Journal of Experimental Child Psychology 184 (2019) 48–64

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

journal homepage: www.elsevier.com/locate/jecp

# The development of the size–weight illusion in children coincides with the development of nonverbal cognition rather than motor skills

Philippe A. Chouinard [a,*], Kezia G. Matheson [a], Kayla A. Royals [a], Oriane Landry [a], Gavin Buckingham [b], Elizabeth J. Saccone [a], Darren R. Hocking [c]

[a] *Department of Psychology and Counselling, School of Psychology and Public Health, La Trobe University, Melbourne, Victoria 3086, Australia*
[b] *Department of Sport and Health Sciences, University of Exeter, Exeter, Devon EX4 4PY, UK*
[c] *Developmental Neuromotor and Cognition Lab, School of Psychology and Public Health, La Trobe University, Melbourne, Victoria 3086, Australia*

## ARTICLE INFO

*Article history:*
Received 23 December 2018
Revised 19 March 2019
Available online 17 April 2019

*Keywords:*
Size–weight illusion
Child development
Perception
Expectancies
Sensorimotor integration
Reasoning

## ABSTRACT

We examined how the strength of the size–weight illusion develops with age in typically developing children. To this end, we recruited children aged 5–12 years and quantified the degree to which they experienced the illusion. We hypothesized that the strength of the illusion would increase with age. The results supported this hypothesis. We also measured abilities in manual dexterity, receptive language, and abstract reasoning to determine whether changes in illusion strength were associated with these factors. Manual dexterity and receptive language did not correlate with illusion strength. Conversely, illusion strength and abstract reasoning were tightly coupled with each other. Multiple regression further revealed that age, manual dexterity, and receptive language did not contribute more to the variance in illusion strength beyond children's abilities in abstract reasoning. Taken together, the effects of age on the size–weight illusion appear to be explained by the development of nonverbal cognition. These findings not only inform the literature on child development but also have implications for theoretical explanations on the size–weight illusion. We suggest that the illusion has a strong acquired

* Corresponding author.
*E-mail address:* p.chouinard@latrobe.edu.au (P.A. Chouinard).

https://doi.org/10.1016/j.jecp.2019.03.006
0022-0965/

component to it and that it is strengthened by children's reasoning skills and perhaps an understanding of the world that develops with age.



## Introduction

The size–weight illusion refers to the perceptual experience of object weight that occurs when a person lifts equally weighted objects that differ in size (Charpentier, 1886, 1891). Namely, smaller objects typically feel heavier than larger objects of the same mass. Although the illusion has been studied for more than 100 years, its precise mechanisms are not completely understood and have yet to be explained satisfactorily. Over the years, researchers have proposed a number of different theoretical explanations for the illusion (Buckingham, 2014; Dijker, 2014; Saccone & Chouinard, 2019).

According to sensorimotor explanations, the illusion is driven by the misapplication of fingertip forces during lifting (Dijker, 2014). When lifting two objects that weigh the same, people apply more force for the larger object than they do for the smaller one, which causes too much lift for the former and too little for the latter. According to these explanations, too much lift will make the object feel lighter, whereas too little lift will make the object feel heavier. However, Flanagan and Beltzner (2000) demonstrated how the motor system quickly learns to apply the correct amount of force for each object after only a few trials, whereas the perception of differences in weight remains the same in magnitude across many trials. This dissociation has been replicated several times (Buckingham & Goodale, 2010a, 2010b; Chouinard, Large, Chang, & Goodale, 2009; Grandy & Westwood, 2006), which undermines the necessity of the underlying mechanisms proposed by sensorimotor theories.

Alternatively, other theories offer more top-down explanations, whereby the illusion arises from the brain comparing prior experiences and current sensory input, which in turn influences weight perception. Bayesian explanations, which have grown in popularity during recent years to comprehensively explain many forms of perception, posit that perceptual experiences are the result of an active process of formulating and testing hypotheses about the world. It then follows that experiences, or priors, are important in shaping perception (Geisler & Kersten, 2002; Gregory, 1980; Helmholtz, 1867).

If one applies these principles to weight perception, then the perceived heaviness of an object should be influenced by any associations that we have developed over time between weight and other physical properties of objects. For example, small objects are usually lighter in the real world. According to Bayesian explanations, one should expect the smaller object in the size–weight illusion to weigh less, which consequently should make that object feel lighter during lifting. However, the reverse is experienced in the size–weight illusion, which is why the illusion is sometimes called an anti-Bayesian illusion (Brayanov & Smith, 2010). Nevertheless, as Peters, Ma, and Shams (2016) demonstrated through mathematical modeling, and discussed further by Saccone and Chouinard (2019), the size–weight illusion fits perfectly well within a Bayesian framework if one considers that the perceived heaviness of objects might be driven by expected density as opposed to size (Chouinard et al., 2009; Harshfield & DeHardt, 1970; Peters et al., 2016; Ross & Gregory, 1970). Manipulable man-made objects tend to be denser as they get smaller, and people consequently tend to estimate their weight according to this relationship (Peters, Balzer, & Shams, 2015). Thus, in the context of the size–weight illusion, the smaller and denser object affords more weight, which causes that object to feel heavier.

If priors are indeed important for the size–weight illusion, then one might expect to find increases in the strength of the illusion during child development. It is conceivable that an adult with years of experience in lifting objects would have a more expansive and deep-seated repertoire of priors about their affordances and would use these priors for the purposes of perception with greater efficiency and influence than a young child whose motor skills are still developing and who has lifted fewer objects. Binet (1895) and Piaget (1969, 1999) proposed that illusions, such as the size–weight illusion, offered opportunities to understand typical development and tease apart perceptual mechanisms that might be innate from those that are acquired. Their arguments stem from their own research demonstrating how the strength of illusions can either decrease or increase with age depending on the illusion (Binet, 1895; Piaget, 1969, 1999). Namely, they argued that innate illusions decrease in strength as children age, whereas the strength of acquired illusions increases with age (Binet, 1895; Piaget, 1969, 1999).

The Müller–Lyer illusion is an example of an innate illusion that decreases in strength with age. This was first demonstrated by Binet (1895) and has since been replicated several times (Brosvic, Dihoff, & Fama, 2002; Frederickson & Geurin, 1973; Hanley & Zerbolio, 1965; Pollack, 1970; Porac & Coren, 1981), but not always (Rival, Olivier, Ceyte, & Ferrel, 2003). Binet (1895) posited that it can be maladaptive to falsely perceive something differently than what it truly is and that children learn to suppress these forms of misperception, but only as cognitive faculties and an understanding of the world develop. Another possibility is that the perceptual system in younger children might exaggerate illusions as a way to compensate for not being able to account for sensory noise as effectively as more developed systems in older children (Duffy, Huttenlocher, & Crawford, 2006). More recently, Gandhi, Kalia, Ganesh, and Sinha (2015) demonstrated how children who gain sight for the first time after the surgical removal of congenital cataracts can see the Müller–Lyer illusion immediately after surgery. These reports on the Müller–Lyer illusion are difficult to explain within a Bayesian framework and call into question the necessity of priors. If experience were truly essential for perceiving the Müller–Lyer illusion, then the illusion would not be strongest during early childhood and the children in Gandhi et al.'s study would not experience the illusion immediately after gaining sight for the first time.

Regarding the size–weight illusion, there is little research on the cognitive and sensorimotor explanations of the illusion in typically developing children. Table 1 provides a summary of all articles written in the English and French languages to date. Both the methods and results of these investigations are mixed. Consequently, the developmental profile for the illusion remains unresolved. Some studies demonstrate that the illusion is weaker in younger children and strengthens as children grow older (Philippe & Clavière, 1895; Rey, 1930), whereas others show the reverse findings whereby the strength of the illusion decreases with age (Robinson, 1964). The studies range in procedures from quickly administered perceptual ranking of stimuli (Dresslar, 1894; Flournoy, 1894; Philippe & Clavière, 1895) to lengthy testing sessions using the methods of constant stimuli (Pick & Pick, 1967; Rey, 1930; Robinson, 1964). Many of the earlier studies did not perform statistical analyses and failed to consider other factors that may have influenced their results such as manual dexterity and cognitive ability. Given the variability in procedures and the number of extraneous variables not considered, it is perhaps not surprising that this literature is contradictory and, therefore, warrants further investigation using modern-day methods and standards, which are far more rigorous. Currently, little is known about how the size–weight illusion might develop with age when other variables, such as motor and cognitive skills, are considered.

Although there is evidence suggesting that the illusion might have a strong innate *bottom-up* component to it (Saccone & Chouinard, 2019), conceptual knowledge can nonetheless also influence weight illusions in a *top-down* manner (Buckingham, 2014; Saccone & Chouinard, 2019), as evidenced by the material–weight illusion in which objects that appear to be metallic feel lighter than objects that appear to be made of Styrofoam of the same size and mass (Buckingham, Cant, & Goodale, 2009; Seashore, 1898). Logically, conceptual knowledge can be obtained only when cognitive faculties are sufficiently developed to understand new experiences. Conceivably, a certain amount of manual dexterity is also required when forming an association between an object's weight and its features because manual dexterity is necessary for gauging weight (Jones, 1986). Manual skills emerge during early infancy and continue to develop into adolescence (Mathiowetz, Federman, & Wiemer, 1985). For preschool children, manual dexterity improves as they learn to cut with scissors and to trace and copy lines and shapes. In primary school, children continue to improve their manual skills with handwriting and the use of computers. More experiences are acquired as these skills develop. Children's repertoire of priors consequently becomes richer and more fine-tuned.

Thus, in theory, previous experiences with objects can only begin to influence how children perceive their weight when cognitive and motor skills reach certain levels of proficiency. These are not new ideas. Piaget (1969, 1999) reasoned that children must first understand size and weight, be able to integrate the two collectively, and know that larger objects typically weigh more than smaller ones

**Table 1**
Summary of previous studies examining the early developmental profile of the size–weight illusion.

| Reference | Age tested | Method | Results |
|---|---|---|---|
| Gilbert, J. A. (1894). Researches on the mental and physical development of school-children. *Studies From the Yale Psychological Laboratory, 2,* 40–100 | 6–17 years | *Matching method:* Two standard blocks and 14 comparison blocks were used. Both standards weighed the same, but one was larger than the other. The comparison stimuli had the same size but had a different weight. The participants needed to pick which comparison stimulus weighed the same as the standard. The procedures were done for each of the two standards | Differences in perceived weight between the two standard stimuli increased from 6 to 9 years of age. These differences decreased after 9 years of age. The authors also showed how variability in the data is highest at 6 years of age and decreased until 9 years of age, where it then stabilized |
| Robinson, H. B. (1964). An experimental examination of the size–weight illusion in young children. *Child Development, 35,* 91–107 | 2–10 years | *Method of constant stimuli:* The study consisted of two parts. *Part 1:* The children underwent a training phase in which they learned to indicate which of two different objects of the same size weighed the most. The weight difference was always the same. After reaching a learning criterion of 19 of 20 correct trials in two consecutive sessions, the children then went on to the next part. *Part 2:* The children were given two objects that differed in both size and weight. The experiment was designed to determine how much heavier the larger object needed to be before it was perceived as heavier than the smaller one in 10-g increments | All children tested experienced the size–weight illusion. Frequency of the illusion was unrelated to age, but its magnitude was greatest in the younger children and decreased with age |
| Pick, H. L., & Pick, A. D. (1967). A developmental and analytic study of the size–weight illusion. *Journal of Experimental Child Psychology, 5,* 362–371 | 6–16 years + adults | *Method of constant stimuli:* The participants were provided with a small bottle and a large bottle. The weight difference between the two bottles varied, with the larger one weighing either the same or heavier in 10-g increments. The participants needed to indicate which of the two was heaviest. The experiment was designed to determine how much heavier the larger bottle needed to be before it was perceived as heavier than the smaller one. This was carried out under three conditions: haptics + vision, haptic only (the participants were blindfolded), and vision only (the participants lifted the bottles with strings) | Age-related changes in illusion strength depended on the condition. No changes were observed in the haptics + vision condition. Illusion strength increased with age in the haptics-only condition but decreased with age in the vision-only condition. The authors also noted that the uncertainty in the participants' judgments decreased with age across the different conditions |
| Flournoy, T. (1894). De l'influence de la perception visuelle des corps sur leur poids objects. *L'Année psychologique, 1,* 198–208 | 6–12 years + adults | *Rank-ordering method:* The participants were presented with a series of household objects ranging in size from a small metallic case to a wooden cigar box. All objects weighed the same. The participants were asked to rank-order the objects' apparent weights | All children aged 6 to 12 years rank-ordered the objects in a manner similar to the adults. The largest object felt the lightest, and the smallest object felt the heaviest |
| Dresslar, F. B. (1894). Studies in the psychology of touch. *American Journal of* | 7–14 years | *Rank-ordering and magnitude estimation methods:* Task objects consisted of cylinders with a constant | The majority of children (92 of 173) rank-ordered the cylinders precisely from largest to |

(*continued on next page*)

**Table 1** (*continued*)

| Reference | Age tested | Method | Results |
|---|---|---|---|
| *Psychology, 6,* 313–368 | | diameter ranging in length. All objects weighed the same. The children were asked to arrange the objects in order of their apparent weight. After this was done, the children needed to indicate in relative terms (e.g., "twice as much") how much the object they believed was the heaviest compared with the one they believed was the lightest. The children were also put into one of three groups according to their academic performance: above average, average, or below average. These assignments were made by their teachers. Gender and age were also compared | smallest. The other children had a few variations but were showing somewhat similar patterns of rank-ordering. Relative judgments between the apparent lightest cylinder and the apparent heaviest cylinder ranged from 1.3 to 10 times as much. Children in the above-average group, as well as boys, tended to rank-order the objects more consistently. No age differences were found comparing the oldest with the youngest children |
| Philippe, J., & Clavière, J. (1895). Sur une illusion musculaire. *Revue Philosophique de la France et de l'Étranger, 40,* 672–682[a] | 3–18 years | *Rank-ordering method:* Children aged 3 to 7 years were presented with a series of cylindrical objects that differed in size but weighed the same. The task was to rank-order the objects in terms of their perceived weight. If the children indicated the largest one to be the lightest, then the illusion was deemed to be present | Two thirds of the children aged 3 to 7 years did not experience the illusion |
| Rey, A. (1930). Contribution à l'étude de poids chez les anormaux. *Archives de psychologie, 22,* 285–287[b] | 5–14 years | *Method of constant stimuli:* The children were asked which of two objects differing in size but not weight would be the heavier one. They then lifted each one using rings attached to them and indicated which one was heavier. The authors then added more weight to the object that felt lighter and repeated the procedure until the child began to say that the other object was the heavier one | The authors compared performance in children aged 5 to 6 years with children aged 7 to 14 years. Both age groups experienced the illusion with the same frequency, but the magnitude of the illusion was greater in the older group |
| Kloos, H., & Amazeen, E. L. (2002). Perceiving heaviness by dynamic touch: An investigation of the size–weight illusion in preschoolers. *British Journal of Developmental Psychology, 20,* 171–183 | 3–5 years | *Method of adjustment:* A total of 18 preschool children (age range: 3 years 1 month to 5 years 4 months) held objects by a handle without seeing them. The objects differed in mass and size. To provide an estimate of perceived weight, the preschoolers played the "mouse game". They were shown a picture of a mouse holding a block of cheese at the bottom of a steep hill while they held the objects representing the cheese in one hand. With the other hand, the child pointed to a position on the hill to indicate where the mouse might take a break if it had to walk up the hill | The authors demonstrated that preschool children perceive the size–weight illusion from holding the objects via a handle and not seeing them |

[a] Also included blind children. Roughly two thirds of the blind children aged 3–12 years did not experience the illusion, which is on par with the sighted children aged 3–7 years, whereas 95% of the older blind children aged 13–18 years perceived the illusion.

[b] Also included atypically developing children aged 7–14 years. The results showed that these children experienced the illusion on par with the typically developing group aged 5 and 6 years.

before children can experience the size–weight illusion. In line with this thinking, we hypothesized that illusion strength increases as children develop their manual and cognitive skills. Our findings demonstrate that the size–weight illusion increases in strength as children grow older and that the development of nonverbal cognition, but not motor or language skills, explains variability in the development of the size–weight illusion.

## Method

### *Overview*

Children from primary schools from a regional center (Bendigo) and a major city (Melbourne) in Victoria, Australia, completed tasks that assessed susceptibility to the size–weight illusion, manual skills, receptive language, and abstract reasoning. Task order was counterbalanced across participants to reduce practice or carryover effects. Testing occurred over two or three sessions, lasting no more than 30 min each. All procedures were approved by the La Trobe University human ethics committee, the Department of Education and Training of Victoria, Catholic Education Melbourne, and the local schools. Legal guardians of all participants provided informed written consent and confirmed that their children were never diagnosed with a psychological, psychiatric, neurological, or neurodevelopmental disorder by a questionnaire prior to testing. Testing was administered at the children's school in cooperation with classroom teachers to minimize disruption.

### *Participants*

A total of 85 typically developing children participated in the study. Of these participants, 2 boys and 5 girls were excluded from the analyses based on having a standard score lower than 70 on either the Peabody Picture Vocabulary Test or the Raven's Progressive Matrices (see below for more information about these tests), which is suggestive of an intellectual disability. An additional 3 boys and 3 girls were excluded from the analyses based on having an illusion strength index (see below on how this was calculated) exceeding ±2 standard deviations. Removing these participants in this manner helped to systematically and objectively remove noise from the data that would otherwise reflect various aspects of misunderstanding, noncompliance, or atypical development. This resulted in a final sample size of 72 participants (39 boys; 64 right-handers; mean age = 8.9 years, range = 5.6–12.5). Age was determined from the date of birth provided by parents on a form filled out prior to the children's participation, which was confirmed by the children during testing.

### *Tasks and procedures*

#### *Size–weight illusion*

The task objects consisted of four plastic spheres created with a three-dimensional printer. We adjusted the weight of each plastic sphere by placing a ballast of lead pellets inside it. The ballast was held in place with compact foam to ensure that the center of mass corresponded to the sphere's center. There were two pairs of objects (Fig. 1). The first pair consisted of two spheres weighing 120 g. One sphere had a diameter of 6 cm (volume = 113.10 $cm^3$, density = 1.06 $g/cm^3$) and was painted yellow (luminance = 62.2 $cd/m^2$), whereas the other one had a diameter of 9 cm (volume = 381.69 $cm^3$, density = 0.31 $g/cm^3$) and was painted red (luminance = 8.2 $cd/m^2$). The second pair consisted of two spheres weighing 405 g. One sphere had a diameter of 6 cm (volume = 113.10 $cm^3$, density = 3.58 $g/cm^3$) and was painted blue (luminance = 7.6 $cd/m^2$), whereas the other one had a diameter of 9 cm (volume = 381.69 $cm^3$, density = 1.06 $g/cm^3$) and was painted green (luminance = 7.3 $cd/m^2$). We also constructed a sliding measurement apparatus to allow participants to give a nonverbal magnitude estimate of the weight for each sphere (Fig. 1). This apparatus consisted of four sliders that were 30 cm in length. Each one was painted a different color corresponding to one of the spheres.

**Fig. 1.** The size–weight illusion apparatus. Two pairs of objects were presented to the participants one pair at a time. One pair consisted of a small yellow sphere and a large red sphere. Both weighed 120 g. The other pair consisted of a small blue sphere and a large green sphere. Both weighed 405 g. The participants held one object in one hand and the other object in a different hand. After weighing the objects, the participants then adjusted the corresponding slider to indicate how heavy each object was relative to the other, with the left side of the slider corresponding to light and the right side of the slider corresponding to heavy.

Seated opposite the participant at a table, the experimenter gave the following instructions: "I'm going to hand you these colored balls. I want you to tell me how heavy they are using the sliding rings in front of you. If this side [indicating the participant's left] means light and this side [indicating the participant's right] means heavy, slide the ring and leave it wherever you think it should go."

These instructions were elaborated if needed, and the experimenter ensured that the participant understood the instructions before proceeding. The participant was then asked to extend his or her hands facing upward with the elbows elevated above the table. The experimenter then placed one object from one of the two pairs in each hand for the participant to weigh (e.g., the yellow sphere in the left hand and the red sphere in the right hand). The participant was given as much time as needed to assess the objects' weights. Afterward, the participant was asked to use the color-coded sliders to indicate the perceived weight of each sphere, and the experimenter recorded the final measurements in millimeters. This was repeated for the next pair of objects (e.g., the blue sphere in the left hand and the green sphere in the right hand). These procedures were repeated with the objects placed in the opposite hands. The average position of the slider in millimeters for the two presentations of each object was taken as a measurement of its apparent weight. The order of presentation was counterbalanced across participants.

*Purdue pegboard test*

We also administered the Purdue Pegboard Test to assess manual dexterity (Tiffin & Asher, 1948). The test consisted of the participant manually inserting pegs into columns of small holes one at a time for 30 s with the participant's preferred hand. The total number of pegs placed inside a hole was taken as the score. Hand preference was determined by the child's self-report when asked whether he or she was right- or left-handed.

*Peabody Picture Vocabulary Test*

We measured receptive language with the Peabody Picture Vocabulary Test–Fourth Edition (PPVT; Dunn & Dunn, 2007). The child was presented with a series of pages containing four pictures and was asked to indicate which picture he or she thought best described the item word spoken by the administrator. The complete test consists of 228 trials. However, the number of trials administered to each child was determined by basal and ceiling rules in accordance with instructions from the test manual

(Dunn & Dunn, 2007). Raw scores reported in our study reflect the total number of correct trials plus credit for all trials not administered below the basal start point. Standard scores were also calculated based on normative data obtained from the test manual to characterize verbal intelligence in our overall sample and across our age groups.

*Raven's progressive matrices*

The Raven's Progressive Matrices (RPM; Raven, Raven, & Court, 2003) is a nonverbal measure of general cognitive ability. The child was provided with a booklet of different patterns with a piece missing in each pattern. For each item, the child was required to select which piece from an array of different options best matched the missing piece. We administered two versions of the RPM, each designed for a different age group. The colored version was administered to children aged 5–9 years and consisted of 36 trials, whereas the standard version was used for the older participants and consisted of 60 trials. Raw scores reflected the number of trials that the participant got correct. For the purposes of data analysis and reporting, all raw scores on the colored form were converted to the scale of the standard form using the conversion table provided in the RPM manual (Raven et al., 2003). Standard scores were also calculated based on normative data obtained from the test manual to characterize nonverbal intelligence in our overall sample and across our age groups.

*Statistical analyses*

We carried out statistical analyses using GraphPad Prism–Version 7 (GraphPad, La Jolla, CA, USA), JASP software–Version 0.8 (University of Amsterdam, Amsterdam, Netherlands), and SPSS–Version 23 (IBM, Armonk, NY, USA). Before proceeding to any statistics, we first calculated a score of illusion strength from the magnitude estimates in the following manner: [(perceived weight of the small object – perceived weight of the large object)/(perceived weight of the small object + perceived weight of the large object)]. An overall score of illusion strength for the two pairs of objects was calculated by taking their average.[1] This method of normalizing is used in many illusion studies (Chouinard, Noulty, Sperandio, & Landry, 2013; Chouinard, Peel, & Landry, 2017; Chouinard, Royals, Sperandio, & Landry, 2018; Chouinard, Unwin, Landry, & Sperandio, 2016; Schwarzkopf, Song, & Rees, 2011; Sherman & Chouinard, 2016) and allows for meaningful comparisons across studies.

We used two approaches to analyze the data. The first consisted of comparing means between different age groups. To this end, we first divided our participants into quartile age groups. The quartile split ensured that a sufficient number of participants ($n = 18$) were evenly distributed in each group. Age Group 1 ranged from 5.6 to 6.9 years, Age Group 2 ranged from 7.0 to 9.3 years, Age Group 3 ranged from 9.3 to 10.8 years, and Age Group 4 ranged from 10.8 to 12.5 years. We then performed an analysis of variance (ANOVA) with age as a between-subject factor on illusion strength and the raw scores on the Purdue Pegboard Test, PPVT, and RPM. Raw scores were chosen for the three latter tests so that we could chart how these skills develop with age. Post hoc pairwise comparisons using Tukey's honest significance difference (HSD) tests (Tukey, 1949), which corrected for multiple comparisons, were performed to test for differences between the various age groups when a main effect of age was obtained. We also performed one-sample $t$ tests to determine whether or not the illusion strength index in each age group differed from zero, which provides an indication as to when the illusion might emerge during development. To account for multiple comparisons against zero, we applied a Bonferroni correction to the reported $p$ values (i.e., $p_{corr} = p_{uncorr} \times$ number of tests comparing differences against zero).

The second approach consisted of performing bivariate correlations and a forward selection multiple regression. Specifically, a correlation matrix of Pearson $r$ coefficients was produced to assess for associations among age, illusion strength, the Purdue Pegboard Test scores, the raw PPVT scores, and the raw RPM scores. Again, raw scores were chosen on the three latter tests so that we could chart how these skills develop with age. To account for multiple correlations, we applied a Bonferroni

[1] Although the illusion strength index for the light and heavy pairs were aggregated for the purposes of this article, this index was actually higher for the lighter pair ($M = 0.23$, $SD = 0.27$) compared with the heavier pair ($M = 0.11$, $SD = 0.16$) as determined by a paired-samples $t$ test, $t(71) = 3.60$, $p < .001$.

correction to the reported $p$ values (i.e.. $p_{corr} = p_{uncorr} \times$ number of bivariate correlations performed). The model for the forward selection multiple regression began with an empty equation. Age, the Purdue Pegboard Test scores, the raw PPVT scores, and the raw RPM scores were added to the model one at a time beginning with the one with the highest correlation with illusion strength until the model could no longer be improved. Given that we had no prior predictions on how to model the regression, this type of regression was favored over others for its exploratory and unbiased nature for determining which predictors should be entered into the model and are most important for explaining illusion strength. Participants with missing values were excluded from the analysis. The resulting standardized beta coefficients ($\beta$) and corrected $p$ values arising from the multiple regression analysis are reported.

All reported $p$ values were corrected for multiple comparisons based on an alpha level of .05 unless specified otherwise.

## Results

### *Standard scores on the PPVT and RPM*

Table 2 provides demographic information as well as standard scores on the PPVT and RPM for each age group. The standard scores on the PPVT for participants included in the analyses had a mean of 104.3, a standard deviation of 14.2, and a range of 70 to 136. A PPVT score was not obtained for 1 participant. There were no differences in PPVT standard scores among age groups, $F(3, 67) = 2.16$, $p = .101$, $\eta_p^2 = .09$, which suggests that verbal intelligence was matched among them. The standard scores on the RPM for participants included in the analyses had a mean of 113.1, a standard deviation of 15.4, and a range of 74 to 135. An RPM score was not obtained for 1 participant (a different participant than the one with a missing PPVT score). ANOVA revealed a main effect in RPM standard scores among age groups, $F(3, 67) = 3.27$, $p = .026$, $\eta_p^2 = .13$, which was driven by a lower score in the 10.8- to 12.5-year-olds (Age Group 4) relative to the 7.0- to 9.3-year-olds (Age Group 2) ($p = .027$). No other pairwise comparisons were significant ($p \geq .095$). It would appear from these data that nonverbal intelligence may have dropped in the oldest age group.

### *Comparison of age groups on illusion strength as well as on motor and cognitive abilities*

In summary, ANOVA demonstrated increases in illusion strength, manual dexterity, receptive language, and abstract reasoning with increasing age.

There was a main effect of age for illusion strength, $F(3, 68) = 3.79$, $p = .014$, $\eta_p^2 = .14$ (Fig. 2A). This was driven by the 10.8- to 12.5-year-olds (Age Group 4) experiencing a stronger illusion than the 5.6- to 6.9-year-olds (Age Group 1) ($p = .020$). No other pairwise comparisons were significant (all $ps \geq .087$). One-sample $t$ tests revealed that illusion strength was different from zero in the 7.0- to 12.5-year-olds (Age Groups 2–4) (all $ps \leq .002$) but not in the 5.6- to 6.9-year-olds (Age Group 1)

**Table 2**
Demographics and standard scores for PPVT and RPM for each age group.

| Age group | *n* | Gender | Handedness | Age | | PPVT (standard scores) | | RPM (standard scores) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | *M* | *SD* | *M* | *SD* | *M* | *SD* |
| 1 | 18 | 12 M, 6 F | 14 R, 4 L | 6.41 | 0.40 | 109.71[a] | 12.51[a] | 115.28 | 10.06 |
| 2 | 18 | 9 M, 9 F | 16 R, 2 L | 8.16 | 0.81 | 106.44 | 15.33 | 117.83 | 15.44 |
| 3 | 18 | 10 M, 8 F | 17 R, 1 L | 9.89 | 0.41 | 98.39 | 13.01 | 115.28 | 19.38 |
| 4 | 18 | 8 M, 10 F | 17 R, 1 L | 11.53 | 0.46 | 103.00 | 14.27 | 103.53[a] | 12.18[a] |

*Note.* M, male; F, female; R, right; L, left. Age Group 1 ranged from 5.6 to 6.9 years, Age Group 2 ranged from 7.0 to 9.3 years, Age Group 3 ranged from 9.3 to 10.8 years, and Age Group 4 ranged from 10.8 to 12.5 years.
[a] A child was missing in the calculation because the test was not performed on him or her.

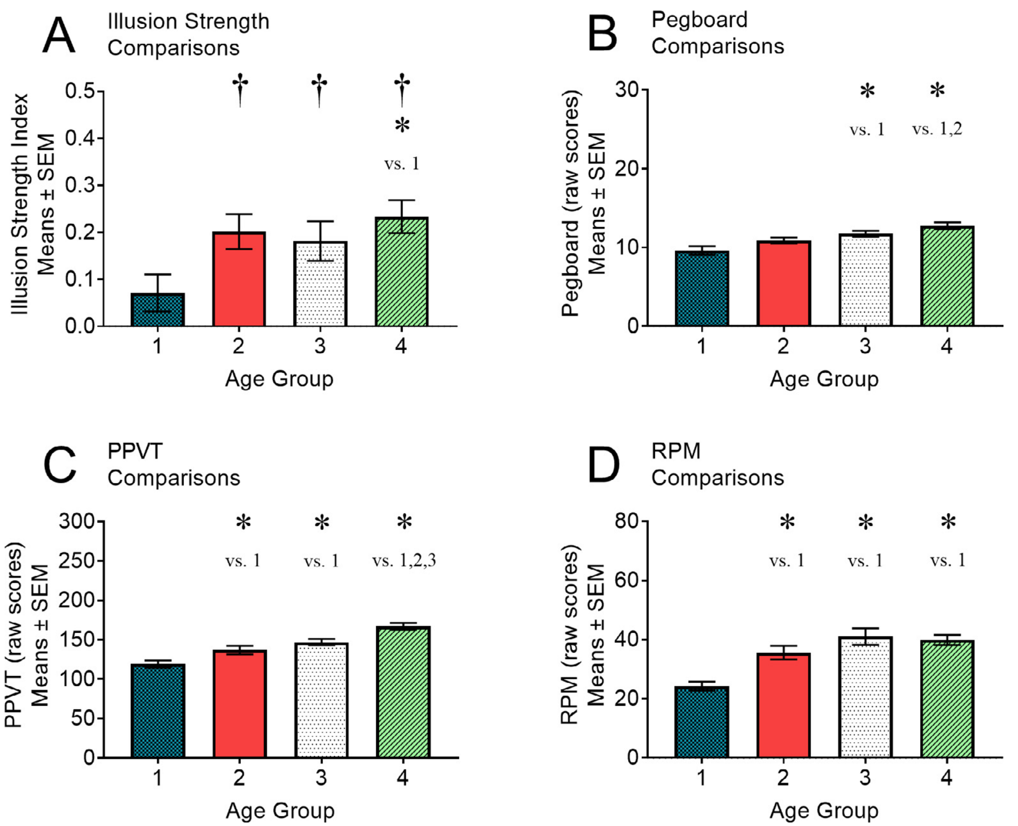


**Fig. 2.** Comparing means across age groups. The different columns represent the means and standard errors around the means (SEMs) for Age Group 1 (5.6–6.9 years; blue [first] columns), Age Group 2 (7.0–9.3 years; red [second] columns), Age Group 3 (9.3–10.8 years; white [third] columns), and Age Group 4 (10.8–12.5 years; green [fourth] columns) for illusion strength (A), the Purdue Pegboard Test (B), raw scores on the PPVT (C), and raw scores on the RPM (D). Daggers (†) denote significant illusion strength against zero after correcting for multiple comparisons using the Bonferroni method ($p_{corr} < .05$), whereas asterisks (*) denote significant differences between conditions after correcting for multiple comparisons using Tukey's HSD method ($p_{corr} < .05$). All measures increased with age. Illusion strength was significantly different from zero in Age Groups 2 to 4 but not in Age Group 1. The descriptive statistics for these charts are presented in Table 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

($p = .354$). In short, illusion strength increased with age, only emerging significant by 7 years. Table 3 provides descriptive statistics and effect sizes for the different age groups as well as for the overall sample.

There was a main effect of age for manual dexterity as measured by the Purdue Pegboard Test, $F(3, 68) = 9.42$, $p < .001$, $\eta_p^2 = .29$ (Fig. 2B). Pairwise comparisons revealed better performance in the 9.3- to 12.5-year-olds (Age Groups 3 and 4) relative to the 5.6- to 6.9-year-olds (Age Group 1) (both $ps \leq .006$) and the 10.8- to 12.5-year-olds (Age Group 4) compared with the 7.0- to 9.3-year-olds (Age Group 2) ($p = .016$). No other pairwise comparisons were significant (all $ps \geq .173$). Thus, manual dexterity increased with age.

There was also a main effect of age on the raw scores for the PPVT, $F(3, 67) = 18.57$, $p < .001$, $\eta_p^2 = .45$ (Fig. 2C). This effect was explained by increases in scores in the 7.0- to 12.5-year-olds (Age Groups 2–4) compared with the 5.6- to 6.9-year-olds (Age Group 1) (all $ps \leq .043$) and for the 10.8- to 12.5-year-olds (Age Group 4) compared with the 7.0- to 10.8-year-olds (Age Groups 2 and 3) (both $ps \leq .015$). No other pairwise comparisons were significant ($p = .416$). Similar to manual dexterity, receptive language increased with age.

**Table 3**
Descriptive statistics for the Purdue Pegboard Test, PPVT (raw scores), RPM (raw scores), and illusion strength.

| Age group | Purdue Pegboard Test | | PPVT (raw scores) | | RPM (raw scores) | | Illusion strength | |
|---|---|---|---|---|---|---|---|---|
| | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* |
| 1 | 9.61 | 2.25 | 119.10 | 18.48 | 24.22 | 6.40 | 0.07 | 0.17 |
| 2 | 10.89 | 1.57 | 136.80 | 22.75 | 35.56 | 9.76 | 0.20 | 0.16 |
| 3 | 11.72 | 1.67 | 146.80 | 17.00 | 40.94 | 11.96 | 0.18 | 0.18 |
| 4 | 12.78 | 1.83 | 166.90 | 18.83 | 39.82 | 7.23 | 0.23 | 0.15 |

*Note.* Age Group 1 ranged from 5.6 to 6.9 years, Age Group 2 ranged from 7.0 to 9.3 years, Age Group 3 ranged from 9.3 to 10.8 years, and Age Group 4 ranged from 10.8 to 12.5 years.

Likewise, the raw scores for the RPM demonstrated a main effect of age, $F(3, 67) = 12.51$, $p < .001$, $\eta^2_p = .36$ (Fig. 2D). Pairwise comparisons revealed that the effect was driven by higher scores in the 7.0- to 12.5-year-olds (Age Groups 2–4) compared with the 5.6- to 6.9-year-olds (Age Group 1) (all $ps \leq .002$). No other pairwise comparisons were significant (all $ps \geq .296$). Thus, abstract reasoning increased with age.

*Bivariate correlations and multiple regression*

Table 4 provides a correlation matrix of Pearson *r* coefficients among chronological age, manual dexterity, receptive language, abstract reasoning, and illusion strength. Age, manual dexterity, receptive language, and abstract reasoning were highly intercorrelated with each other (all $rs \geq .44$, $p \leq .001$). Illusion strength increased as a function of age, $r(70) = .34$, $p = .034$ (Fig. 3A) and abilities in abstract reasoning, $r(69) = .33$, $p = .046$ (Fig. 3B). In contrast, illusion strength was not correlated with either manual dexterity, $r(70) = .13$, $p = 1.00$, or abilities in receptive language, $r(70) = .27$, $p = .217$.

To establish the importance of these different variables in predicting illusion strength, a forward selection approach was used in a multiple regression. In this analysis, age, manual dexterity, receptive language, and abstract reasoning were selected as predictors for entry. The first step, which included abstract reasoning as the predictor, was significant, $F(1, 68) = 7.72$, $p = .007$, and explained 10.2% of the variance in illusion strength. The standardized beta coefficient for abstract reasoning was significant ($\beta = 0.32$, $p = .007$). The forward selection analysis did not add age, manual dexterity, or receptive language as additional predictors, indicating that none of them significantly explained more variance in illusion strength beyond what was already shared with abstract reasoning.

## Discussion

We sought to characterize the development of the size–weight illusion in typically developing children and determine the contribution of manual dexterity, receptive language, and abstract reasoning underlying these changes. As hypothesized, the strength of the illusion increased with age. Manual

**Table 4**
Correlation matrix.

| | Purdue Pegboard Test | | PPVT (raw scores) | | RPM (raw scores) | | Illusion strength | |
|---|---|---|---|---|---|---|---|---|
| | *r* | *p* | *r* | *p* | *r* | *p* | *r* | *p* |
| Age | .57* | <.001 | .70* | <.001 | .56* | <.001 | .34* | .037 |
| Purdue Pegboard Test | | | .58* | <.001 | .45* | .001 | .13 | 1.000 |
| PPVT (raw scores) | | | | | .44* | .001 | .27 | .217 |
| RPM (raw scores) | | | | | | | .33* | .046 |

*Note.* All *p* values reported in this table were corrected for multiple correlations using the Bonferroni method. Asterisks (*) denote significance after corrections for multiple correlations were made using this method ($p < .05$).

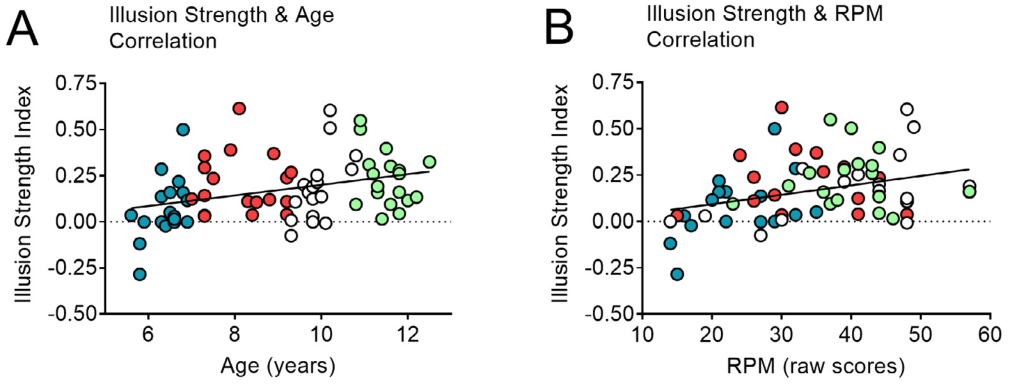


**Fig. 3.** Bivariate correlations. The graphs illustrate two bivariate correlations that were significant after correcting for multiple correlations using the Bonferroni method ($p_{corr} < .05$). The correlation on the left shows how illusion strength increased with age (A), whereas the correlation on the right shows how illusion strength increased with raw scores on the RPM (B). The different colored circles denote the different age groups. Age Group 1 (5.6–6.9 years) is represented by blue circles, Age Group 2 (7.0–9.3 years) is represented by red circles, Age Group 3 (9.3–10.8 years) is represented by white circles, and Age Group 4 (10.8–12.5 years) is represented by green circles. This color coding is the same as the one used in Fig. 2. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

dexterity and receptive language did not correlate with illusion strength. Conversely, illusion strength and abstract reasoning were tightly coupled. The multiple regression revealed that age, manual dexterity, and receptive language did not contribute significantly more than the 10.2% of variance in illusion strength already explained by abstract reasoning. Taken together, the effects of age on the size–weight illusion appear to be explained by nonverbal cognition. In the ensuing discussion, we outline how this study contributes to our understanding of the size–weight illusion and how our findings should be interpreted within the context of previous research that has characterized the development of the size–weight illusion in children.

### *Factors contributing to the size–weight illusion*

Illusion strength increased with abstract reasoning skills as measured by the raw scores on the RPM. Conversely, illusion strength did not change with manual dexterity as measured with the Purdue Pegboard Test, nor did it change with language skills as measured with the PPVT. These findings provide clues about the mechanisms underlying the size–weight illusion. In particular, our findings underscore the importance of cognitive processing and are in line with Piaget's ideas that certain cognitive faculties need to be developed before a child can experience the size–weight illusion to its fullest (Piaget, 1969, 1999). Namely, the illusion increases in strength as reasoning skills also increase. Reasoning skills are conceivably important for conceptually understanding size, weight, and how the two are distinct and typically associated with each other (Piaget, 1969, 1999). Future research can verify this by testing children's understanding of size and weight and correlating this with illusion strength. Previous research demonstrates that children begin to conceptually understand size at 3 years of age (Smith, 1984) and weight at 5 years of age (Cheeseman, McDonough, & Clarke, 2011). If Piaget's (1969, 1999) theory is correct, then forming associations between size and weight must proceed these stages. Only then can associations be reinforced to exert an influence on the illusion.

In line with this thinking, the ordinary rectangle is perceived as an illusion in adults (Ganel & Goodale, 2003) but not in children aged 4 and 5 years (Hadad, 2018). In adults, the apparent width of the ordinary rectangle is contingent on its length. Longer rectangles are perceived as more narrow than shorter rectangles with the same width. Hadad (2018) examined the developmental profile of this illusion in children aged 4–8 years. The 4- and 5-year-olds could not see the illusion, whereas the 7- and 8-year-olds could. From these results, Hadad concluded that children can begin to perceive the ordinary rectangle as an illusion only after they gain the ability to process and combine width and length information.

The lack of correlation between the PPVT and illusion strength is also revealing for two reasons. First, the PPVT measures receptive vocabulary, which is the ability to comprehend language. Hence, comprehension of task instructions cannot explain illusion strength in the overall sample. Second, the lack of a correlation suggests that the mechanisms underlying the size–weight illusion do not depend on language processing. This is not a particularly contentious finding. We are unaware of any size–weight illusion explanation that is centered on language processing.

The lack of correlation between manual dexterity and illusion strength is also informative because it sheds light on the merits of sensorimotor explanations for the size–weight illusion (Dijker, 2014). It is conceivable that age-related improvements in manual dexterity are accompanied by more accurate and precise somatosensory information regarding the size and weight of objects. Yet our results reveal that more refined motor skills, and the possibility of more veridical size and weight information obtained by somatosensory channels, did not translate into a stronger illusion in the overall sample, nor did it explain age-related changes in illusion strength. These findings add to the growing evidence demonstrating a dissociation between how one handles objects motorically and their perceived weight (Buckingham & Goodale, 2010a, 2010b; Buckingham, Ranger, & Goodale, 2012; Chouinard et al., 2009; Flanagan & Beltzner, 2000; Grandy & Westwood, 2006). Nonetheless, sensorimotor explanations should not be discarded entirely (Saccone & Chouinard, 2019). The development of rudimentary motor abilities is likely to be an important precursor to the development of the size–weight illusion. Only by manually handling objects can one reinforce associations between size and weight, which can then strengthen the illusion. Further investigation in younger children on the size–weight illusion would be needed to test this explanation.

*Earlier research on the development of the size–weight illusion*

The examination of the size–weight illusion in children emerged during the 1890s (Dresslar, 1894; Flournoy, 1894; Gilbert, 1894; Philippe & Clavière, 1895). This pioneering work seemed to be geared toward determining whether the size–weight illusion first described by Charpentier (1886, 1891) was innate or acquired and develops with age, and also whether the task could be used as an index of intelligence that could differentiate typically developing children from delayed or disabled children. These earlier studies used either a matching paradigm (i.e., the children needed to indicate which stimulus from an array of comparison stimuli weighed the same as the standard stimulus) or a rank-ordering paradigm (i.e., the children were given an array of stimuli and needed to order them according to their apparent weight) (Table 1).

The results from these early studies converge well with our findings in that they also demonstrate that the size–weight illusion is weaker in younger children. Philippe and Clavière (1895) tested children aged 3–7 years and found that the majority of them did not experience the illusion. The other studies tested older children from 6 years of age and found that the illusion was present in either all or the vast majority of the participants (Dresslar, 1894; Flournoy, 1894; Gilbert, 1894). Using a method of constant stimuli paradigm, Rey (1930) later confirmed these trends, with children aged 5 and 6 years being less susceptible to the illusion than children aged 7–14 years.

Two other studies later emerged during the 1960s (Pick & Pick, 1967; Robinson, 1964). Neither converges with the earlier findings and with the findings obtained in our investigation. The first of these was by Robinson (1964). The study was influenced by behaviorism (Skinner, 1953), which featured prominently in psychological research at the time. Being concerned that the younger participants might not understand the concept of weight, Robinson (1964) introduced an intensive reinforcement training phase before testing them on the illusion. Namely, children as young as 2 years were trained by reinforcement to indicate which of two objects differing in mass was heaviest. The participants received a food reward whenever they got the answer correct. The introduction of this kind of reinforcement training likely influenced the outcome of the testing phase in which the author examined the magnitude of the size–weight illusion using a method of constant stimuli paradigm. The youngest children required more reinforcement training to reach the learning criterion than the older children, which could have magnified their subjective reports during the testing phase to please the experimenter. Perhaps for this reason, contrary to all earlier work, as well as the current investigation, Robinson demonstrated that the strength of the illusion decreased with age.

The second study was by Pick and Pick (1967). The authors performed a series of experiments to characterize how the strength of the illusion increased with age in children aged 6–16 years when haptic, vision, or both types of cues specifying object size were available to the participants. The participants hefted the objects wearing a blindfold in the haptic-only condition, lifted the objects using strings in the visual-only condition, and hefted objects without a blindfold in the haptic and visual condition. The study yielded some interesting dissociations. The authors demonstrated that illusion strength (a) was the same for all ages when both haptic information and visual information were provided, (b) increased with age when only haptic information was provided, and (c) decreased with age when only visual information was provided. We view these results with some skepticism. It is unclear as to why the direction of change with age would depend on the sensory modality of available cues. Pick and Pick did not offer any explanation. In addition, this dissociation has not been described further since it was first reported by the authors more than 50 years ago. There is the possibility that the effect of age in the visual-only condition differed in its direction because of differences in the manner in which the participants lifted the objects as opposed to the manner in which object size was presented to them.

We know of only one other study of the size–weight illusion in children that was performed since the 1960s. This study was performed by Kloos and Amazeen (2002) in preschool children aged 3–5 years. The study's paradigm was simple (Table 1) and arguably more conducive to testing very young children than the paradigm used in our study. In short, the children were shown a picture of a mouse holding a block of cheese at the bottom of a steep hill while they held a task object representing the cheese in one hand. With the other hand, the children pointed to a position on the hill to indicate where the mouse might take a break if it needed to walk up the hill, which served as an index of the children's perceived weight of the object they were holding. Using this paradigm, the authors demonstrated that preschoolers perceive the size–weight illusion. The effects of age were not investigated given the small age range tested. Kloos and Amazeen could have perhaps also demonstrated increases in illusion strength had they included older children in their sample. Nonetheless, their results are important. They suggest that the size–weight illusion might not be completely acquired with experience but that the illusion is present from early development. Our study further reveals that the illusion is reinforced by cognitive development, which we speculate is required for the acquisition of priors and their influence on perception.

*Methodological considerations*

The study demonstrates that the size–weight illusion has a strong acquired component to it given that the age-related changes were linked to cognitive development. However, one should not consider the absence of an illusion in the youngest age group as evidence that the size–weight illusion is completely acquired. It may still have an innate element to it. After all, Kloos and Amazeen (2002) demonstrated that the illusion is present in children younger than those we tested. A simpler and perhaps more engaging task, like the one used by Kloos and Amazeen, could have increased this study's sensitivity for detecting size–weight illusion effects in younger children.

Another consideration is that the task objects had different colors and did not match in luminance (Fig. 1). We painted the spheres different colors to make them more interesting for the children and to help facilitate the matching of each one to a slider. Previous research has demonstrated that the luminance of objects can have a small effect on their perceived weight. Specifically, *lighter* objects feel heavier (De Camp, 1917; Walker, Francis, & Walker, 2010). This effect could have contributed to a stronger weight illusion in the red–yellow pair, which had a considerable luminance difference of 53.8 cd/m$^2$, than in the blue–green pair, which had a negligible luminance difference of 0.3 cd/m$^2$. Color can also influence the perceived size (Tedford, Bergquist, & Flynn, 1977; Walker et al., 2010) and weight (De Camp, 1917; Walker et al., 2010) of objects. However, these effects disappear when luminance is matched between objects (Walker et al., 2010), which is perhaps why color does not always influence the perceived weight of objects (Buckingham, Goodale, White, & Westwood, 2016; De Camp, 1917). Although we cannot discard the possibility that the luminance differences between the red and yellow spheres contributed to the weight illusion in this pair of objects, the effects of color (driven by luminance differences) on perceived weight is generally regarded as much weaker than those exerted by size (Buckingham, 2014; Saccone & Chouinard, 2019; Walker et al., 2010).

In addition, one should consider that the Purdue Pegboard Test measures only fine finger dexterity and does not measure other aspects of manual performance such as applied forces and gross movements. The Purdue Pegboard Test was chosen over other tests because it is quick to administer and continues to be the most widely used clinical test for assessing manual dexterity after 70 years of existence (Yancosek & Howell, 2009). Its reliability and validity are excellent and are understood better than any other dexterity assessment (Yancosek & Howell, 2009). Future work could examine the application of fingertip forces, as is the case in many studies of the size–weight illusion in adults (Buckingham & Goodale, 2010a; Chouinard et al., 2009; Flanagan & Beltzner, 2000; Grandy & Westwood, 2006). To our knowledge, the recording of fingertip forces has never been performed in children experiencing the size–weight illusion.

*Closing remarks*

The current study provides a novel investigation into the development of the size–weight illusion in primary school-aged children by considering a number of factors not considered in previous studies. We conclude that the development of the illusion coincides with age-related changes in nonverbal cognition rather than motor or language skills. We argue that the findings add to the growing amount of evidence supporting expectancy-based theories of the illusion, which depend on being able to form and apply conceptual knowledge.

## Acknowledgments

This study was funded by a La Trobe University Building Healthy Communities Research Focus Area award to P.A.C., a Discovery Project grant to P.A.C. from the Australian Research Council (DP170103189), and a Discovery Early Career Researcher Award to D.R.H. from the Australian Research Council (DE160100042). We thank Anna Atkinson for helping us with recruitment of the participants. We also thank the State of Victoria's Department of Education and Training, Catholic Education Melbourne, Camp Hill Primary School (Bendigo), Big Hill Primary School (Big Hill), St. Francis Xavier Primary School (Montmorency), and St. Stephen's Catholic Primary School (Reservoir East) for allowing us to recruit and test their students.

## References

Binet, A. (1895). La mesure des illusions visuelle chez les enfants. *Revue Philosophique de la France et de l'Étranger, 40*, 11–25.

Brayanov, J. B., & Smith, M. A. (2010). Bayesian and "anti-Bayesian" biases in sensory integration for action and perception in the size–weight illusion. *Journal of Neurophysiology, 103*, 1518–1531.

Brosvic, G. M., Dihoff, R. E., & Fama, J. (2002). Age-related susceptibility to the Müller-Lyer and the horizontal–vertical illusions. *Perceptual and Motor Skills, 94*, 229–234.

Buckingham, G. (2014). Getting a grip on heaviness perception: A review of weight illusions and their probable causes. *Experimental Brain Research, 232*, 1623–1629.

Buckingham, G., Cant, J. S., & Goodale, M. A. (2009). Living in a material world: How visual cues to material properties affect the way that we lift objects and perceive their weight. *Journal of Neurophysiology, 102*, 3111–3118.

Buckingham, G., & Goodale, M. A. (2010a). The influence of competing perceptual and motor priors in the context of the size–weight illusion. *Experimental Brain Research, 205*, 283–288.

Buckingham, G., & Goodale, M. A. (2010b). Lifting without seeing: The role of vision in perceiving and acting upon the size weight illusion. *PLoS One, 5*(3), e9709.

Buckingham, G., Goodale, M. A., White, J. A., & Westwood, D. A. (2016). Equal-magnitude size–weight illusions experienced within and between object categories. *Journal of Vision, 16*(3), 25.

Buckingham, G., Ranger, N. S., & Goodale, M. A. (2012). Handedness, laterality and the size–weight illusion. *Cortex, 48*, 1342–1350.

Charpentier, A. (1886). Sur les sensations de poids (note présentée par M. D'Arsonval le 3 avril). *Comptes Rendus Hebdomadaires des Séances et Mémoires de la Société de Biologie, 38*, 169–170.

Charpentier, A. (1891). Analyse experimentale de quelques elements de la sensation de poids. *Archives de Physiologie Normale et Pahtologique, 3*, 122–135.

Cheeseman, J., McDonough, A., & Clarke, D. (2011). Investigating children's understanding of the measurement of mass. In J. Clark, B. Kissane, J. Mousley, T. Spencer, & S. Thornton (Eds.). *Mathematics: Traditions and [new] practices* (Vol. 1,

pp. 174–182). Adelaide, South Australia: Australian Association of Mathematics Teachers and Mathematics Education Research Group of Australasia.
Chouinard, P. A., Large, M. E., Chang, E. C., & Goodale, M. A. (2009). Dissociable neural mechanisms for determining the perceived heaviness of objects and the predicted weight of objects during lifting: An fMRI investigation of the size–weight illusion. *NeuroImage, 44*, 200–212.
Chouinard, P. A., Noulty, W. A., Sperandio, I., & Landry, O. (2013). Global processing during the Müller-Lyer illusion is distinctively affected by the degree of autistic traits in the typical population. *Experimental Brain Research, 230*, 219–231.
Chouinard, P. A., Peel, H. J., & Landry, O. (2017). Eye-tracking reveals that the strength of the vertical–horizontal illusion increases as the retinal image becomes more stable with fixation. *Frontiers in Human Neuroscience, 11*. https://doi.org/10.3389/fnhum.2017.00143.
Chouinard, P. A., Royals, K. A., Sperandio, I., & Landry, O. (2018). The Shepard illusion is reduced in children with an autism spectrum disorder because of perceptual rather than attentional mechanisms. *Frontiers in Psychology, 9*. https://doi.org/10.3389/fpsyg.2018.02452.
Chouinard, P. A., Unwin, K. L., Landry, O., & Sperandio, I. (2016). Susceptibility to optical illusions varies as a function of the autism-spectrum quotient but not in ways predicted by local–global biases. *Journal of Autism and Developmental Disorders, 46*, 2224–2239.
De Camp, J. E. (1917). The influence of color on apparent weight: A preliminary study. *Journal of Experimental Psychology, 2*, 347–370.
Dijker, A. J. (2014). The role of expectancies in the size–weight illusion: A review of theoretical and empirical arguments and a new explanation. *Psychonomic Bulletin & Review, 21*, 1404–1414.
Dresslar, F. B. (1894). Studies in the psychology of touch. *American Journal of Psychology, 6*, 313–368.
Duffy, S., Huttenlocher, J., & Crawford, L. E. (2006). Children use categories to maximize accuracy in estimation. *Developmental Science, 9*, 597–603.
Dunn, L. M., & Dunn, D. M. (2007). *Peabody Picture Vocabulary Test, fourth edition (PPVT-4)*. New York: Pearson Education.
Flanagan, J. R., & Beltzner, M. A. (2000). Independence of perceptual and sensorimotor predictions in the size–weight illusion. *Nature Neuroscience, 3*, 737–741.
Flournoy, T. (1894). De l'influence de la perception visuelle des corps sur leur poids objects. *L'Année psychologique, 1*, 198–208.
Frederickson, W. A., & Geurin, J. (1973). Age difference in perceptual judgment on the Mueller-Lyer illusion. *Perceptual and Motor Skills, 36*, 131–135.
Gandhi, T., Kalia, A., Ganesh, S., & Sinha, P. (2015). Immediate susceptibility to visual illusions after sight onset. *Current Biology, 25*, R358–R359.
Ganel, T., & Goodale, M. A. (2003). Visual control of action but not perception requires analytical processing of object shape. *Nature, 426*, 664–667.
Geisler, W. S., & Kersten, D. (2002). Illusions, perception and Bayes. *Nature Neuroscience, 5*, 508–510.
Gilbert, J. A. (1894). Researches on the mental and physical development of school-children. *Studies From the Yale Psychological Laboratory, 2*, 40–100.
Grandy, M. S., & Westwood, D. A. (2006). Opposite perceptual and sensorimotor responses to a size–weight illusion. *Journal of Neurophysiology, 95*, 3887–3892.
Gregory, R. L. (1980). Perceptions as hypotheses. *Philosophical Transactions of the Royal Society of London B: Biological Sciences, 290*, 181–197.
Hadad, B. S. (2018). Developmental trends in susceptibility to perceptual illusions: Not all illusions are created equal. *Attention, Perception, & Psychophysics, 80*, 1619–1628.
Hanley, C., & Zerbolio, D. J. (1965). Developmental changes in five illusions measured by the up-and-down method. *Child Development, 36*, 437–452.
Harshfield, S. P., & DeHardt, D. C. (1970). Weight judgment as a function of apparent density of objects. *Psychonomic Science, 20*, 365–366.
Helmholtz, H. V. (1867). *Handbuch der physiologischen Optik*. Leipzig, Germany: Leopold Voss.
Jones, L. A. (1986). Perception of force and weight: Theory and research. *Psychological Bulletin, 100*, 29–42.
Kloos, H., & Amazeen, E. L. (2002). Perceiving heaviness by dynamic touch: An investigation of the size–weight illusion in preschoolers. *British Journal of Developmental Psychology, 20*, 171–183.
Mathiowetz, V., Federman, S., & Wiemer, D. (1985). Box and block test of manual dexterity: Norms for 6–19 year olds. *Canadian Journal of Occupational Therapy, 52*, 241–245.
Peters, M. A., Balzer, J., & Shams, L. (2015). Smaller = denser, and the brain knows it: Natural statistics of object density shape weight expectations. *PLoS One, 10*(3), e119794.
Peters, M. A., Ma, W. J., & Shams, L. (2016). The size–weight illusion is not anti-Bayesian after all: A unifying Bayesian account. *PeerJ, 4*, e2124.
Philippe, J., & Clavière, J. (1895). Sur une illusion musculaire. *Revue Philosophique de la France et de l'Étranger, 40*, 672–682.
Piaget, J. (1969). *The mechanisms of perception (G. N. Seagrim, Trans.)*. London: Routledge & Kegan Paul.
Piaget, J. (1999). *The psychology of intelligence*. Philadelphia: Taylor & Francis.
Pick, H. L., & Pick, A. D. (1967). A developmental and analytic study of the size–weight illusion. *Journal of Experimental Child Psychology, 5*, 362–371.
Pollack, R. H. (1970). Mueller-Lyer illusion: Effect of age, lightness contrast, and hue. *Science, 170*, 93–95.
Porac, C., & Coren, S. (1981). Life-span age trends in the perception of the Mueller–Lyer: Additional evidence for the existence of two illusions. *Canadian Journal of Psychology, 35*, 58–62.
Raven, J., Raven, J. C., & Court, J. H. (2003). *Manual for Raven's Progressive Matrices and Vocabulary Scales*. San Antonio, TX: Harcourt Assessment.
Rey, A. (1930). Contribution à l'étude de poids chez les anormaux. *Archives de psychologie, 22*, 285–287.
Rival, C., Olivier, I., Ceyte, H., & Ferrel, C. (2003). Age-related differences in a delayed pointing of a Müller-Lyer illusion. *Experimental Brain Research, 153*, 378–381.

Robinson, H. B. (1964). An experimental examination of the size–weight illusion in young children. *Child Development, 35*, 91–107.
Ross, H. E., & Gregory, R. L. (1970). Weight illusions and weight discrimination—A revised hypothesis. *Quarterly Journal of Experimental Psychology, 22*, 318–328.
Saccone, E. J., & Chouinard, P. A. (2019). The influence of size in weight illusions is unique relative to other object features. *Psychonomic Bulletin & Review, 26*, 77–89.
Schwarzkopf, D. S., Song, C., & Rees, G. (2011). The surface area of human V1 predicts the subjective experience of object size. *Nature Neuroscience, 14*, 28–30.
Seashore, C. E. (1898). Some psychological statistics: II. The material weight illusion. *University of Iowa Studies in Psychology, 2*, 36–46.
Sherman, J. A., & Chouinard, P. A. (2016). Attractive contours of the Ebbinghaus illusion. *Perceptual and Motor Skills, 122*, 88–95.
Skinner, B. F. (1953). *Science and human behavior*. New York: Macmillan.
Smith, L. B. (1984). Young children's understanding of attributes and dimensions: A comparison of conceptual and linguistic measures. *Child Development, 55*, 363–380.
Tedford, W. H., Jr., Bergquist, S. L., & Flynn, W. E. (1977). The size–color illusion. *Journal of General Psychology, 97*, 145–149.
Tiffin, J., & Asher, E. J. (1948). The Purdue Pegboard: Norms and studies of reliability and validity. *Journal of Applied Psychology, 32*, 234–247.
Tukey, J. W. (1949). Comparing individual means in the analysis of variance. *Biometrics, 5*(2), 99–114.
Walker, P., Francis, B. J., & Walker, L. (2010). The brightness–weight illusion. *Experimental Psychology, 57*, 462–469.
Yancosek, K. E., & Howell, D. (2009). A narrative review of dexterity assessments. *Journal of Hand Therapy, 22*. 258–269; quiz 270.