Young Children's Understanding of 'More' and Discrimination of Number and Surface Area

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Abstract

The psychology supporting the use of quantifier words (e.g., 'some', 'most', 'more') is of interest to both scientists studying quantity representation (e.g., number, area) and to scientists and linguists studying the syntax and semantics of these terms. Understanding quantifiers requires both a mastery of the linguistic representations and a connection with cognitive representations of quantity. Some words (e.g., 'many', 'much') refer to only a single dimension, while others, like 'more' refer to comparison by numeric ('more dots') or non-numeric dimensions ('more goo'). In the present work, we ask two questions. First, when do children begin to understand the word 'more' as used to compare non-numeric substances and collections of discrete objects? Second, what is the underlying psychophysical character of the cognitive representations children utilize to verify such sentences? We find that children can understand and verify sentences including 'more goo' and 'more dots' at around 3.3 – younger than some previous studies have suggested – and that children employ the Approximate Number System and an Approximate Area System in verification. These systems share a common underlying format (i.e., Gaussian representations with scalar variability). The similarity in the age of onset we find for understanding 'more' in number and area contexts, along with the similar psychophysical character we demonstrate for these underlying cognitive representations, suggest that children may learn 'more' as a domain-neutral comparative term.

Young Children's Discrimination of Area and Number and the Understanding of 'More'

As children acquire language, they come to understand sentences in a way that lets them verify whether these sentences are true or false. The verification of a sentence relies not only on the child's ability to linguistically understand the sentence, but also on successfully navigating an interface between language and non-linguistic cognitive systems. For instance, verifying the sentence "More of the dots are blue than yellow" might involve engaging both visual attention (to select just the blue and yellow dots) and a representation of number (to enumerate and compare them) as well as a linguistic system which composes an understanding of the meaning of the sentence from its individual words. Studying this language/cognition interface, which is presumably necessary for language use, may inform both theories of lexical acquisition and theories of basic cognition (Lidz, Pietroski, Hunter & Halberda, 2011).

Here, we ask at what age children begin to understand comparative expressions involving the word 'more' as applied to continuous extents (e.g., "there is more yellow goo than blue goo"), and to collections of countable items (e.g., "there are more yellow dots than blue dots"), and we make use of psychophysical methods to characterize the cognitive systems children engage to verify such expressions. Doing so enables us to inform debates in both language acquisition and the non-linguistic representations of quantity.

Quantifier words, such as 'some', 'many', and 'most', play a critical role in our communication and reasoning about amounts. A classic case-study, and one that has drawn both fruitful research and controversy, has been the acquisition of the comparative 'more' (e.g., "There are more apples than oranges"; Bloom, 1970; Donaldson & Wales, 1970; Hohaus and Tiemann, 2009; Townsend, 1974). One point of contention has been whether children immediately understand comparative 'more' as having the adult meaning – a comparative

operation that can be applied to any dimension – or whether they might initially have a less

general meaning for 'more' that is incrementally added to throughout development (Clark, 1970;

Gathercole, 1985, 2009; Mehler & Bever, 1967).

Evidence for the incremental learning account of 'more' has come from three sources.

First, although children produce 'more' by two-years of age (e.g., "More juice"; Bloom, 1970;

Mehler & Bever, 1967), many researchers have argued that this early meaning is that of an

additive, not the comparative 'more' (e.g., "Some books are on this desk, and more are over

there"; Beilin, 1968; Thomas, 2010; Weiner, 1974). In turn, some incremental learning theories

have suggested that children first learn 'more' as having an additive meaning, and later on

supplement it with the comparative form (Clark, 1970). This evidence has been controversial,

however, because the two forms of 'more' may not be related (Beilin, 1968; Weiner, 1974).

Indeed, some languages use different words for the additive vs. comparative 'more' (e.g., 'još'

vs. 'više' in Serbo-Croatian; Odic et al, in prep). As such, evidence for the acquisition of additive

'more' may not be informative about the development of the comparative form. Here, we focus

only on comparative uses of 'more' in children learning English.

The second source of evidence for the incremental learning account has been the contrast

of how children learn 'less' from 'more'. Donaldson and Balfour (1968), for example,

demonstrated that young three-year-olds understand the word 'less' to mean 'more', and argued

that it takes an additional stage of development for the adult-like meaning of 'less' to emerge

(see also Palermo, 1973). Other work has suggested that this 'less-is-more' effect stems from

experiment demands and not from children's use of lexical knowledge (Carey, 1978).

Nevertheless, many theories of 'more' development have argued for a stage-like development of

comparative 'more' understanding that only resembles the adult meaning after about four years

of age (Clark, 1970; Gathercole, 1985, 2009).

The final source of evidence for the incremental view, one that has deep connections to

the psychological literature on magnitude representations, comes from how children understand

comparative 'more' in numeric versus non-numeric contexts. For example, while some words in

English, like 'many' and 'much', are restricted with regard to what they can modify ("I have too

many rocks" means that my individual hunks of rock are too numerous, while "I have too *much*

rock" means that my volume of rock stuff is too great), other words, including 'most', 'some',

and 'more', are dimension-neutral. For example, 'more' can refer to quantification by number ("I

have more apples than you"), by area ("I have more land than you"), by normative quantity ("I

have more charm than you"), etc.

Because 'more' can be used to modify various dimensions in grammatical sentences

(e.g., number or area) use of 'more' remains equivocal as to the specified dimension and other

indicators in the phrase or the context must specify the intended dimension. The problem of

determining the correct quantity dimension might be made easier by the presence of a

mass/count-noun distinction, as in English (Barner & Snedeker, 2005; Gathercole, 1985).

Roughly, this distinction is between words that typically refer to individuals – count-nouns like

'dot' and 'cow' – and those that typically do not refer to individuals – mass-nouns like 'goo' and

'beef'[1] (Bale & Barner, 2009; Gillon, 1992). The mass/count distinction is grammatical. Only

count-nouns can be pluralized ('cow'/'cows', 'pebble'/'pebbles'; 'beef'/*'beefs',

'gravel'/*'gravels'), and only count-nouns can co-occur with numerical determiners (three

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[1] Importantly, not all mass-nouns refer to non-objects (e.g., 'furniture', 'mail'), and children are aware of this from early on (Barner & Snedeker, 2005). Thus, while count-nouns surely suggest individuals and a comparison by number, mass-nouns are neutral and may depend on world-knowledge or context for the selection of the appropriate dimension (Bale & Barner, 2009).

cows/*beef; for evidence that children learn the distinction as a syntactic one, see Gordon, 1985).

Thus, given that children know the syntactic difference between mass- and count-nouns, they

could use this knowledge to interpret 'more' as indicating a numerical dimension when used with

count-nouns (e.g., "you have more cows than me,"), and indicating a non-numerical dimension

when used with mass-nouns (e.g., "you have more beef than me,").

Even with a mass/count distinction in place, the development of 'more' may be

incremental. Gathercole (1985; 2009), for example, suggests that children may initially

understand 'more' to only apply to count nouns (thus resembling 'many'), and only later revise

the meaning of 'more' to be dimension-neutral and include quantification by non-numeric

dimensions (e.g., area). The alternative is that children might learn the meaning of 'more'

immediately as a domain general comparative that can apply equally well to multiple dimensions

(e.g., number or area). This issue of incremental versus immediate acquisition of the meaning of

'more' remains contentious in the literature (see Barner and Snedeker, 2005).

Early theories of 'more' acquisition were relatively unconcerned about the contrast

between numeric and continuous stimuli, and almost exclusively tested children with discrete

objects and count nouns (Donaldson & Wales, 1970; Mehler & Bever, 1967; Beilin, 1968;

Weiner, 1974). The few studies that did use non-numeric stimuli tested children older than four

(Palermo, 1973; Hudson, Guthrie & Santilli, 1982), by which point the dimension-neutral form

of comparative 'more' may have been acquired. This has, at least in part, been the inheritance of

a literature that focused on children's understanding of 'more' in the context of understanding

conservation of volume and conservation of number, which tended to target children older than

age three (Piaget, 1965, but see Mehler & Bever, 1967).

An important methodological innovation came in a series of studies that directly pit numerical and continuous dimensions against one another (Barner and Snedeker, 2005, 2006; Gathercole, 1985; Huntley-Fenner, 2001). In these studies, children saw displays of items that might either typically be described with count-nouns (e.g., candles, feet) or typically described with mass-nouns (e.g., ribbon, candy) and children had to judge which of two displays had more of that noun (e.g., "Which piece of paper has more ribbon?" or "Which piece of paper has more bows"). Critically, while one option always had more by number, the other option always had more by area (e.g., 1 giant candle versus 3 small candles). This allowed trials to serve as their own controls, as children could demonstrate flexibility in quantifying either by mass (e.g., 'ribbon') or by count (e.g., 'bows'; Barner & Snedeker, 2005). Results with this method have sometimes supported an incremental acquisition of 'more' (Gathercole, 1985) and sometimes supported an immediate acquisition of both number and area 'more' (Barner & Snedeker, 2005; 2006; Huntley-Fenner, 2001). For example, Gathercole (1985) found that children can verify 'more' for numerical quantities relatively early – by around 3.5 – but that they also inappropriately verify all mass-nouns by number up until at least age 5.0. And while children can successfully quantify via mass for familiar substance-like mass nouns such as 'toothpaste' (Barner & Snedeker, 2005, 2006), Barner & Snedeker (2006) have argued convincingly that 3-year-olds are willing to quantify using number for both familiar and novel mass nouns (e.g., counting the pieces of a novel mass-noun 'fem' rather than its mass). Thus, though evidence from the method that directly pits area against number remain equivocal, as between immediate and incremental acquisition.

Evidence that may resolve this issue includes investigating the interface between children's first understanding of 'more' and the psychological systems that represent area and

number information. If children are to learn 'more' immediately as a domain general

comparative, they must also learn how this meaning interfaces with the cognitive systems that

code area and number information. In the present work, we focus on how the interface between

linguistic meaning and the cognitive systems that represent number and area may provide

evidence for or against this incremental 'more' account. As reviewed above, on at least one

version of the incremental account (Gathercole, 1985, 2009), 'more' is initially understood as

applying only to count-nouns. At this stage, 'more' would have the restricted *greater-in-number*

meaning, while lacking the adult-like *greater-in-amount* meaning (Figure 1). This would imply

that when children acquire 'more', they first form an interface between the linguistic meaning

and the cognitive systems that represent number. Only later in development, as incremental

learning lets children generalize 'more' to other dimensions, would the interface be extended to

other cognitive representations of quantity.

-- FIGURE 1 HERE --

On the alternative "immediate" account, children learn 'more' as dimension-neutral

meaning *greater-in-amount* (Figure 1). So they must also immediately form an interface with

each of the relevant cognitive representations of quantity (e.g., area and number), and eventually

rely on a count/mass distinction or contextual cues to identify which dimension is intended for

any given utterance. One challenge for the immediate account is that it makes the problem of

learning the interface between 'more' and cognition potentially difficult: if there is very minimal

similarity between the cognitive systems that represent e.g., area and number, the children would

have to somehow immediately form an interface with disparate quantity representations. The

learning of a domain-neutral 'more' would require not only learning the meaning of the word in

the linguistic system, but also learning how to make this meaning interface correctly with the

various cognitive systems that code for e.g., area and number information. The interface

problem is simpler, however, if these cognitive systems share some underlying formal character

that can support a single interface between a domain-neutral meaning of 'more' and the cognitive

representations of e.g., area and number. That is, immediately learning a domain-neutral

meaning of 'more' might be aided if the cognitive representations of area and number share an

underlying psychophysical character.

Thus, understanding the cognitive representations of area and number (e.g., whether or

not they share a common format) becomes a relevant source of evidence for understanding the

immediate or incremental acquisition of 'more'. Here, we sought to determine (a) whether there

are underlying similarities in the cognitive representations of area and number that could support

the immediate acquisition of a domain-neutral meaning of *greater-in-amount*; and (b) whether

there is developmental evidence that children can successfully verify sentences with area and

number 'more' at approximately the same ages. Positive evidence for each of these would serve

as evidence in favor of an immediate acquisition of a domain-neutral 'more'

Evidence for (a) has been mounting. Recent work has suggested that from very early on,

infants have access to noisy, approximate representations of various dimensions including

number (Dehaene, 1997; Feigenson, Dehaene, & Spelke, 2004; Izard, Sann, Spelke, & Streri,

2009), volume (Huttenlocher, Duffy, & Levine, 2002), and area (Brannon, Lutz, & Cordes,

2006; *for reviews, see* Cantlon, Platt, & Brannon, 2009 *and* Feigenson, 2007). A key aspect of

these representations is that they are 'noisy' in that they do not represent these continua precisely

(i.e., there is always some error surrounding the estimates they generate). The underlying

cognitive system purported to support these discriminations, the Approximate Number System

(ANS), demonstrates several key behavioral signatures, chief amongst which is Weber's law –

discrimination of numerosity depends not on the absolute difference between the cardinalities of the two sets, but on their ratio (Feigenson et al., 2004). Thus, discriminating 20 from 10 items (a ratio of 2.0) is relatively easy, while discriminating 20 from 18 items (a ratio of 1.11) is relatively difficult. Recent work has also demonstrated that the most difficult numerical ratio children can successfully discriminate improves with age (Halberda & Feigenson, 2008).

This dependency on ratio and Weber's law is also present in infant's judgments of surface area. For example, Brannon and colleagues (2006) habituated infants to a face of a particular size, and then presented them with the same face in a different size. Infants could discriminate the change if the area ratio between the original and new face was around 3.0 (3:1) or 2.0 (2:1), but not if it was more difficult. Furthermore, Huntley-Fenner (2001) demonstrated that children around age 4 could discriminate two piles of sand that differed by a ratio of 1.5 (3:2). These findings suggest that area, like number, relies on an approximate representation system, and that the representational precision of this system, much like in the case of number, may improve with age (Cantlon et al., 2009).

However, although the evidence from infancy suggests that both number and area share a common representational format (i.e., approximate representation with scalar variability), surprisingly there has been no direct evidence to support the idea that young children approximate area in accordance with Weber's law. Psychophysicists have long debated whether representations of all quantity dimensions obey Weber's law (Bizo, Chu, Sanabria, & Killeen, 2006; Getty, 1975), and work with adults has led some authors to suggest that area approximation does not occur via a dedicated mechanism, but rather that, when presented with geometrical figures, adults fail to estimate area and rely on diameter or aspect-ratio as a proxy for area (Chong & Treisman, 2003; Morgan, 2005; Nachmias, 2008). A similar issue exists in the

infancy literature, where area discrimination tasks could, in principle, be done through many other dimensions, such as perimeter, radius, etc. Before we can conclusively state that there are similarities in the underlying representations of number and area we need a direct test of children's abilities to approximate area with stimuli that can disrupt attempts to use alternative dimensions like diameter or aspect-ratio as a proxy for area.

Evidence for (b) – that children verify sentences with area or number 'more' at approximately the same age – is controversial. As reviewed above, Gathercole (1985) found that children do not verify via area until age 5, while Barner and Snedeker (2005) also found a number-bias in their novel mass-noun conditions, thus suggesting that an interface between 'more' and number may emerge prior to the interface with area representations. However, the methods used in paradigms such as Gathercole (1985) and Barner and Snedeker (2005; 2006) are not conclusive, as they require children to resolve a conflict between two number and area. If, independent of language, a child's underlying representations of number and area are biased in favor of number, then children's competence at understanding 'more' as applied to non-numeric stimuli may be overshadowed by their inability to ignore the numbers of items in the scenes (i.e., number may simply be a more interesting contrast of the two scenes, independent of language). In fact, several studies have demonstrated that 6- and 7-month-olds, when habituated to a display of several boxes or circles, will dishabituate when the number of boxes changes, but not when their total area changes leading authors to suggest that numerical changes are more salient than changes in cumulative area (Cordes & Brannon, 2008, 2009, 2011)[2]. Three-year-old children also find quantifying via number easier than area in non-linguistic contexts. Cantlon, Safford, and Brannon (2010) played a match-to-sample game, and showed children a card with a standard

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[2] This may not always be the case, however, as both Clearfield & Mix (2001) and Feigenson and colleagues (Feigenson, Carey & Spelke, 2002) found that when the number of objects is fewer than 3 and the objects are identical in appearance infants may prefer to quantify by area rather than by number (*see also* Feigenson, 2005).

object, and then two cards as choices for the match. Critically, neither of the two cards were identical to the standard – one had the same number of objects as the standard, but was vastly off in area, and the other had the same area as the standard, but a different number of objects. Preschoolers consistently chose to match by number in this language-neutral context, once again demonstrating a preference for processing number rather than area in the presence of discrete stimuli (*and for evidence that even 6-, 8- and 10-year old children are swayed by number over cumulative area see* Jeong, Levine, and Huttenlocher, 2007). The existence of a non-linguistic bias towards number over area may make a linguistic task that pits number against area particularly difficult for young children.

In the present experiment, we asked children to verify sentences with 'more' applied to either area or number in non-conflicting stimuli. In the area condition (e.g., "is more of the goo blue or yellow"), the stimuli clearly resembled a continuous mass of stuff with two colors that did not create a conflict between number and area (Figure 2). In the number condition (e.g., "are more of these dots blue or yellow"), the stimuli clearly resembled two groups of discrete objects where total surface area was always equated, thereby removing any conflict between number and total surface area (Figure 2). Additionally, the stimuli used in the area condition were not geometric figures, thereby promoting surface area as the only reliable cue to area. We tested a large group of children ranging from 2 to 4 years of age. By alleviating the potential conflicts between number and area representations, we sought to determine whether young children successfully verify sentences with both number and area 'more' at approximately the same age. In addition, we relied on psychophysical modeling to determine if the cognitive representations of number and area had a similar underlying psychophysical character (i.e., Gaussian with scalar variability) that could support a single interface between a domain-neutral understanding of

'more' and the cognitive representations of number and area. Answering this question, while perhaps not controversial in the psychological literature, is absolutely necessary for understanding the interface between the linguistic meaning of 'more' and the cognitive systems that represent number and area information, and it has yet to be answered for non-geometric figures in any age group.

We expect that if children understand 'more' as a domain-neutral *greater-in-amount*, they will approximate the relevant quantity that the noun is indicating (number for count-nouns, and area for mass-nouns in our contexts), and their discrimination performance will adhere to the behavioral signatures of the extralinguistic cognitive systems that represent quantity. Unlike previous work, we will use psychophysical modeling to test whether each *individual* child understands 'more'. If we find that children, at roughly the same age, demonstrate an understanding of 'more' in both mass noun (area) and count noun (number) contexts, and that performance in both contexts is consistent with children relying on Gaussian representations with scalar variability, this would support the proposal that 'more' is learned as a domain-neutral comparative term from the earliest ages of comprehension and that this understanding is empowered by a single domain-neutral interface between the linguistic meaning of 'more' and the Gaussian representations of approximate area and approximate number.

Experiment

Subjects. 96 children from age 2.0 to age 4.0 (Mean Age = 3.2) were tested. Of these, sixteen had to be removed from data analysis for: being a non-native English speaker (1), parental interference (2), refusal to participate (12) [3], or technical problems with sound recording (1). Of the remaining children, 40 participated in the "Area task" (i.e., testing mass-noun 'more'), and

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[3] In all but two cases, these children were younger than 2;6 and did not appear to understand the game – in most cases the child simply did not respond to our requests.

40 in the "Number task" (i.e., testing count-noun 'more'). All children were learning English as their first language and were recruited from the greater Baltimore community and tested with methods certified by the Johns Hopkins University Internal Review Boards. Children received a small gift for participating.

<center>--- FIGURE 2 HERE ---</center>

Materials. For the Area task, the materials consisted of sixteen color 'goo' images each printed on a 8.5x11" sheet of paper that was subsequently laminated (see Figure 2). The images were selected from a larger databank of two-colored, circular blob-like images that had been drawn by hand to instantiate a wide range of ratios. To calculate the ratio (i.e., difficulty) between the two colored areas in each image we created a program that counted the number of pixels of each color in each image; ratios were calculated by dividing the larger area by the smaller (e.g., a ratio of 2.0 had twice as many pixels in the larger color area). We chose 16 images from the larger databank that were grouped into four approximate ratio bins with four images in each bin: 1.22, 1.85, 2.5, and 4.2. To make the 'goo' images more interesting, we varied the colors used on each trial. Children needed only to point during the task and were not required to know the names of the colors. Yellow, blue, red, orange, purple, and green were used randomly throughout and all colors occurred equally often.

For the Number task, we took the same goo images and used a custom-made program to extract individual dots from them (see Figure 2). This guaranteed that the relative spread of the two collections was matched to the spread in the goo images. Additionally, we made the ratio of the dots exactly the same as the ratio of the goo images (e.g., a 2.5 ratio on a blue and yellow goo card was converted into a e.g., 25 blue and 10 yellow dots card). For all dots cards, the cumulative area of the two sets was identical. For half of the cards, the larger set of dots

appeared in the smaller area of the blob – thereby ensuring that neither cumulative area, nor the area envelope surrounding the dots, nor density of dots could serve as a stable correlate to number.

Procedure. Before the experiment, parents signed a consent form and filled out a version of the McArthur-Bates III vocabulary inventory (Fenson et al., 2007).

Children were brought into the room and played a short number titration warm-up game ("What's on this Card"; *see* Le Corre & Carey, 2007; Halberda, Taing, & Lidz, 2008) with the experimenter that involved counting pictures of animals on cards. After number titration, the experimenter said that they had some pictures of 'goo' to show the child or some pictures of 'dots' to show the child. The parents remained with the child at all times but were seated so that they could not see the cards presented.

In the Area task, each trial began with the experimenter putting a single 'goo' card on the table and saying: "Look at *this* goo. Some of the goo is *blue*, and some of the goo is *green*. Is *more* of the goo *blue* or *green*?" (italics indicate increased prosodic stress on those words). While naming the color, the experimenter ran her fingers over the color in a smudging motion in case the child did not know the color name. Children were allowed to respond by either pointing or saying the name of the color.

In the Number task, each trial began with the experimenter putting a single dots card on the table and saying: "Look at *these* dots. Some of the dots are *blue*, and some of the dots are *green*. Are *more* of the dots *blue* or *green*?". While naming the colors, the experimenter would touch individual dots to make sure children knew which color was being referred to. Children were not allowed to count the dots and, if they attempted to, the experimenter removed the card

and reminded the child that they should simply give their best guess without counting; all children complied with the instruction not to count.

Cards were presented in one of two possible orders with the ratio presented varying pseudo-randomly from trial to trial. Because the dots cards were made from the goo cards, the order of the cards was identical across the two conditions. Whether the larger color was said first or second in the sentence was counterbalanced across trials. Every trial ended with neutral-positive feedback from the experimenter. The entire experiment was digitally audio-video recorded and was later coded for whether the child indicated the correct or incorrect color.

Results.

We first analyzed the data by averaging performance across all sixteen trials (i.e., ignoring ratio). Across all children, the average accuracy on the Area task was 63% (SE = 3.17%) which was significantly above chance (t (39) = 4.01, $p < 0.01$), indicating that children, as a group, succeeded on the task. Across all children, the accuracy on the Number task was 60% (SE = 2.98%), which was also significantly above chance (t(39) = 3.352, $p < 0.01$). There was no significant difference in accuracy between the two tasks (t(78)= -0.618, $p > 0.5$).

We computed a step-wise linear regression with accuracy as the DV and Age, Task, Vocabulary, What's-On-This-Card performance, and Order as the IVs. Age was the only IV that significantly predicted the DV ($\beta = 0.450$; $p < 0.01$; $r^2 = 0.20$; see Figure 3), i.e., once Age was entered as an IV, none of the other IVs were significant predictors of average performance. Examining the scatter plot, it appears that children can perform above chance on the Area and the Number task starting between the ages of 3.3 and 3.5.

--- FIGURE 3 HERE ---

This method of analysis – relying on overall percent correct – is standard in the word-learning literature (e.g., Barner and Snedker, 2006). However, a more sensitive measure of children's word knowledge is possible when we consider the psychophysics of the underlying area and number representations. We next used psychophysical modeling to determine which individual children succeeded at the task and whether their performance was consistent with Weber's law.

We predicted that if children understand 'more' as *greater-in-amount*, children would rely on a cognitive system that encodes the approximate area or approximate number on each trial (depending on the syntax and stimulus context), and that discrimination performance would be consistent with Weber's law in the following sense: performance should be ratio-dependent and well-modeled by a Gaussian cumulative density function (*see modeling details below*; Halberda & Feigenson, 2008; Pica, Lemer, Izard, & Dehaene, 2004; Lidz, Halberda, Pietroski, & Hunter, 2011).

For each child, performance was grouped into 4 ratio bins, with 4 trials falling into each of these bins ranging from harder trials (ratio bin = 1.22) to easier trials (ratio bin = 4.2). Performance was fit by a standard psychophysical model of Weber's law (Barth et al., 2006; Green & Swets, 1989; Halberda & Feigenson, 2008; Pica et al., 2004; Pietroski et al., 2009). We have previously applied this model to adult area and number perception with good results (Odic et al., under review):

$$\frac{1}{2} erfc(\frac{n_1 - n_2}{\sqrt{2}w\sqrt{n_1^2 + n_2^2}}) * 100$$

The model assumes that the underlying representations of area or number are distributed along a continuum of Gaussian random variables (with one value for the trial having mean of n_1,

and the other having a mean of n_2). An important implication of this model is that the two

different numbers (or areas) on each trial will often have overlapping representations. In other

words, as the means of the two distributions becomes increasingly similar (i.e., as the numbers

become closer and the ratio moves closer to a ratio of 1.0), their Gaussian representations should

overlap more and participants should have a more difficult time determining which is larger, thus

resulting in decreasing accuracy at the task as a function of ratio – in accord with Weber's law.

This model has only a single free parameter – the Weber fraction (w) – which indicates

the amount of noise in the underlying Gaussian representations (i.e., the standard deviation of the

n_1 and n_2 Gaussian representations where $SD_n = w \times n$). Larger w values indicate higher

representational noise and, thus, poorer discrimination across ratios (i.e., lower Weber fractions

indicate better discrimination performance). If a child is successfully discriminating in a manner

consistent with Weber's law, the model will determine the most plausible w for the child. If a

child is not successfully discriminating in a manner consistent with Weber's law, the model will

fail to find a value for w.

In the Area task, the model returned a w value for 22/40 children with an average w of

0.62 (SE = 0.11; approx. 3:2 ratio), and in the Number task the model returned a w value for

19/40 children with an average w of 0.63 (SE = 0.12; approx. 3:2 ratio). Figures 4 and 5 display

the average percent correct in each ratio bin for the children who were successfully fit by the

model and for those who were not; it is clear that children who could not be fit simply guessed at

every ratio. For the children who could be fit, the smooth curve is the least squares value for the

cumulative density function for the group. Agreement between the psychophysical model and

children's performance was quite good for both Area ($r^2 = .92$) and for Number ($r^2 = .82$)

suggesting that children did rely on the Approximate Number System (ANS) and on approximate

representations of area that are consistent with Weber's law (i.e., an Approximate Area System ,

or AAS). The good fit also confirms that these systems share an underlying Gaussian scalar

variability format (cf. Cantlon et al., 2009). Further validating the performance on the Number

task, the least-squares value for w for the group ($w = .63$) is in agreement with previously

documented developmental trends for this age group (Halberda & Feigenson, 2008; Piazza et al.,

2010) where no understanding of the word 'more' was required. There are no previously

documented developmental trends for area discrimination for these ages as our study is the first

to test children's abilities with blob-like stimuli.

-- FIGURES 4 and 5 HERE --

Even more remarkably, the distribution of w scores for Area and Number is extremely

similar (Figure 6). In the quantity representation literature, some have argued that similarity in

observed w scores in two tasks suggests quite strongly that a shared representational system is

responsible for the similar performance (Cantlon, Brannon & Platt, 2009; Meck & Church,

1983). Weber fractions (w) have been found for many discrimination tasks and can range from

very poor performance (e.g., $w = 1$ in 6-month-olds for number and area; Brannon et al., 2006) to

very accurate performance ($w = .03$ in adults for line length; Coren, Ward & Enns, 1994) – a

difference of nearly 2 orders of magnitude. With this in mind, it is particularly noteworthy that

the observed w scores in our Area and Number tasks were so similar. This is consistent with the

proposal that children initially learn 'more' as a domain-neutral comparative term that, in the

case of area and number, maps to a single shared approximation system, or to a system that

shares a common psychophysical character for area and number [4].

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[4] For our purposes here—arguing that children learn the comparative 'more' as a domain-neutral comparative that can interface with either number or area—it is enough that successful performance in both the Number and Area tasks was well fit by the psychophysical model of Weber's law. But taking a broader view, there are other dimensions besides number and area that will be of interest for investigating the acquisition of 'more', and not all of

Next, we turn to the question of the immediate acquisition of a domain-neutral 'more'.

The average age of children who were fit in the Area task was 3.4 (SE = 0.09) and in the Number

task was 3.5 (SE = 0.10) suggesting that, by at least age 3.5 years, children understand 'more' in

both count- and mass-noun contexts. Additionally, the average age of children who were

successfully fit was significantly higher than those who could not be fit for both area (t(38) = -

3.35; *p* < 0.01) and number (t (38) = -3.27; *p* < 0.01). The similar age of success in area and

number contexts presents difficulty for the incremental acquisition of 'more' (cf., Gathercole,

1985).

The presence of children who could not be fit by the model provides a convenient control

for methodological concerns about our tasks. For example, it could be argued that, because even

infants can make discriminations of area (Brannon et al., 2006) and number of items (Izard et al.,

2009) in visual displays – without language – it is possible that our stimuli were such that

children of any age would simply settle into choosing the greater area or number without having

to understand the word 'more' at all. In fact, young children in the Area and Number tasks

performed at chance and failed to choose the greater area or number. If it were solely a default

behavior or a bias to choose the greater quantity – observable in young infants – it would be

mysterious why younger children in our task would perform at chance and why the estimated age

of acquisition of understanding 'more' would be so similar in our tasks and other reported

studies (e.g., Barner and Snedeker, 2006; Beilin, 1968; Weiner, 1974).

--- FIGURE 6 HERE ---

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these will share the same Weber fraction. Just so long as these other systems share a common abstract format with
number and area (e.g., Gaussian scalar variability) the interface between 'more' and these dimensions will remain
transparent. We note the similarity in Weber fractions for area and number in the present paper because many
authors are currently interested in the possibility that dimensions like time, space and number may rely on a single
more general Analog Magnitude System which may have a single common Weber fraction (Bueti & Walsh, 2009;
Dehaene and Brannon, 2011). Our results are consistent with this possibility, though we caution that any such
shared system would still require representations that allow one to distinguish e.g., number thoughts from area
thoughts.

Our final question concerns developmental changes in the acuity of the two approximate systems. Our age range afforded us the opportunity to ask whether the precision of area and number representations improves during the late preschool years. In fact, area w for children who were successfully fit by the model improved (i.e., went down) with age as revealed by a linear regression ($r(21) = -0.53$; $p < 0.05$; Figure 6), but a linear regression with age and number w did not reach significance ($r(18) = -0.34$; $p = 0.16$; Figure 6). The improvements in area w are most likely a result of developmental improvements in the acuity of the AAS rather than any change in children's understanding of the word 'more' and the non-significant result for number w is likely a function of power (n=19) as other studies that did not involve linguistic contrasts have demonstrated developmental improvements in w for number across these same ages (Halberda & Feigenson, 2008; Piazza et al., 2010).

General Discussion.

Theories on the acquisition of comparative 'more' fall into two categories: some, like Gathercole (1985), advocate the incremental learning account, where the child's earliest understanding of 'more' is consistent with meaning *greater-in-number* and only later enriched to include an understanding of other dimensions (e.g., area) that generalizes to *greater-in-amount* (Figure 1); others, like Barner and Snedeker (2005) and Mehler and Bever (1967), have argued that children immediately understand 'more' to mean *greater-in-amount* (Figure 1). We have highlighted an important challenge for the latter (immediate, domain-neutral) account that has not been the focus of previous investigation: namely, in order to use and understand 'more' across various contexts (e.g., area and number), children must also master an interface between the meaning of 'more' and the various cognitive representations of quantity. We noted that if each quantity representation had a different underlying format, learning each of these interfaces

immediately would be unlikely. Here, we sought to determine (a) whether there are underlying similarities in the cognitive representations of area and number that could support the immediate acquisition of a domain-neutral meaning of *greater-in-amount*; and (b) whether there is developmental evidence that children can successfully verify sentences with area and number 'more' at approximately the same ages. Positive evidence for each of these would serve as evidence in favor of an immediate acquisition of a domain-neutral 'more'.

The present experiment provided support for the immediate acquisition of a domain-neutral 'more'. First, we found a close relationship between representations of number and area: we found that both representations obey Weber's law and are, thus, represented as mental magnitudes with Gaussian tuning and scalar variability. This was known for representations of approximate number (Halberda & Feigenson, 2008) and not entirely surprising given suggestions about area (e.g., Brannon et al., 2009), though it had yet to be demonstrated for amorphous stimuli in children. We also found that area representations, like number representations (Halberda & Feigenson, 2008; Piazza et al., 2010), improve in acuity over the preschool years. Perhaps of even greater note, we found that children had very similar Weber fractions (w) for number and area, suggesting the possibility of a shared underlying system. This similarity between number and area representations supports the possibility that children might immediately learn a domain-neutral 'more' meaning *greater-in-amount* as it may support a single interface between the meaning of 'more' and the cognitive systems that represent number and area.

Next, we showed that children begin to understand 'more' as applied to both count- and mass-nouns (and, in the context of our experiments, number and area) at the same ages (3.3 years). Thus, not only do children have the kind of representations that would support the

learning of a dimension-neutral 'more', but we also found evidence that they immediately

understand 'more' as applying to either number or area. Our estimate of 3.3 years as the age of

first understanding number and area 'more' is consistent with the findings of Barner and

Snedeker (2006), and contrasts with those of Gathercole (1985), and suggests that children of

this age know that 'more' can be applied to both numeric and non-numeric stimuli. Children's

success with our stimuli that remove any conflict between number and area also suggests that

some of the number bias in the Gathercole (1985) study and in the Barner and Snedeker (2006)

novel noun condition may have been due to a general cognitive bias towards number over area

whenever these dimensions are placed in conflict (i.e., this number bias may be independent of

children's language understanding). This too is consistent with an immediate acquisition of a

domain-neutral 'more' meaning *greater-in-amount.*

One important future direction is to determine the relationship between approximate

representations of area, number and other quantities. For example, does the similarity between

number and area discrimination performance reflect two distinct cognitive systems that are

similar in format, or a single unified magnitude system (cf. Bueti and Walsh, 2009, Cantlon et

al., 2009)? At present, our data are consistent with either account, although the highly similar

Weber fraction has, in the past, been used as evidence for a single system (e.g., Meck and

Church, 1983). Likewise, the similar growth pattern in the acuity of these systems may be used

as evidence for their identity, although we stress that changes in acuity may be either due to

changes of the representation of number and area, or due to more peripheral factors, like changes

in attention, working memory span, etc. (see Halberda & Feigenson, 2008).

More generally, our findings highlight the potential value of studying the interface

between linguistic meanings and the extralinguistic cognitive representations used during

verifications of these meanings. The study of such an interface can shed important light on our interpretations of both psycholinguistic data (e.g., the acquisition of quantifiers, comparatives, gradable adjectives, etc.) and on cognitive theories of quantity representation and selection (e.g., developmental changes in the precision of quantity representations). While linguistics and psychology remain independent disciplines, new questions may arise and become answerable in light of evidence for how language and psychology interface with each other.

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Figure Captions

Figure 1. (Right) Hypothesized development of the interface under the "incremental account".

Initial mapping is from 'more' to only representations of number. Later, through development,

the mapping is extended to include representations of area. (Left) Hypothesized development of

the interface under the "immediate account". Shared properties between number and area

representations allow 'more' to be mapped to both of them at the same time.

Figure 2. On the top are four examples of the 'dots' cards, and on the bottom are four examples
of the 'goo' cards.

Figure 3. The average performance across all 16 cards over age for both the dots and Area task.

The pattern shows a clear linear increase in performance with age and a high degree of overlap

between the two tasks.

Figure 4. The average performance across the 4 ratios for children in the Area task whose data

could be fit by the Weber's law model (N = 23) and those who could not (N = 21). Error bars are

standard error of the mean. Also presented is the group fit with the w of 0.66 ($r^2 = 0.92$).

Figure 5. The average performance across the 4 ratios for children in the Number task whose

data could be fit by the Weber's law model (N = 22) and those who could not (N = 19). Error

bars are standard error of the mean. Also presented is the group fit with the w of 0.65 ($r^2 = 0.74$).

Figure 6. Each individual More-Knower's Weber fraction over Age for the Area task. As can be

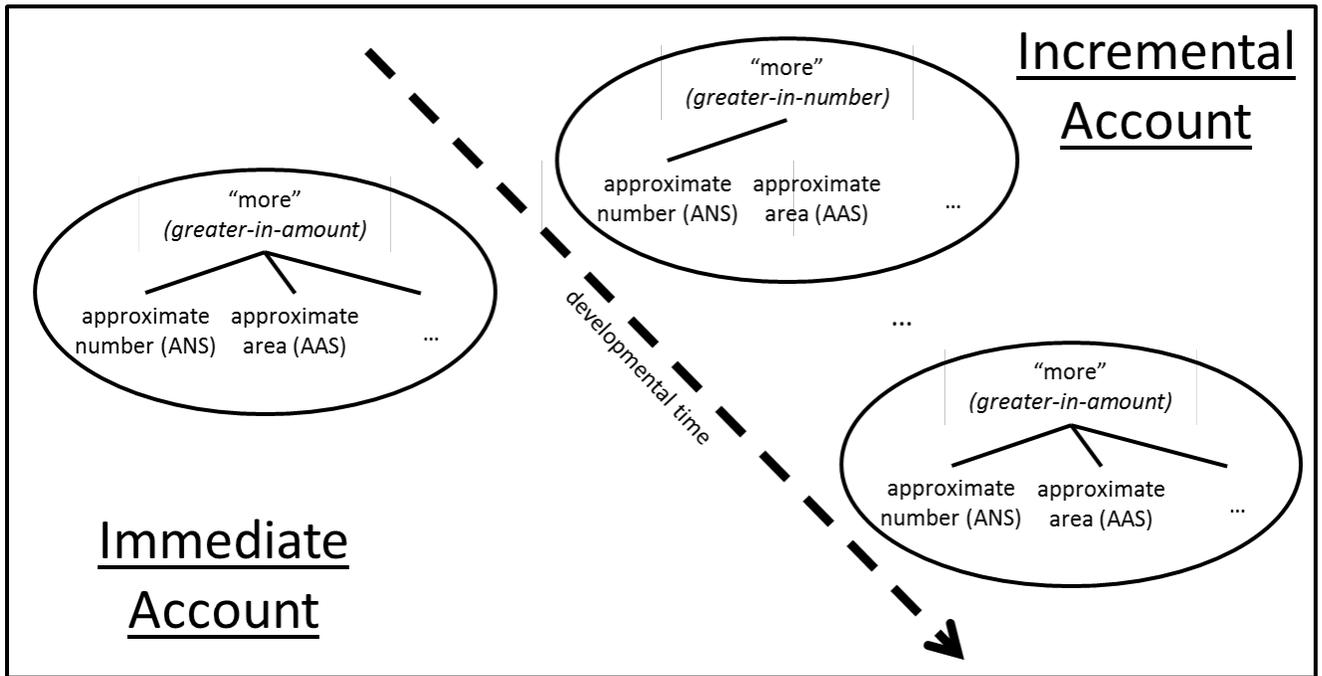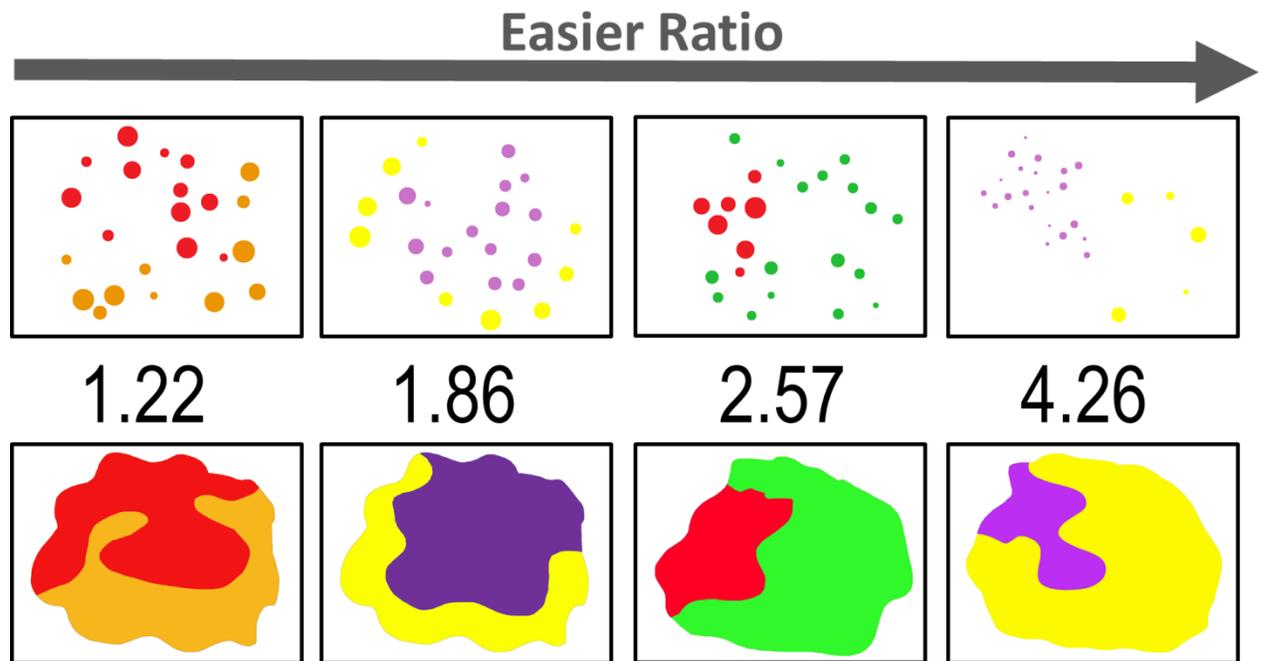seen, there is a clear downward trend for lower Weber fractions (i.e., better area discrimination)
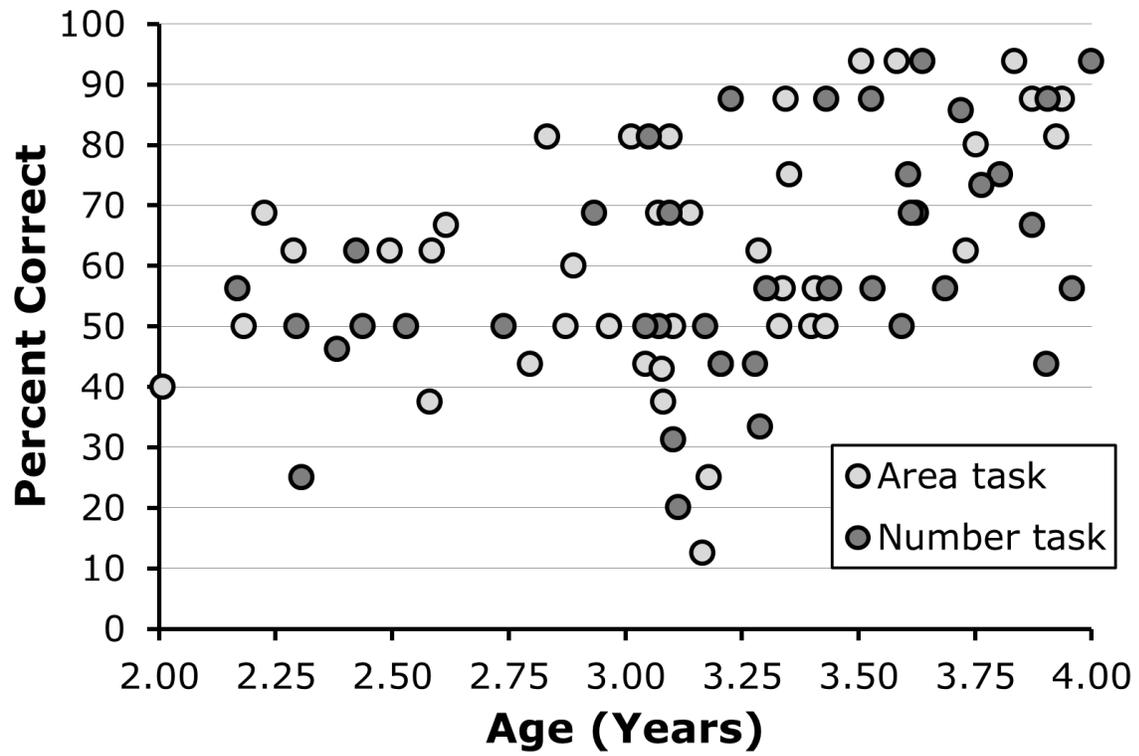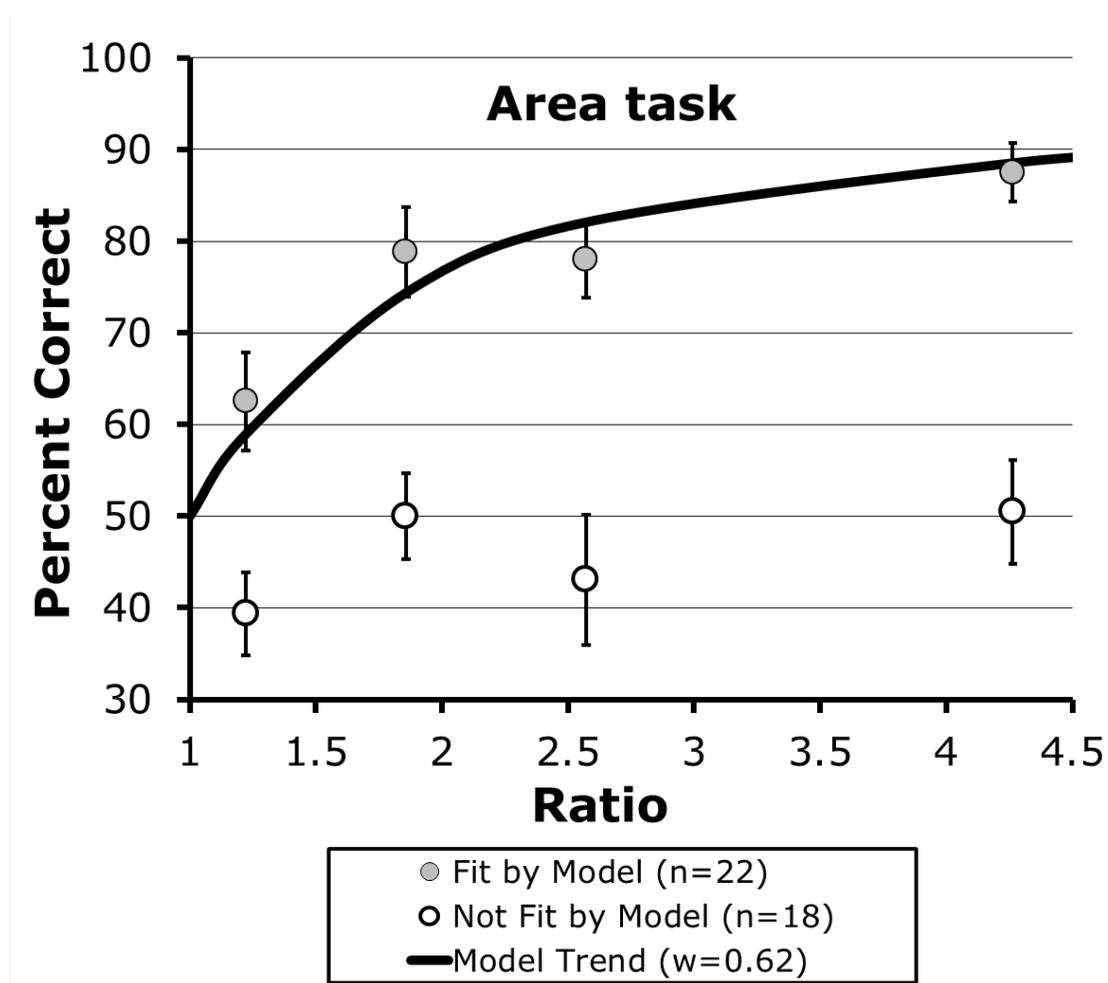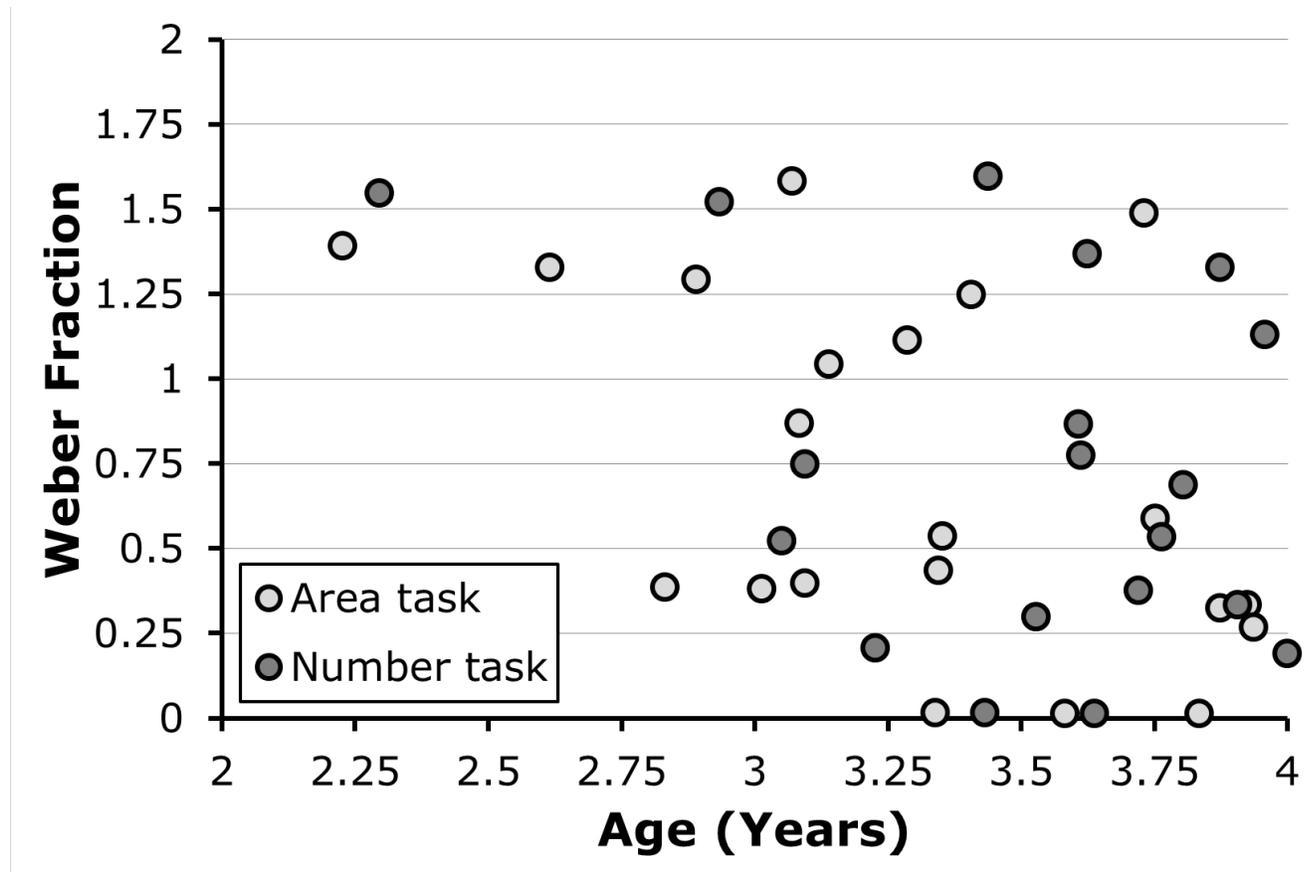
with age.

Figures

Figure 1.

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6