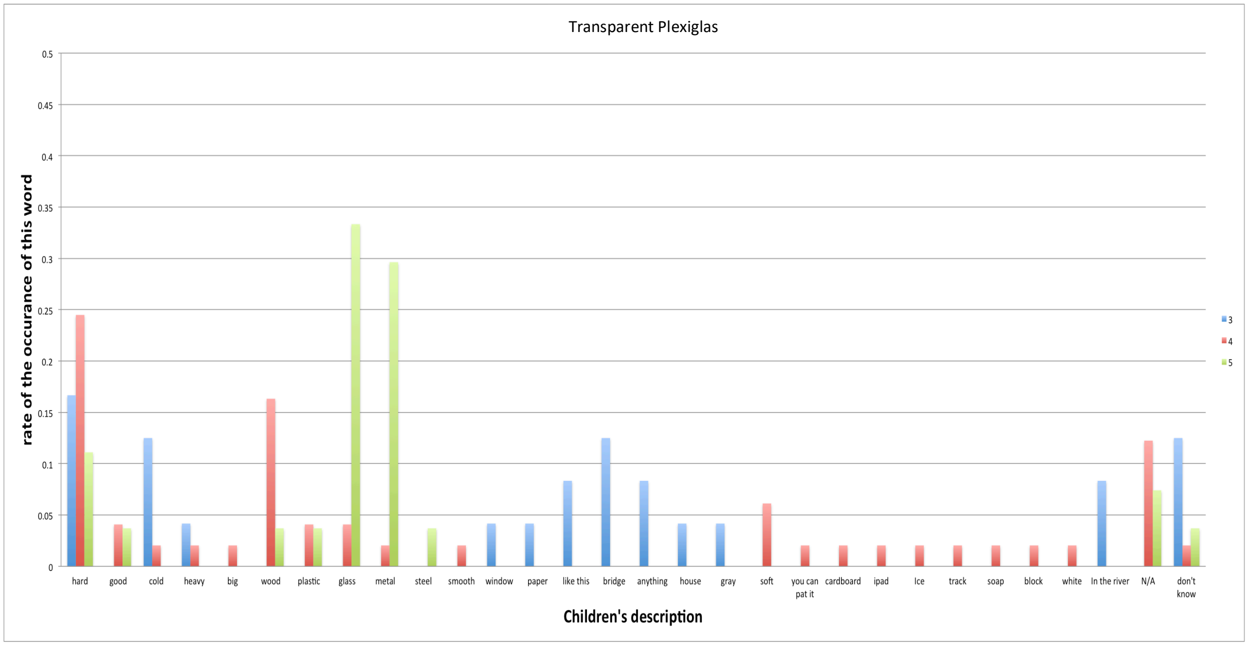



Figure A.9. Children's specific descriptions of "what does this feel like" for material Transparent Plexiglas by different age groups

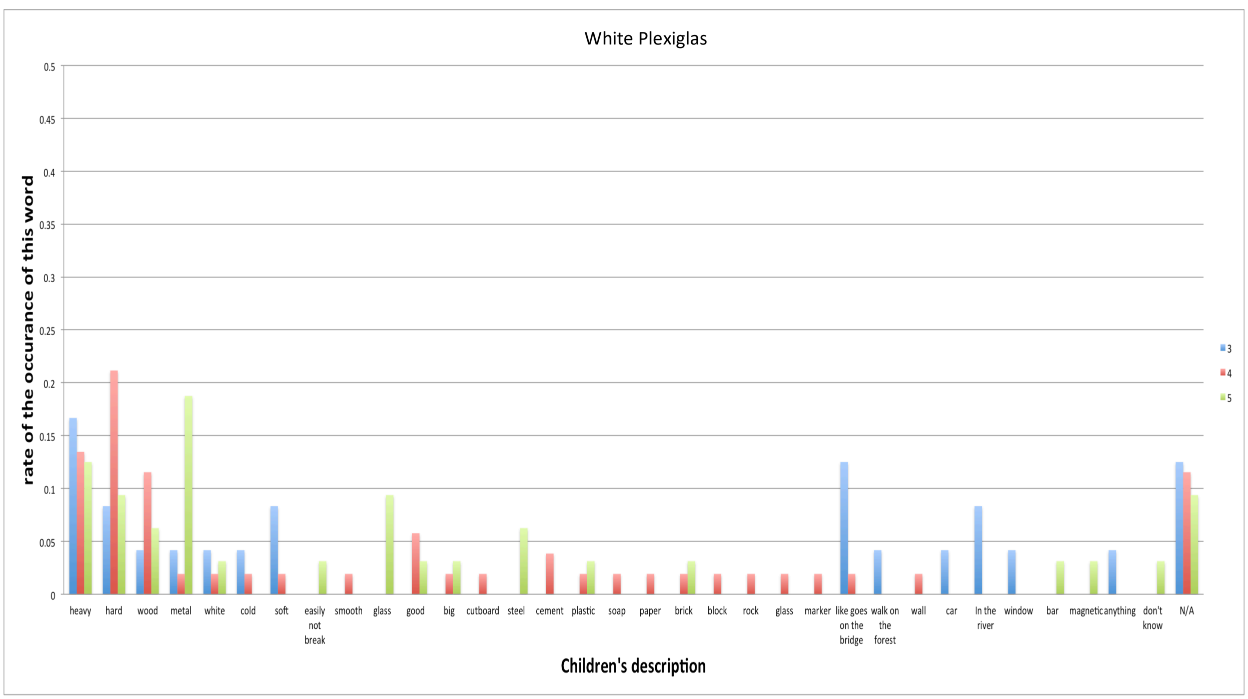



Figure A.10. Children's specific descriptions of "what does this feel like" of material White Plexiglas by different age groups

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