The Heaviness of Objects and Heaviness of a Material Kind: Some 11 to 12-year-old Children's Understandings of Mass and Density

Leane Senzamici
University of Sydney
< lsen6892@uni.sydney.edu.au >

Heather McMaster
University of Sydney
< heather.mcmaster@sydney.edu.au >

The aim of this research was to explore 11 to 12-year- old children's understanding of the mass of objects made from different materials, and the measurement of this attribute. In depth task-based interviews were conducted with six children attending six different schools; five were in Year 6 and one in Year 7. The children were found to hold alternative conceptions about mass, which they understood as being synonymous with weight. These conceptions appear to stem from confusion between the heaviness of an object and the heaviness of the material (its density) from which an object is made. It is recommended that measurement of mass in the Australian Curriculum: Mathematics be integrated with 'Chemical Sciences' in the Australian Curriculum: Science.

Conceptual understanding of mass and density is intrinsic to students' understanding of the physical world (Klopher, Champagne, & Chaiklin, 1992). It bootstraps big ideas in scientific teaching and learning about objects and their matter (Smith, Wiser, Anderson & Krajcik, 2006). The topic of density is absent from the primary (Foundation to Year 6) Australian Mathematics and Science curricula (ACARA, 2017a). Students learn to measure mass at every year level in the primary Mathematics Curriculum; however; the only mention of *mass* in the primary Science curriculum is "observing that gases have mass and take up space, demonstrated by using balloons or bubbles" in Year 5. In science, students learn about the physical properties of materials but do not relate the mass or weight of an object to the heaviness (density) of material from which it is made. The mathematics and science curricula do not appear to support each other in integrating the development of these important and complexly intertwined concepts of mass and density.

The recently introduced National Numeracy Learning Progression (NNLP) (ACARA, 2017b) combines the measurement of length, area, mass, and volume into a single sub-element progression with nine levels called 'Understanding Units of Measurement' (UuM) (pp. 31-34). Comparing the weight of objects (heavier/lighter) is at Level 2, then mass (as weight) proceeds from using informal units (Level 3) to formal units (Level 7). The ability to explain the difference between different measures of the same object (e.g., one object being smaller and heavier than another) is not reached until Level 7. *Density* is not mentioned within the NNLP though it could be raised within a different sub-element called 'Comparing Units' at level 2 (CoU2) where 'rates' are interpreted as a relationship between two different types of quantities and used to determine how quantities change.

Literature Review

A review of mathematics education literature reveals that young children confuse the attributes of mass and volume (MacDonald 2010; McDonough, et al., 2013) and the attributes of mass and density (Lehrer, Schauble, Strom & Pligge, 2001), yet there has been little research into primary students' learning about the relationships between these attributes and a lack of consensus about how they conceive these relationships (Hitt, 2005, Kohn, 1993; Kloos, Fisher, & Orden, 2010).

2019. In G. Hine, S. Blackley, & A. Cooke (Eds.). Mathematics Education Research: Impacting Practice *(Proceedings of the 42nd annual conference of the Mathematics Education Research Group of Australasia)* pp. 636-643. Perth: MERGA.

Definitions of Mass, Weight and Density

Mass is defined in the Australian Mathematics curriculum as "*how much matter is in a person, object or substance*" (ACARA 2017a). The term 'matter' is complex so the term 'stuff' is commonly used in science educational literature (Klopher et al., 1992; Smith et al., 2006). Weight is "*the size of a force exerted on an object"* (Siemon et al., 2017) so when referring to objects on earth, mass and weight are interchangeable.

The *weight* of an object is a function of its volume (the space it occupies) and the material it is made of (Smith et al, 2006). In mathematics, students initially compare the weight of objects directly by hefting them (Cheeseman, McDonough & Ferguson, 2014). Smith et al. (2006) call the apparent weight when hefted, 'felt weight'. Denser objects feel 'heavier' because they have greater inertia when rotated around a joint (e.g., a wrist). According to Smith et al. (2006), understanding the difference between 'measured weight' and 'felt weight' is a prerequisite to understanding density.

Density is not defined in the mathematics or science curricula. The density of an object is the ratio of its mass to its volume. It depends on the substance or material that the object is made of. In science, 'substance' is differentiated from 'material'. A substance is composed of only one element or compound. A material is a composition of substances (Skamp, 2015). Density describes a characteristic that holds true for any amount of the same substance or material.

Conceptual Development

Many researchers have reported that pre-school and early primary aged children have an intuitive understanding of density (Kloos, Fisher & van Orden, 2010; MacDonald, 2010; Kohn, 1993). Children come to school with prior knowledge (Kalpana, 2014) and some experiences lend themselves to confusing children if not made explicit.

Smith et al. (2006) report that "the concept of material precedes the general concept of matter" (p. 19) and that often when children refer to *material* they are actually referring to the properties of that material. Skamp (2015) reinforced this conceptual foundation, reporting that children aged 5 to 11 classify objects based on a "hierarchy of five criteria, with the composition and the function of the material being of primary significance" (p. 310). That alternate, albeit naive, conception about material weight persists even after quantifying the weight, is evidenced in research literature that states that prior knowledge often survives new learning (Potvin, Masson, Lafortune & Cyr, 2015).

Dole, Clarke, Wright, and Hilton (2009) promote the teaching of mass and volume as foundational to understanding density. They showed that children in Year 5 could understand that density increases if volume stays constant and mass increases, and also note that children realising volume is "the amount of space an object takes up" can be a foundation for understanding density. Furthermore Smith et al. (2006) claim that teaching children about the big ideas of matter, including an understanding of properties such as density, will take sustained learning and should be informally introduced to children in Years 3-5, and formally in Years 6-8.

The absence of the concept of density in the Australian primary mathematics and science curricula, led to the research question: *How do 11 to 12-year-old Australian children understand the relationship between mass and volume?*

The Study

The research took a psychological constructivist perspective that children construct knowledge schema through their experiences (Kalpana, 2014). Consistent with this theoretical framework, a case study method was used. Six children participated in a one-on-one semi-structured task-based interview to probe their thinking about the attributes of mass and volume and how they conceived the relationship between these attributes. This paper focuses specifically on aspects of those tasks that revealed their understanding of 'mass' and 'density'.

Context and Participants

The children, given the pseudonyms Alex, Billy, Chris, Drew, Emmet and Fargo, had varied levels of mathematics and science achievement. The six different schools they attended had ICSEA values ranging from 898 (Chris) to 1170 (Drew). Five of the children were in Year 6 (primary school) and one was in Year 7 (secondary school). The Year 7 child (Drew) had formally encountered the concept of density at school in science. This was not anticipated by the researchers. Under the topic 'Chemical Sciences' in the Science curriculum, density is first encountered in Year 8 when the particle model is introduced to explain the structure of matter. The outcome ACSSU151 states: 'Properties of the different states of matter can be explained in terms of the motion and arrangement of particles' (ACARA, 2017a). The motion and arrangement of the atoms of a material determine its density.

Prior to the interview reported in this paper, the participants had been interviewed on their understanding of the words 'volume' and 'capacity' when presented with containers. In this interview the children were only presented with solid objects.

The Task-based Interviews

The semi-structured task-based interviews were developed by the authors conducted in July 2018 by the first author with a second researcher present to take field notes. The children were sequentially given the five tasks outlined in Table 1. While completing the tasks, they were questioned to reveal their reasoning. Tasks 1b, 2, 3b, 4b, 5b focused on their understanding of mass. Tasks 4c and 5c introduced the idea of density.

Table 1
The Descriptions of the Tasks

Task-1	Make a play-dough object with the same volume (1a) and mass (1b) as a wooden rectangular prism.
Task-2	Measure the mass of a wooden rectangular prism on balance scales given one gram units (plastic centicubes each weighing one gram).
Task-3	Predict then compare the volume (3a) and mass (3b) of three objects, each about 10 cm long. Two objects (a plastic rod and a wooden rod made of centicubes) had the same volume but different mass, and two (a plastic rod and a nail) had the same mass, but different volume.
Task-4	Group five discs according to volume (4a), mass (4b) and density (4c). Two pairs were made from the same material: a pair of red plastic counters (one large, one small) and a pair of gold coins (one dollar and two dollar). The remaining disc was a gold plastic medal.
Task-5	Push kinetic sand into a box (already full of kinetic sand), and describe what happens to its volume (5a), mass (5b) and density (5c).

The research adopted the interview procedures of Drake (2013). A variety of probing questions were used to assist them to think-aloud in order to reveal their thought processes (Presser et al., 2004). Probing questions were practised prior to the research and adjustments were made to remove perceived ambiguity.

When a child requested the definition of a term or the interviewer (the first author) deemed this appropriate, the syllabus definition (BOSNSW, 2012) was read to them. All the children were told the formal definition of density when undertaking Task 4c. They were told: "*Density is the mass of an object or substance compared to its volume. For two objects the same size one object is denser than another object if it is heavier for its size.*" The words 'heavier for size' as distinct from 'heavy' were drawn from Smith et al. (2006).

If a child did not appear confident in answering a question or was unable to formulate a response, the researcher moved on. The interviews varied in length from twenty to thirty-five minutes depending on the child's responses. Each interview was video-recorded.

Analysis

The data were unfolded across three stages, with the rationale for the application of specific categories based on the observations. Firstly, the two researchers present during the interviews and their supervising lecturer (the second author) met twice to review all video footage and identify significant words and gestures. The first author then re-examined the video footage, transcribed the dialogue and noted gestures related to the identified observations. All noted responses were coded according to the attribute (mass, volume or density) or a measurement procedure. This set of codes also tracked what each child said or did, how many times they did it and in which task. Secondly, common understandings were identified across participants. The third stage was a summarising of the observations into key themes. The second and third stages were conducted over eight weeks in conjunction with meetings at which the two researchers and the supervising lecturer discussed and came to agreement in their interpretation of the findings.

Results and Discussion

Across the six interviews, a number of themes emerged about how the children understood mass, their understanding of the relationship between mass and volume, and their understanding of density before and after being given a definition of this attribute.

How the Children Understood Mass

Two key themes emerged about how the children understood mass. The first was their linking of mass with weight. The second was their linking of the type of material to mass.

All children demonstrated the understanding that mass is like weight and can be measured similarly. In Task1b, Alex, Billy, Chris and Fargo used hefting (one object in each hand) when comparing the mass of their play-dough object with the mass of a wooden block, and three of them verified that they could quantify the informal measurement on the balance scales and/or the kitchen scales. Emmet did not heft the objects. He only used the balance scales to make a play-dough object with the same mass as the wooden block.

Drew (the only Year 7 student) described mass as material weight throughout the tasks. In Task 1b he could not make an object out of play-dough to match the mass of the wooden block, saying, "it's kind of hard, because this [wood] might be heavier than this [play-dough] because that's wood." It is worth noting the wooden object was lighter for its size than the lump of play-dough.

As well as associating mass with weight, all six children demonstrated an understanding that the mass of an object was related to the type of material from which it was made. This understanding was most commonly revealed through Task 3b when the children were asked to group three objects based on mass. Two of the objects (the plastic rod and the nail) had approximately the same mass, and the third object (the wooden rod) was lighter. All children had the expectation that the nail would be heavier than the plastic rod due to its material (metal). For example, Alex said, “I think these two might be approximately a little bit of the same, and the nail might be heavier because it's a different material and it’s a heavier material than both of them.” Drew said, “these two could have similar masses, but this [nail] is, metal I think, and so it makes it heavier because of its fabric.” Emmet said, “this one [nail] is made out of metal, and metal is heavier.” Chris thought the plastic rod and nail had the same mass but stated “the wood feels lighter than both of them and the plastic feels heavier, and of course the metal would be heavy.”

The conception that material determines weight was so well established that three children did not believe the measuring devices when they checked their assertions. For example, Chris compared the plastic rod and nail on the balance beam, and when this showed they weighed the same said “wait, it’s pretty off, I could try a different one,” and then swapped the nail for the wooden rod. Then, when the balance beam showed the wood was lighter than the plastic rod claimed, “both of these [plastic and nail] kind of weigh the same, but the metal weighs a little bit more.” Fargo was surprised when the kitchen scales didn’t support his belief and said, “Oh! I guess I just would have thought this [nail] would be heavier because it’s a different material, it probably is the same but right now I feel it, for me I think its heavier for some reason.”

The linking of material type with mass was further demonstrated in Task 4b when the children were asked to group five objects on the basis of mass. Four of the six children immediately grouped the two coins that were made of the same material but were different sizes. Fargo’s response was typical; “these are both made out of the same material and, well, yeah, so they would be the same.” These findings show that the children had reached the understandings of mass expected in the mathematics curriculum for children of their age. However, their statements linking mass with the properties of the material were somewhat unexpected though not unforeseen in light of science education research literature (Smith et al., 2006; Skamp, 2015). It appears that conceptions about material weight have persisted even after quantifying the mass of an object. The process of hefting also appears to have contributed to the confounding of the weight of an object with the density of the material from which it is made. This would explain the responses of all six children when they hefted the nail and the plastic rod and believed the nail was heavier (Smith et al., 2006).

Confounding density with mass could also explain why Drew (the student in Year 7) who apparently understood and could quantify mass, was unable to create an object out of play-dough to match the mass of the wooden block. He might have believed this task was impossible because play-dough and wood are different materials and different materials have different densities. Unlike the other children, Drew said he had heard the word ‘density’ in Science. It could be inferred that because Drew had not had the opportunity to develop an understanding of density when quantifying mass in primary school, he confused these two attributes. The ‘heaviness’ of an object (its mass) is not the same as the heaviness of a material (due to its density). These findings highlight that “helping students learn about materials and their properties is not as straight forward as it may seem.” (Skamp, 2015, p. 303).

How the Children Understood the Difference between Mass and Volume

An alarming finding was that four of the six children confused mass and volume across a range of activities. In Task 2 when asked to work out the mass of the wooden block, three children wanted to construct (from the plastic centicubes) a rectangular prism the same size and shape as the wooden block, yet they had shown previously that they knew mass was different from volume and could measure it. For example, when Billy was asked how she would calculate the mass of the wooden block, she constructed the same sized block out of centicubes and said it was "length times width times height … and then because they are all grams that's the answer but in grams."

Three of those children who confounded mass and volume in Task 2, also confounded them in Task 4a. When asked to group five objects based on volume, Billy, Drew and Emmet grouped them based on the materials they were made from and Drew described volume as being 'heavier' and 'lighter'. In Task 3a, Drew and Chris thought the volume of the three objects (made from different materials) could be verified by weighing them.

Whilst these findings support literature that children confuse the attributes of mass and volume (MacDonald 2010; McDonough, et al., 2013), it is worrying that Drew (Year 7) used adjectives for weight to describe volume. These findings reconfirm that children need to attend to the distinction between material and object, and the conception that for an object, mass is a function of its volume as well as the substance it is made from (Smith et al., 2006). Experiences such as weighing the same material on a scale may show for example that as more product is being added, both mass and volume are increasing.

Billy (and possibly Chris and Emmet) however, may be confused between mass and volume because they specifically equate a gram to a cubic centimetre. In the New South Wales Mathematics syllabus (BOSNSW, 2012) Stage 3 students (Years 5 and 6) learn conversions between metric units and that one millilitre is equated to one cubic centimetre. As one millilitre is one cubic centimetre for all substances, students might overgeneralise that one millilitre of all fluids (and possibly all materials) equates to one gram. With only three connections made between mass and volume in the New South Wales syllabus (BOSNSW, 2012), these connections are significant. In Stage 2 (Years 3 and 4) children distinguish between mass and volume, and are then prompted to associate 1 litre of milk with a mass of approximately 1 kg. In Stage 3, children relate the mass of 1 litre of water to 1 kilogram. Although the syllabus states as background information, that "the same volume of other substances might have different weights" (p. 234), this could easily be overlooked because children's school experiences often involve measuring water.

How the Children Understood Density

The findings revealed that whilst the mathematics and science curricula do not support learning about density, all six children had prior knowledge of density before being provided with the definition during Task 4c.

When questioned about the meaning of density in Task 4c, Drew and Fargo associated density with strength and hardness. Alex and Emmet said they had heard the word but did not remember the definition. After being given the definition they identified both coins as having the same density as they were made from the same kind of stuff. For example, Alex stated "I think these two might have the same, because it doesn't really matter about the size, it matters about what it's made of." Billy, who had previously used the word *denser* to describe differences in mass, was not helped by the formal definition of density. She correctly selected a coin to have the greatest density of the five discs however selected only one of the coins (the one with the greater mass).

Confusion between mass and density had also been apparent in Task 3b when both material type and ‘felt weight’ led them all to predict that the nail would be the heaviest. Predicting then measuring the weights of objects that are light or heavy 'for their size' could lead children to differentiate between the heaviness of an object (mass) and the heaviness of the material from which it is made (density), before being introduced to a formal definition of ‘density’.

Task 5, when compared with Task 4c, revealed that context can improve the salience of density. Only Alex and Emmet could correctly identify the property of density during Task 4c. Drew and Fargo had some intuitive understanding that a coin had a greater density than a plastic disc with about the same volume, however it was unclear if they were equating this understanding to the mass of the object. Throughout Task 5 however, all six children could correctly identify that the kinetic sand was increasing in density as more sand was being pushed into the container.

What is clear from this research is that children in upper primary school already have an appreciation of density. Age-appropriate engagement with density over the primary years, rather than complete exclusion, would seem to better serve children’s understanding for when it is mentioned in secondary school. If the idea that materials have different densities was introduced earlier as recommended by Smith et al. (2006), this might also reduce primary school students’ confusion between the mass and volume of objects, as well as provide children with a language to describe their experiences of the properties of substances and materials.

The findings also reveal that the context of any activity can limit success if it is isolated from everyday experiences. The salience of density across Task 4c was limited because it included five objects made from three different materials and there were pairs of objects of the same size but having different densities. Task 5 on the other hand greatly improved the salience of density, because only one material (kinetic sand) was used and only mass changed as the children filled the container. When they started filling, the container already looked as if it was full of the sand, hence the volume was held constant. This evidence supports Kloos et al. (2010) who outlined how task context can impact the salience of understanding density, and shows that activities which are relatable to children and improve the salience of density are useful when developing understanding of this property. From a constructivist perspective, Task 5 was useful in allowing the children to experience density changing and may possibly relate to their prior experiences such as pressing flour or brown sugar into a measuring cup to get more of it in the cup. This activity may be useful to support teacher’s introduction of density, which is known to be a difficult concept to explain (Kohn, 1993; Dole et al., 2009).

Conclusion

The research found that whilst children aged 11-12 can measure mass, they do not necessarily have a clear understanding about the distinction between mass and volume, and they confuse mass with the density of the material type. In addition, this research demonstrates that children of this age have prior understandings and experiences of density and that their misconceptions and alternative conceptions might be due in part to the relationship between mass and density not being addressed earlier in either the mathematics or science curricula. This requires further investigation. Though limited in their scope, these findings have implications for teaching the measurement of mass. They suggest that students learn about density as a property of materials (possibly in the ‘Chemical Sciences’ strand of the Science Curriculum) and that a learning progression for measuring mass include an understanding that the ‘heaviness’ of an object depends on both the size (volume) of the object and the material it is made of.

Reference List

Australian Curriculum and Reporting Authority [ACARA] (2017a). *The Australian curriculum (F-10),* Author. Retrieved from https://www.australiancurriculum.edu.au/f-10-curriculum.

Australian Curriculum Assessment and Reporting Authority [ACARA]. (2017b). *National Numeracy Learning Progression*, Author. Retrieved from https://www.australiancurriculum.edu.au/resources/ national-literacy-and-numeracy-learning- progressions/pdf-documents/

Board of Studies New South Wales [BOSNSW] (2012). NSW syllabus for the Australian curriculum, Author. Retrieved from http://syllabus.nesa.nsw.edu.au/download/.

Cheeseman, J., McDonough, A., & Ferguson, S. (2014). Investigating young children's learning of mass measurement. *Mathematics Education Research Journal, 26*(2), 131-150.

Dole, S., Clarke, D., Wright, T., & Hilton, G. (2009). Developing year 5 students' understanding of density: implications for mathematics teaching. In R. Hunter, B. Bicknell, & T. Burgess (Eds.), *Crossing divides* (Proceedings of the 32nd Annual Conference of the Mathematics Education Research Group of Australasia, Palmerston North, pp. 153-160). Palmerston North, NZ: MERGA.

Drake, M. (2013). How heavy is my rock? An exploration of students' understanding of the measurement of weight. In V.Steinle, L. Ball & C. Bardini (Eds.), *Mathematics education: Yesterday, today and tomorrow* (Proceedings of the 36th annual conference of the Mathematics Education Research Group of Australia pp. 250-257). Melbourne: MERGA.

Hitt, A. M. (2005). Attacking a dense problem: A learner centered approach to teaching density. *Science Activities*, *42*(1), 25-29.

Kalpana, T. (2014). A constructivist perspective on teaching and learning: A conceptual framework. *International Research Journal of Social Sciences*, *3*(1), 27-29.

Kloos, H., Fisher, A., & van Orden, G. C. (2010). Situated naïve physics: Task constraints decide what children know about density. *Journal of Experimental Psychology General, 139*(4), 625-637.

Klopfer, L., Champagne, A. & Chaiklin, S. (1992). The ubiquitous quantities: explorations that inform the design of instruction on the physical properties of matter. *Science Education, 76*(6), 597-614.

Kohn, A.S. (1993). Preschoolers' reasoning about density: Will it float? *Child Development, 64*(6), 1637-1650.

Lehrer,R., Schauble, L., Strom, D., & Pligge, M. (2001). Similarity of form and substance: Modeling material kind. In S. Carver & D. Klahr (Eds.), Cognition and instruction: Twenty-five years of progress, pp. 39-74. Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

MacDonald, A. (2010). Heavy thinking: Young children's theorising about mass. *Australian Primary Mathematics Classroom, 15*(4), 4-8.

McDonough, A., Cheeseman, J., & Ferguson, S. (2013). Young children's emerging understandings of the measurement of Mass. *Australasian Journal of Early Childhood*, *38*(4), 13-20.

Potvin, P., Masson, S., Lafortune, S., & Cyr, G. (2015). Persistence of the intuitive conception that heavy objects sink more: A reaction time study with different levels of interference. *International Journal of Science and Mathematics Education, 13*(1), 21-43.

Presser, S., Couper, M. P., Lessler, J. T., Martin, E., Martin, J., Rothgeb, J. M., & Singer, E. (2004). Methods for Testing and Evaluating Survey Questions. *The Public Opinion Quarterly*, *68*(1), 109-130.

Siemon, D., Beswick, K., Brady, K., Clark, J., Faragher, R., & Warren, E. (2015). *Teaching mathematics foundations to middle years. Second edition*. South Melbourne: Oxford University Press.

Skamp, K. (2015). Materials. In K. Skamp & C. Preston (Eds.), *Teaching Primary Science Constructively* 5th *Edition* (pp. 302-346). South Melbourne, Victoria, Australia: Cengage Learning Australia Pty Limited.

Smith, C., Wiser, M., Anderson, C.W., & Krajick, J. (2006). Implications on research for children's learning for standards and assessment: A proposed learning progression for matter and atomic molecular theory. Measurement: *Interdisciplinary Research and Perspectives 14*(1&2), 1-98.