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Sharing as a Model for Understanding Division

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Abstract

Emerging research suggests children's ability to divide is the best predictor of later arithmetic development. Although division is typically taught around grade 3, children much younger than this practice division when sharing and allocating resources (e.g., sharing food). To test the hypothesis that social sharing abilities are linked to the emergence of complex numerical division abilities, we examined sharing and division abilities in adults and children. The first study used functional Near Infrared Spectroscopy (fNIRS) to examine the neurocognitive bases of division in adults ($N=28$; age range 18–23) during a task that evaluated their judgment of proportions in the context of sharing, as well as traditional numerical division tasks. The second study explored the relation between sharing and emergent math abilities in children ($N=53$; age range 4–6) using the same sharing task and established math measures. Our findings suggest that social sharing activities might engage similar cognitive mechanisms that support mathematical reasoning. The study informs theories of numerical cognition and highlights the importance of examining gaps in how early life activities support cognitive development.

Keywords

sharing; math; division

Introduction

Math skills are important for future academic success [1, 2]. Recent evidence suggests that elementary school children's ability to divide is a critical component of emergent numerical cognition and one of the best predictors of later mathematical achievement as compared to children's ability to add, subtract, or multiply [3]. Theories of math acquisition posit that, because division requires understanding that a numerical unit can be composed of multiple and manipulable parts, it thus reflects higher order processing that is essential to successful mathematical reasoning [4].

The numerical principles of division are only taught in elementary school (e.g., 3rd grade in the US). However, division-related activities permeate our daily lives. Whether one is serving food or working on a group project, studies have even shown preschoolers engage in basic division through tasks such as sharing toys and food [5]. We refer to these as 'social division' activities.

With this in mind, we hypothesize that there is a relation between children's sharing activities and numerical abilities. If sharing provides a foundation for future basic division principles, we propose that there may be variability in children's sharing abilities early in life, and that this variability may be related to children's basic number sense.

Unfortunately, while the field has been actively exploring early-acquired numerical skills such as addition and subtraction, the relation between these early social division abilities and higher order mathematical competence remains understudied.

Children have demonstrated sensitivity to proportions when evaluating the sharing behavior of others. For instance, in a 'Giving Game' task [6], two puppets shared chips with a child who then judged which puppet was "nicer." Generally, 4- and 5- year olds thought the puppet that shared a greater amount of candy, in absolute terms, was a nicer sharer, regardless of proportion. Yet, when absolute amount was held constant, 5- year olds were able to use proportions to determine which puppet was nicer. In the present study we build upon these findings to ask whether the ability to evaluate acts of sharing relates to performance on measures of mathematical competence.

To test the hypothesis that social division abilities are linked to numerical division abilities, we examined judgments about sharing and division abilities in adults and children. The first study used *fNIRS neuroimaging* to explore the neural correlates of sharing judgments and division abilities in a sample of adults. We chose fNIRS because the study is ultimately aimed at child cognition and education; this non-invasive approach is child-friendly, compact, cost-effective and can be easily adapted for school settings. Our guiding hypothesis was that common neural regions support division across symbolic and non-symbolic domains. To test this hypothesis, adult participants completed a task based on the "Giving Game" described above, hereafter named the Sharing Judgment Task (Fig.1) as well as tasks involving symbolic division

The second study explored the relation between judgments about sharing and emergent math abilities in young children. Our guiding hypothesis was that young children's emerging mathematical capacities would be associated with their performance on a social sharing task. To test this hypothesis children completed the Sharing Judgment Task and established measures of numerical cognition.

Study 1

Method

Participants.—Adults from southeast Michigan, USA were recruited and tested in a laboratory setting. Ten participants were excluded from neuroimaging analyses due to equipment and data artifacts (e.g., motion). There were no other issues with data recording. The final sample included 18 participants (6 males, ages 18–23 years, mean= 20.75 years). Participants completed a background questionnaire about their handedness, developmental and educational history, as well as any familial risk for learning disabilities. They also completed a standardized Woodcock-Johnson III Subtest, Math Calculation Skills (W-J III;

45 items) [7], yielding a right-handed sample with no history of learning disabilities and normative math abilities (WJ Calculation scores *range*=25–43, *mean*=33.61).

Tasks.—Adults completed a simple numerical equations task during neuroimaging that included three conditions (addition, subtraction, and division). During each trial, participants saw an equation (e.g., $8+4$, $3-1$, or $6 \div 3$) with one possible answer on the left side of the screen, and another possible answer on the right side of the screen. Participants indicated their responses by pressing the appropriate response button to indicate the side of the screen that contained the correct answer. Adults also completed the Sharing Judgment Task during neuroimaging. Both neuroimaging tasks were event-related designs with each trial lasting 3500 milliseconds and jitter trials ranging from 1000–4000 milliseconds. The Social Division task 26 Baseline trials, 20 Absolute trials and 18 Conflict trials. The Numerical Equation task had 54 trials per difficulty level (easier equation trials involved adding, subtracting, or dividing by the number 1 and more difficult trials involved adding, subtracting, or dividing by any number other than 1). In order to examine performance on these tasks, one-way repeated-measures ANOVAs were conducted for each task.

fNIRS Neuroimaging.—Prior neuroimaging evidence suggests symbolic division is likely to engage bilateral intraparietal regions, whereas non-symbolic division is likely to engage the prefrontal cortex (PFC) and right parietal regions [8]. Probe localization was designed to maximally capture signal from frontal and parietal regions (Fig. 2).

Participants underwent head measurement and the fNIRS cap procedure for the neuroimaging tasks. Data processing was completed using Homer2, a MATLAB-based software [9], along with several customized scripts. We performed the following preprocessing steps in the following order: optical density change data conversion, data examination for all channels, motion artifact detection and correction, filtering, concentration change data conversion and ordinary least squares base (OLS) regression. For more information regarding the TechEN imaging system and the approaches we used for probe localization/digitization, signal processing, and statistics, see Arredondo, Xiao-Su, Satterfield & Kovelman (2017) and Hu et al. (2015). One-way ANOVAs were performed to examine neural activation during these tasks, and t-tests were performed in order to examine activations across the target Absolute and Division conditions.

Results

The accuracy variable of the Sharing Judgment Task presented ceiling effects; therefore, reaction time was used in all behavioral measures. With all assumptions met, a one-way repeated-measures ANOVA was conducted to compare the effect of condition on reaction time in both tasks. There was a significant effect of condition on reaction time in the Sharing Judgment Task, Wilks' Lambda = .63, $F(2,24) = 7.02$, $\eta^2 = .37$, $p < .01$. Participants performed fastest during the Baseline condition, and slowest during the Conflict condition. There was also a significant effect of condition on reaction time in the equations task, Wilks' Lambda = .26, $F(2,24) = 33.55$, $\eta^2 = .74$, $p < .001$. Participants performed fastest during the Addition condition, and slowest during the Subtraction condition.

Although we had hypotheses about activation in the bilateral intraparietal regions and the prefrontal cortex, we opted to collect data from a large number of channels, and therefore correcting for multiple comparisons was an overly stringent approach that led to concerns about Type II errors. Therefore, neuroimaging analyses were performed using one-way ANOVA analyses, with a threshold of $p < 0.05$, uncorrected for multiple comparisons. For the Sharing Judgment Task, the results revealed main effects of condition in one left (CH2) and three right frontal channels (CH29, CH30, CH32) and bilateral parietal (left: CH9, CH10, CH14; right: CH26, CH28). For ease of reporting, individual values are not presented, however, p -values range from .003-.05. The absolute and baseline conditions incurred more activation in these significantly active channels than the conflict condition, even though the reaction time analyses revealed greater latencies for the conflict ($\bar{x} = 1620\text{ms}$) than the other conditions ($\bar{x}$ absolute = 1511ms, $\bar{x}$ baseline = 1461ms ; $p < 0.05$). Note that accuracy was at ceiling).

Numerical Equations Task one-way ANOVA analyses were performed on participant's beta values for each of the conditions and revealed significant main effects of condition in one left (CH2) and three right frontal (CH29, CH33, CH34) regions; and bilateral parietal (left: CH7, CH8, CH9, CH10, CH11, CH14, CH15, CH16; and right: CH22, CH23, CH28) (p -values range from .002-.05). The addition and subtraction conditions incurred more activation in these significantly active channels than the division condition, even though the reaction time analyses revealed division ($\bar{x} = 1103\text{ms}$) latency to be slower than subtraction ($\bar{x} = 1178\text{ms}$), but faster than addition ($\bar{x} = 1036\text{ms}$; $p < 0.05$). Note that accuracy was at ceiling).

The primary goal of neuroimaging was to examine if division, both symbolic and sharing, engaged similar neurocognitive processes. The Absolute condition was viewed as the most relevant condition (because Baseline was too easy whereas Conflict was meant to prevent participants from forming heuristics such that the greater shared amount corresponds to better sharing). Therefore, single-group t-tests (Absolute > rest; Division > rest) revealed that both tasks activated right frontal (CH 34; BA 46, MFG/SFG; Absolute Cohen's $d=1.70$; Division Cohen's $d=1.64$) and right parietal (CH 23; BA 40, SMG; Absolute Cohen's $d=1.15$; Division Cohen's $d=1.15$) regions classically associated with numeracy development (Fig. 2).

Study 2

Method

Participants.—Children from southeast Michigan, USA were recruited and tested either in the laboratory setting or in a quiet room at a preschool that served a diverse group of families ($N=53$; 30 males; *mean age*= 5.2 years; *range*=4–6). The parents completed background questionnaires similar to the one specified for the adults in Study 1, yielding a sample with no history of learning disabilities.

Tasks.—Children's ability to divide in a sharing context was measured through the Sharing Judgment Task described in Fig. 1. Children completed 4 practice trials (one baseline, one absolute, two conflict) and received feedback. The main Sharing Judgment task presented

children with 17 scenarios (3 baseline, 7 absolute, 7 conflict) and no feedback. Location of the nicer character was randomized and the task was not timed. Performance was measured as percent of trials completed accurately across conditions.

Children's general math abilities were measured with standardized Woodcock-Johnson III, Applied Problems (WJ-III AP) [12] that includes questions such as, "how many trees are in this picture?" Children also completed a version of the Number Line Estimation Task [13] where children were asked to map a symbolic number to a place on a number line using a hash mark. Some children ($n=16$) did not complete the Number Line Estimation task due to time constraints. Pairwise correlations were performed in order to examine the relation between established math measures and the Sharing Judgment Task.

Results

To examine the relation between sharing and math abilities we conducted pairwise correlations. Children who performed better on the Sharing Judgment Task overall also scored higher on the WJ-III AP ($r(48)=.37, p < 0.01$). The association strength decreased once age was controlled ($r(47)=.19$). The association between children's sharing and Number Line performance did not reach significance ($r(35)= -.26$), and decreased when controlling for age ($r(34)= -.06$).

Discussion

Research and theory have suggested that an understanding of division is one of the best predictors of children's math ability because it demonstrates a relatively mature ability to manipulate numbers and how parts relate to a whole [4]. Our findings are twofold: first, in adults there is a neurological overlap between formal, numerical division, and social division abilities. These findings in the adult sample underscore the importance of exploring the trajectory of math acquisition, because they suggest that sharing activities may engage neural mechanisms of numerical cognition.

Second, we did not find a relation between sharing judgments and math ability in children after controlling for age. Although the correlation is non-significant and small ($r=.19$), it is within range of other psychological constructs and thus the lack of power to find this significant is a problem in this study. Given the findings in our adult sample, this issue deserves attention in future developmental studies.

The present research represents an initial step to understanding the potential role of an individual's ability to evaluate social sharing related to performance in other aspects of numerical cognition. In adults, the Sharing Judgment Task (Absolute) and Numerical Equations Task (Division) conditions incurred activation in similar brain regions in the right fronto-parietal network (CH 23, CH 34, Fig. 2). These findings are consistent with our hypothesis as these regions are thought to be critical for numerical processing [8]. This provides preliminary evidence to suggest that across-context manipulations of division tap into similar regions. Therefore sharing abilities might provide a foundation neurologically for more complex numerical division abilities, however, future research should examine this question in a more confirmatory manner, perhaps with more difficult neuroimaging tasks.

Although we did not find a significant association between our Sharing Judgment Task and the WJ-III AP task in children after controlling for age, future studies of this topic should employ a variety of measures of both sharing behavior and cognition, and a variety of measures of mathematical ability. For example, the WJ-III AP items for the ages we tested focus on children's counting abilities, whereas division requires the ability to manipulate numbers and ratios that were addressed by our task. Further research with an appropriately powered study is thus needed to examine this question of whether insights into social sharing serve as a foundation for numerical division. It is important to examine this question as it offers a window for better understanding how early life activities support cognitive development.

In conclusion, our studies offer new findings and methodological considerations in this area of research on numerical cognition and its antecedents. However, more research is needed to better understand the relation between social division and numerical cognition.

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Figure 1.

Sharing Judgment Task. The first frame represents two characters that have an initial amount of candy. A portion of candy then dropped to the bottom of the screen, resulting in the second frame. The second frame represents candy the character shared with the participant (lower portion) and kept for itself (upper portion). Participants were asked to identify the nicer sharer in 3 experimental conditions: **(A) Baseline** Condition. The nicer sharer gives an outright and proportionally larger amount of candy **(B) Absolute** Condition. Both characters give the same absolute amount, but the nicer sharer gives a larger proportion of candy. **(C) Conflict** Condition. The nicer sharer gives a smaller absolute number but larger proportion of candy.

Figure 2.

Functional NIRS probe configuration. Probe-set and channel configuration for right and left hemispheres, respectively. Graphs: Examination of overlap for participant t-values for Division > Rest and Absolute > Rest.