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The Cross-Modal Relationship Between Language and Mathematics: A Bi-Directional Training Paradigm

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THE CROSS-MODAL RELATIONSHIP BETWEEN LANGUAGE AND MATHEMATICS: A BI-DIRECTIONAL TRAINING PARADIGM

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Abstract

The cross-modal relationship between language and mathematics is extensively debated (see for review, Peng et al., 2020). The present research examined the nature of this cross-modal relationship across three experiments. Experiment 1 examined whether training participants in linguistic problem-solving facilitates performance in mathematical problems. Participants were 156 adults recruited using Amazon Mechanical Turk and randomly assigned to one of three linguistic training conditions (i.e., linguistic reasoning, structural priming, or no-training) and tested on mathematical problems. No significant difference in mathematical performance was found across training conditions [$F(2, 153) = 1.69$, $p = .18$]. Experiment 2 examined whether training participants to solve mathematical problems facilitates performance in linguistic problems. Participants were 144 adults assigned to one of three mathematical training conditions (i.e., mathematical reasoning, structural priming, or no-training) and tested on linguistic problems. Results showed a significant difference in linguistic performance across training conditions [$F(2, 142) = 3.86$, $p = .02$, $\eta 2 = .05$]. Post-hoc analysis revealed a significant difference between the structural priming ($M = 9.37$, $SD = 1.99$) and no-training conditions ($M = 8.04$, $SD = 2.66$). Experiment 3 examined whether the explicitness of mathematical training differently impacts linguistic problem-solving. Participants were 75 undergraduate students assigned to one of three mathematical training conditions (i.e., explicit training, structural priming, or no-training) and tested on linguistic problems. A significant difference between training conditions was found [$F(2, 72) = 5.40$, $p = .006$, $\eta 2 = .13$]. Post-hoc analysis showed a significant difference between explicit instruction ($M = 9.00$, $SD = 2.61$) and no-training ($M = 7.32$, $SD = 2.88$), as well as structural priming ($M = 9.40$, $SD = 1.32$) and no training ($M = 7.32$, $SD = 2.88$). Implications of these results and avenues for future research are discussed.

Keywords: language, mathematics, reasoning, problem-solving

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Chapter 1: General Introduction

The presence of a cross-domain interaction between language and mathematics has been extensively debated in the literature (for a recent meta-analysis, see Peng et al., 2020). Evidence for the relationship between these two domains comes from two distinct lines of research with different linguistic populations. On one hand, cross-linguistic studies show that individuals who speak different languages (e.g., Spelke & Tsivkin, 2001) or have varied levels of proficiency in one language (e.g., Planas, 2014) show differences in performance on mathematical problems. On the other hand, studies comparing children with linguistic difficulties to typically-developing counterparts show difference in mathematical performance between the two linguistic groups (e.g., Cross et al., 2019). Both lines of research suggest that language acquisition and development are associated with numerical development and mathematical performance.

Although these population differences lend insight into the possible role of language in mathematical cognition, literature on the subject remains disconnected, and experimental evidence connecting these two domains is limited. Cross-linguistic studies suggest that language and mathematics rely on domain-specific features that might support cross-modal interactions (e.g., Purpura et al., 2019; Spelke, 2017), whereas research on co-morbid linguistic and mathematical difficulties suggests that the two abilities might also rely on domain-general cognitive processes to facilitate cross-modal processing and performance (e.g., DeSmedt et al., 2010; Fazio, 1999). The current research aims to move beyond population-based descriptions of this cross-modal association and investigate the domain-specific and domain-general processes underlying the relationship between language and mathematics.

Domain-Specific Features

Evidence for domain-specific transfer and exchange between language and mathematics representations comes from literature studying the role of linguistic processes in the development of number and mathematics. Several domain-specific features of language may contribute to cross-linguistic variations in number cognition and mathematical development. Domain-specific linguistic features, including symbolic awareness, vocabulary, grammatical cues, etc. may be involved in the development of number knowledge. For example, young children's understanding of numbers may be influenced by linguistic word-learning. Number words are the first symbolic quantitative knowledge acquired by young children, who develop the ability to pair number words with items in a set through counting (Fuson, 1988). Understanding the cardinal values of number words represents the first explicit understanding of formal mathematical concepts in young children. Success in determining the meaning of one number word, along with repeated contextual cues allows young children to understand both cardinality and succession (Carey, 2004; Le Corre & Carey, 2007).

Children may use the morphological distinction between singular and plural to determine the exact meaning of the number 'one' against larger numerals (Le Corre & Carey, 2007). For example, Sarnecka et al. (2007) found that English-speaking- and Russian-speaking children learned the exact meaning of 'one' earlier than Japanese-speaking children. This difference in acquisition may be explained by the fact that both English and Russian have consistent morphological markers (e.g., use of the letter 's' in English) to distinguish singular and plural words, but Japanese does not. It is possible that such syntactic regularities in the number system of a language influence the rote-counting abilities of young children.

Moreover, syntactic irregularities in the number systems of different languages influence the acquisition of rules needed to produce count sequences correctly. Young children's understanding of the structure of the count list in a language may impact how they represent the relative distances between number words in that language. Miller and Stigler (1987) found that Chinese-speaking children are able to count significantly higher than age-matched English-speakers. The authors suggest that this difference shows up in the 'teen numbers (11-19) where English, unlike Chinese, lacks a consistent rule for generating number names. Chinese number names are more linguistically transparent than English number names. For instance, the English number word 'eleven' translates to 'ten-one' in Chinese, communicating a clearer syntactic operation underlying the number word. In a similar study, LeFevre et al. (2002) found that Canadian English-speakers were able to master the count sequence earlier than French-speakers. This difference may be due to greater syntactic irregularities in the French number system, compared to the English system. One example of this is the 'teen' numbers of both languages. Both English and French have similarly irregular numbers for 11 and 12 (eleven, twelve vs. onze, douze). However, the numbers 13 to 19 are more predictable in English than in French. In English, all numbers between 13 and 19 end in the word 'teen', and most combine the unit-word with teen (e.g., sixteen, seventeen), such that only 'thirteen' and 'fifteen' are not entirely consistent with the simple rule, but share the same structure as all other 'teen' words. By comparison, in French the number-names continue to remain irregular till the number 16 (treize (13), quatorze (14), quinze (15), seize (16)). Following this, a new rule is used to generate the last three 'teen' number words. i.e., where the unit word follows ten (dix-sept (17), dix-huit (18), and dix-neuf (19)). It is possible that greater predictability of the English count system, compared to the French system makes counting in English comparatively easier to master. Both these studies suggest that the syntactic regularity of a count systems impacts the ways in which number words in that language are learned.

Spelke (2017) proposed that the grammar of conjunctive noun phrases (i.e., two cats and three dogs) and prepositional phrases (i.e., three piles of two waffles) facilitates the acquisition of new number words. To test this, Guerrero and colleagues (2020) conducted two independent studies in English and Korean to assess 4-to-10-year-old children's understanding of numerical syntax, using a novel (Give-a-number Base-10) task designed to probe their knowledge about the embedded structure of cardinal numbers. Children were asked to give a large number of items (e.g., 32 items) from a pool of items organized in sets of ten. The task was used to assess children's awareness of the embedded structure of numbers, i.e., knowing that 32 items are composed of three sets of ten and two ones. Korean-speaking children understood the embedded structure of cardinal numbers earlier than English-speaking children. These variations in acquisition maybe due to the ways in which the English and Korean number systems are syntactically different. The Korean number system is considered more syntactically regular than the English system, such that it reflects clear arithmetic operations whereas English system does not. In Korean, the number 12 is 'sib-ee' or 'ten-two', and the number 20 is 'ee-sib' or two-ten', wherein the same digit and multiplier are merged to represent the additive relationship (10+2) and the multiplicative relationship (10x2) respectively. By contrast, the English number words for 12 and 20 are lexically non-transparent. These results indicate that the regularity of the numerical syntax of a language may impact the point at which children understand the embedded structure of cardinal numbers. Therefore, understanding the meaning or cardinal value of each recursively embedded number word of a complex numeral and their operational relations is important for acquiring number concepts.

Linguistic influence on mathematical symbols extends beyond whole numbers to young children's part-whole thinking and fraction competence. Miura et al. (1999) compared the initial fraction ideas of first and second-grade Korean, Croatian, and American students.

According to the Korean naming system, a direct translation of a fraction such as 1/3 is “of three parts, one”. In comparison, the fraction is referred to as “one-third” in both English and Croatian. The Korean system allows for a direct mental representation of the magnitude, which is less clear in the other systems. As such, the researchers predicted a greater foundational knowledge of fractions in Korean, compared to Croatian and American students. The results of the study supported their hypothesis. These findings demonstrate that linguistic differences may influence the ways in which young children employ part-whole thinking to understand how different elements or quantities combine and decompose to solve fractions, and basic symbolic and non-symbolic arithmetic problems.

Beyond these developmental studies, research conducted with adults suggest that there may be a cognitive cost associated with shifting from one language to another. Spelke and Tsivkin (2001) trained bilingual adults in arithmetic fact retrieval, and found a language-specific advantage on exact arithmetic in trained, compared to untrained languages. Results demonstrated that participants needed more time to solve exact arithmetic problems when the language of training differed from the test language, compared to when the training and test language were the same. No language-related response latencies were found in the approximate number problems. In a similar study, Venkatraman et al. (2006) trained English-Chinese bilinguals on an exact base-7 addition task, as well as an approximate number task, which required percentage value estimations. Participants completed trained problems faster than untrained problems, and took less time to solve the exact base-7 addition task, than the approximate percentage estimation task. Presumably, the approximate number task required greater processing demands than the exact number task. Moreover, fMRI data showed a language-switching effect in the language-related areas of the brain (left inferior frontal gyrus (Left IFG) and left inferior parietal lobule extending to the angular gyrus) when switching from the trained to the untrained language during the exact number task. In the approximate number task, language-switching effects were predominantly found in the bilateral posterior intraparietal sulcus, a region typically involved in visuospatial attention and non-verbal processing, as well as the left IFG, slightly dorsal to the activation seen during the exact number task. These results indicate there are costs to language-switching for the retrieval of number facts, and highlight the ways in which exact number processing relies on verbal and language-related networks. These findings are also supported by research on multiplication and subtraction. Grabner and colleagues (2012) trained Italian-German bilinguals on two-digit multiplication and subtraction problems in both languages in an fMRI study. Participants were tested on both previously trained and novel problems. Results demonstrated language-switching costs, accompanied by activation of brain areas involved in numerical-stimulus recognition, magnitude-comparisons, visuo-spatial imagery, and executive functions. These differences may be due to some additional calculation processes required to transfer knowledge from the language of instruction to the language of retrieval. From these studies, it seems that individuals may be required to translate their knowledge from the language of learning to the language of application, and additional task-specific information processing may be required while switching languages.

Taken together, these studies demonstrate that linguistic processes may be recruited in, and crucial to mathematical problem-solving. Numerical development might rely heavily on domain-specific features of language, such that symbolic representations, morphology, syntax, and phonological cues might be important for accessing the cognitive processes – such as sound-symbol associations, number word-learning, and arithmetic fact retrieval – that are important for mathematical performance.

Domain-General Representations

Although this evidence from cross-linguistic developmental research suggests that domain-specific linguistic competence may be crucial for mathematical performance, a range of studies on children with co-morbid language and mathematics difficulties show that domain-general factors may also facilitate the cross-modal relationship between language and mathematics.

Key skills of language and mathematics, such as literacy (the ability to read and write) and arithmetic (the study of numbers and the operations between them) may draw on some shared domain-general representations. Children who have difficulties with mathematics often face challenges with literacy and language problems. For instance, Willcutt et al. (2013) found that students with mathematics or reading difficulties both demonstrated low verbal comprehension, and students who showed combined mathematics and reading difficulties showed additive negative effects. It is possible that the decoding skills – which refer to the ability to identify symbols and make phonological sound-symbol associations from memory – required for reading, may also be elicited during arithmetic fact retrieval, which is essential for mathematical competence. Arithmetic fact retrieval may recruit the same areas of the brain and may also share the same neurocognitive processes as reading (De Smedt et al., 2010).

This possible reliance on domain-general mechanisms is supported by research on children with Developmental Language Disorder (DLD), who perform less accurately on timed arithmetic problems compared to age-matched and younger typically-developing children. They also recall math facts less accurately than age-matched controls (Fazio, 1996; 1999). However, when calculation and performance was not constrained by time, Fazio (1999) found that children with DLD performed similarly to age-matched controls on arithmetic problems. No time-related improvements were found in the age-matched and younger control groups, suggesting that additional time for DLD children may facilitate fact retrieval, which in turn contributes to more efficient processing similar to typically-developing controls. It is possible that more time might allow children with DLD to access the resources they need to retrieve arithmetic facts from memory and solve arithmetic problems. These findings suggest that children with DLD may face difficulties using fact retrieval strategies to solve arithmetic problems, since they might have trouble with the recall of linguistic representations.

Further evidence for this comes from children with DLD who experience difficulty in mathematics development and performance. Kleemans et al. (2011) examined the extent to which 5-to-7-year-old children with DLD differ from typically-developing controls in early numeracy skills. Children were tested on their backwards and forward rote counting skills, as well as their ability to count organized and disorganized quantities of objects. A regression model showed that phonological awareness and grammar were significant predictors of count task performance. A significant relationship between naming speed and count tasks was found in the DLD group, but not the control group. By contrast, no significant relationship was found between nonverbal numeracy measures and verbal tasks, such as naming speed, grammar, and phonological awareness. The authors suggest that numerical representations and logical operations might draw on linguistic capacities such as phonological awareness and grammar, but variance in numerical estimation might be explained by domain-general factors, such as intelligence and visuo-spatial memory. In a similar study, Cowan et al. (2006) found that individual differences in language predicted count performance, in addition to other domain-general cognitive processes, including working memory and nonverbal reasoning in children with DLD.

Children with DLD have a lower count range compared to age-matched and vocabulary-matched typically-developing controls. Nys and colleagues (2013) examined the impact of linguistic skills on the later development of exact and approximate number skills in children with DLD compared to typically-developing children. Children with DLD performed worse on exact arithmetic tasks compared to age-matched and vocabulary-matched controls; performance was related to phonological measures. By contrast, children with DLD performed worse than age-matched controls on the symbolic approximate tasks, but there was no difference between children with DLD and younger vocabulary-matched controls. There was no significant difference between children with DLD and the two control groups on non-symbolic approximate tasks. More importantly. accuracy in approximate number tasks was not related to linguistic measures. According to the authors, linguistic competencies might be recruited for exact number tasks, but not approximate number performance.

Altogether these studies suggest that count proficiency might depend on domain-specific linguistic skills, but also on more domain-general cognitive processes. From these findings, it seems that domain-specific featural cues of language may play a role in the development of number concepts and mathematical performance. However, there is little to no evidence exploring the opposite pathway, i.e., the use of mathematical competencies in the development of linguistic concepts. Moreover, given the intermodal exchange (e.g., individuals relying on different cognitive processes, such as phonological processing, symbolic representations, etc.), it is possible that children who experience linguistic and mathematical difficulties might also recruit domain-general competencies, such as attention, working memory, and general intelligence for linguistic and mathematical representations. Different cognitive processes may be recruited, both within and outside language and mathematics.

Common Structural Representations

These two lines of evidence leave several questions open for consideration. Although there is evidence for a connection between linguistic and mathematical processes, the association between them, as described in the literature, is based entirely on population differences. There is little clarity about the nature of the cognitive processes underlying language and mathematics. Cross-linguistic studies suggest that domain-specific features of language may be important for mathematical development and processing, whereas research on children with co-morbid difficulties in the two domains suggest that other domain-general mechanisms, such as memory and intelligence may be crucial for cross-modal cognitive development. The research discussed thus far does not provide a sufficient explanation for the ways in which the two domains interact or draw from each other, or any other cognitive processes underlying the two domains. It might be possible that both language and mathematics draw on common or shared featural cues that are readily available to engage when solving linguistic and mathematical problems.

One way to think about the relationship between language and mathematics is to consider that linguistic and mathematical processes may draw on some common structural representations, such that access to specific featural cues might facilitate the cross-modal relationship between the two domains. Some limited experimental research from structural priming studies show evidence for this. Scheepers et al. (2011) demonstrated evidence for shared structural representations between the two domains. Participants were primed using mathematical equations either with parentheses, i.e., 80 – (9 +1) x 5 or without parentheses, i.e., 80 – 9 + 1 x 5. They were subsequently presented with a target sentence fragment, such as “I visited a friend of a colleague who lived in Spain.” There were two alternative interpretations to this sentence: a high-attachment or low-attachment. In the high-attachment alternative, the relative clause “who lived in Spain” attaches with the complex noun-phrase “a friend of a colleague” to imply that the friend lived in Spain. In the low-attachment alternative, the relative clause modifies the most recent simple noun-phrase to suggest that the colleague lived in Spain. The researchers found that when the mathematical equations were solved correctly, their structure – either with parentheses (high attachment) or without parentheses (low attachment) – influenced the noun-phrase that was chosen to complete the target sentence.

In a follow-up experiment, Scheepers and Sturt (2014) examined the cross-domain representation of structural information between language and mathematics by investigating the effects of the structure of a correctly solved mathematical equation on subsequent sentences containing high-attachment versus low-attachment relative clause ambiguities, and vice-versa. Participants solved structurally left-branching equations (5 x 2 + 7) or right-branching equations (5 + 2 x 7). They provided sensicality ratings (on a 5-point Likert scale from ‘makes no sense’ to ‘makes perfect sense’) for adjective-noun-noun compounds that were either left-branching (Alien monster movie) or right-branching (lengthy monster movie). In the first experiment, mathematical expressions were used as primes, and linguistic expressions were used as targets. In the second experiment, linguistic expressions were used as primes, whereas mathematical expressions were used as targets. A bi-directional priming effect – from language to arithmetic, and from arithmetic to language – was found. The results of these two studies suggest that some shared knowledge of the rules governing similar linguistic and mathematical problems may impact reasoning in the two domains.

Nakai and Okayona (2018) assessed whether neural activation reflected the structural integration between language and arithmetic demonstrated by Scheepers and colleagues (2011) in an fMRI study. Sentences and arithmetic expressions with the same and different syntactic structures were prepared, and presented in consecutive structurally congruent or incongruent pairs. A significant repetition suppression effect was observed in regions including the bilateral inferior frontal gyrus. Neural activation with an arithmetic expression decreased after a sentence with the same syntactic structure was presented, and vice versa. These results support the idea of a shared neural basis for processing language and arithmetic syntactic structures. Taken together with Scheepers et al. (2011) and Scheepers and Sturt

(2014), these findings suggest that structural similarity between language and mathematics problems may be a key element facilitating cross-modal interactions between the two domains.

The Current Research

Extensive research over the last few decades suggests that language and mathematics are related and interacting domains (e.g., Peng et al., 2020; Donlan et al., 2007; Geary et al., 1993). However, possible explanations for such findings remain largely absent from the literature. Experimental research assessing the connection between the two domains through training studies, interventions, etc. is limited.

This lack of experimental evidence limits our understanding of the role of other domain-general cognitive factors, such as intelligence, and working memory, as well as social factors, such as socio-economic status, educational attainment, age, and experience in potentially facilitating or confounding the cross-domain interaction between language and mathematics. It is possible that shared structural representations between the two domains facilitates cross-modal interaction, but the extent to which domain-specific featural cues – including symbolic letter and number representations, syntactic elements such as grammar and order of operations, as well as semantic associations like word-meaning – are limited to one domain or facilitate development across both language and mathematics also remains unclear. Additionally, and perhaps more importantly, it is not entirely clear whether this connection between language and mathematics is functional, which means that language is needed for communicating and engaging with mathematics, or whether the two domains rely on some shared structural integration or processing resource. The latter explanation would imply that the connection between the two domains is bi-directional – i.e., not only would language be needed for mathematics, but mathematics may also facilitate language development and skill – and that the same or similar cognitive systems may be recruited for processing linguistic and mathematical reasoning.

The current set of studies seeks to explore the nature of the cross-modal relationship between language and mathematics. Broadly, these studies seek to examine whether language serves a functional purpose, i.e., serves as a means to mathematics, or whether the two domains rely on some shared or interacting cognitive resource. The second chapter investigates the role of different domain-specific featural cues in facilitating linguistic and mathematical performance. The third chapter explores the role of explicitness of these cues in facilitating performance across the two-domains. Both studies seek to understand the role of domain-general competencies such as part-whole thinking and relational reasoning on performance in both domains.

Chapter 2: Introduction

Extensive evidence from studies with multi-lingual populations, children with developmental language disorders, and some limited experimentation and intervention suggests that the development of language and mathematics is interconnected and possibly interdependent. While some research argues that language may serve a functional purpose as a means to mathematics, other evidence suggests that language and mathematics rely on some shared common resource or deep structure that supports the development of both domains.

Language as a Pathway to Mathematics

Various models of cognitive development propose that language is a means to mathematics, i.e., individuals draw on their linguistic knowledge to perform mathematical tasks. LeFevre et al. (2010) proposed a pathway model of mathematics development, such that the development of early numeracy is dependent on three precursor pathways: quantitative skills, spatial skills, and linguistic skills. These pathways contribute independently to the development of early numeracy in preschool-aged children and kindergarteners. The three skills were differentially related to performance on different mathematical outcomes two years later. Linguistic skills (i.e., vocabulary and elision) were related to number naming, but not non-linguistic arithmetic, whereas quantitative skills (i.e., subitizing latency) were related to non-linguistic arithmetic performance. Spatial skills were related to number naming and numerical magnitude, supporting the idea that three independent precursor pathways contribute to mathematical development and performance. All three precursor pathways relate differently to different mathematical skills, but linguistic skills were found to be a consistent and stronger predictor of mathematical skill across tasks. This model suggests that mathematical performance may rely on underlying language competencies. However, it does not provide an explanation for the ways in which the linguistic and mathematical pathways are integrated, and the role of domain-general factors, such as attention and working memory in their integration.

In a similar proposal, the triple-code model of number processing suggests that representations from both verbal and non-verbal domains are involved in mathematics (Dehaene, 1992; Dehaene & Cohen, 1995). Similar to the pathways model, this model proposes that three mental representations (codes) support performance on numerical tasks: first, the visual Arabic numeral form, which represents numbers as digit strings (e.g., *5*); second, the verbal word frame, which represents numbers in linguistic form (e.g., *five*); and third, the analogue magnitude representation frame, which is comprised of semantic representations of magnitudes and approximations (e.g., a dotted array with five dots). One or more codes is accessed when performing numerical tasks. There are multiple routes linking one code to another, such that two types of codes can be accessed, without accessing the third. These two models suggest that language facilitates access to numerical representations, and that linguistic competencies support mathematical development in some way. Evidence supporting these models suggests that mathematical processing draws on some linguistic knowledge.

These two developmental models of cognition purport that language is a way of understanding mathematics. This would fall in line with existing research which suggests that linguistic processes are involved in the development of number concepts. Presumably if the relationship is pathway-dependent and unidirectional – such that linguistic competencies are accessed during mathematical cognition – then exposure to, or priming in language ought to facilitate better mathematical performance compared to no-exposure to linguistic stimuli. In addition, if linguistic representations are a unidirectional pathway to mathematical skills, similar exposure to mathematical representations ought not to impact linguistic performance. This means that exposure, to or priming in mathematics would not facilitate linguistic performance compared to no-exposure to mathematical stimuli. The current study investigates whether exposure to linguistic problems would facilitate performance in mathematics, and vice versa, i.e., whether the cross-modal relationship between language and mathematics is unidirectional (i.e., pathway-dependent as suggested by the multiple pathways and triple-code model) or bi-directional.

Shared Deep Structures

Contrary to the pathways models of cognitive development, another line of research argues that rather than one domain (language) facilitating the other (mathematics), the two domains have some common or shared deep structure or resource to draw on.

Chi and van Lehn (2012) suggested that academic tasks (e.g., reading and arithmetic) employ both surface features and deep structures: surface features include letters and words for literacy, and numbers and operational symbols for arithmetic, whereas deep structures refer to the rules, schemas, and principles involved in the linguistic or mathematical academic task. Collin and Laski (2019) suggested that early literacy and numeracy vary in surface level features, but have two common deep structures: symbolic mapping and relational reasoning. First, shared symbolic mapping refers to the process of fluently accessing the name and meaning of symbols. This includes letter identification, numerical identification, letter-sound knowledge, and numerical-quantity knowledge. Second, shared relational reasoning refers to rhyme awareness, magnitude comparison, phonological operations, and non-symbolic arithmetic problems. Relational reasoning involves pattern-extrapolation, analogical reasoning, part-whole thinking, and comparative thinking. Children are required to understand the ways in which different symbols relate to one-another by comparing and decomposing different words, quantities, and sounds. Additionally, knowledge about how small units of information (parts) combine to create larger units of meaning (wholes) is required in both early literacy and early mathematics. These two deep structures – symbolic mapping and relational reasoning – are involved in both linguistic and mathematical representations and problem-solving.

The current study tests these two deep structures proposed by Collins and Laski (2019) – symbolic mapping and relational reasoning – through different tasks. This study examines whether training participants to draw on different aspects of their knowledge, i.e., symbolic mapping or relational reasoning in one domain – language or mathematics – will impact their performance in the other domain.

The linguistic and mathematical reasoning conditions in this study ask participants solve different word and number analogies respectively. These problems ask participants to understand the ways in which two words in a pair relate to each other, and further explore the ways in which one word-pair might relate to a similar pair. Presumably, the task elicits some form of relational reasoning in one domain – language or mathematics – that can then be transferred to the other domain. The task is intended to highlight the presence of more domain-general cognitive mechanisms, such as working memory and intelligence, that might be involved in relational reasoning across the two domains. If participants are successful in solving these word or number analogies, they should be able to extrapolate similar patterns in different reasoning problems – either alphabetical sequences or number sequences – presented at test. By comparison, two structural prime conditions ask participants to solve sequences in one domain – alphabetical or numerical – and then ask them to solve corresponding sequences in the other domain. This task is intended to elicit the second of the deep structures: symbolic mapping. Participants need to draw on their knowledge of different letters and numbers and understand what they mean, and how they relate to each other. This task is intended to highlight a domain-specific featural cue in language and mathematics. Presumably, understanding the ways in which different symbols connect in one domain should facilitate participants' ability to do so in another domain.

These different tasks are intended to elicit different shared deep structures – symbolic mapping or relational reasoning – in facilitating the cross-modal interaction between language and mathematics. More broadly, these two tasks aim to understand the ways in which different domain-specific and domain-general featural cues are accessed to perform both linguistic and mathematical tasks.

The two experiments in this chapter examine whether the cross-modal relationship between language and mathematics is functional, i.e., linguistic knowledge facilitates mathematical understanding, or whether language and mathematics draw on some shared common resource or deep structure that facilitates performance in both domains. Experiment 1 focuses on the language to mathematics training-transfer and attempts to shed light on the directionality of this cross-modal relationship, whereas Experiment 2 focuses on the mathematics to language training-transfer. Both experiments explore the role of common or shared domain-specific and domain-general representations of language and mathematics in facilitating cross-modal interaction. The specific research questions asked in these two experiments are as follows:

1. Does training adults to extrapolate patterns and engage in linguistic reasoning in facilitate performance in corresponding mathematical reasoning, and vice-versa?
2. Does exposure to structurally and symbolically similar linguistic questions facilitate performance in corresponding mathematical questions, and vice-versa?

Experiment 1

Method

Participants

Participants were 156 adults aged 18 to 72 years *(M* = 38.60 years*)*, who were fluent in the English language and had completed secondary or high school-level education. All participants reported English as their first language. Participants were randomly assigned to one of three language training conditions: linguistic reasoning, structural priming, and a no-training control condition. A total of 52 participants were assigned to each training group.

Materials

Participants were trained on a set of novel linguistic stimuli and tested on corresponding mathematical stimuli. These included:

Word Analogies

The word analogies require participants to use their vocabulary knowledge to engage in analogical reasoning. Participants need to discern the pattern between each term in a problem and decide which of the given options best fits the problem. These were used as training items for the linguistic reasoning group. Examples include:

Warm : Hot :: ______ : Hilarious
Options: (a) humid (b) summer (c) sunny (d) funny

Reading : Books :: ______ : Movies
Options: (a) watching (b) eating (c) TV (d) listening

Alphabetical Sequences

The alphabetical sequencing task recruit participants' letter recognition and sequencing knowledge. Participants need to identify individual letters and how they might relate to other letters or letter series in a given problem. These were used as training items in the structural priming group. Examples include:

Complete the series: A C E G ?

Complete the series: jJ kK lL mM nN ?

Number Sequences

Participants need to identify the value of individual numbers and recognize how they might relate to the other numbers or number sequences in a meaningful manner. These were used as test items. Examples include: "Complete the series: 1 3 5 7 ?

Complete the series: 4 8 12 16 20 ?

Pilot data collected prior to this experiment using a sample of 104 participants showed moderate correlations between these training and test items, as depicted in *Table 1*.

Table 1. *The Correlations between All Novel Training and Test Items Used in the Study.*

		Pearson's r*	Lower 95% CI	Upper 95% CI
Number Analogies	- Word Analogies	0.54	0.38	0.66
Number Analogies	- Number Sequences	0.47	0.30	0.60
Number Analogies	- Alphabetical Sequences	0.44	0.27	0.58
Word Analogies	- Number Sequences	0.35	0.16	0.50
Word Analogies	- Alphabetical Sequences	0.42	0.25	0.57
Number Sequences	- Alphabetical Sequences	0.63	0.49	0.73

*$p < .001$

In addition to these training and test stimuli, participants were asked to report their age and whether English was their first language.

Procedure

Participants were trained on linguistic problems and tested on mathematical problems. They were randomly assigned to one of three training conditions: linguistic reasoning, structural priming, or a no-training control condition.

In the linguistic reasoning condition, participants were asked to complete a series of 12 word-analogies that were progressive in difficulty. Feedback was provided on each question. Once a question was answered, participants were able to review an explanation and solution for it. In the structural priming condition, participants were presented a series of 12 alphabetical sequences that were progressive in difficulty. Participants were given no feedback on their responses. In the no-training control condition, participants received no linguistic training and were directed to the test phase.

Training criterion was set at eight correct responses for both training conditions – linguistic reasoning and structural priming. Participants who received a score of eight or more were considered trained. Conversely, participants who received a score of seven or less in either of the two training conditions were removed from the study. In the test phase, all participants answered 12 number sequence questions that were progressive in difficulty. Participants had one minute to answer each question and received no feedback on their responses.

Results

A One-Way Analysis of Variance (ANOVA) was conducted to analyse the effectiveness of the three different types of linguistic training – linguistic reasoning, structural priming, and no-training – on mathematical performance. Results indicated no significant difference between training conditions $F(2, 153) = 1.69$, $p = .18$, on participants' mathematical performance.

These results suggest that linguistic training does not impact mathematical performance, highlighting that the relationship between language and mathematics is not pathway-dependent, i.e., language is not a functional means to mathematics. To understand whether this association might be guided by other common or shared representations, the next experiment explores whether mathematical training facilitates performance in linguistic problem-solving.

Experiment 2

Method

Participants

Participants were 144 adults aged 18 to 69 years (M = 39.29 years), who were fluent in the English language and had completed secondary or high school-level education. All participants reported English as their first language. Participants were randomly assigned to one of three mathematical training conditions: mathematical reasoning, structural priming, and a no-training control condition. A total of 48 participants were assigned to each training group.

Materials

Participants were trained on a set of novel mathematical stimuli and tested on corresponding linguistic stimuli. The correlations between these items are referenced in *Table 1*. These include :-

Number Analogies

Number analogies require participants to use their knowledge of numbers and arithmetic facts to engage in analogical reasoning. Participants need to discern the pattern which connects the different numbers in a given problem, and decide which of the given options best fits the problem. These were used as training items for the mathematical reasoning condition. Examples include:

3 : 1 :: 7 : ______
Options: (a) 3 (b) 5 (c) 6 (d) 1

4 : 6 :: ______ : 16
Options (a) 14 (b) 11 (c) 2 (d) 8

Number Sequences

These items are the same as the sequences used in the test phase in Experiment 1. These were used in the structural priming condition for this experiment.

Alphabetical Sequences

These items are the same as the sequences used in the structural priming training condition in Experiment 1. These were used in the test phase of this experiment.

Procedure

This experiment was conducted in a similar fashion to Experiment 1. Participants were randomly assigned to one of three training conditions: mathematical reasoning, structural priming, or a no-training control condition.

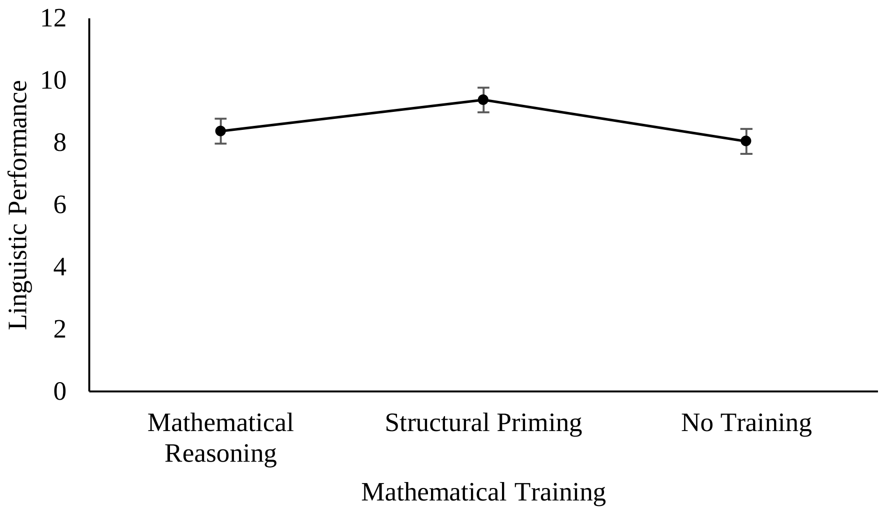
Similar to the linguistic reasoning condition, participants in the corresponding mathematical reasoning condition were asked to complete a series of 12 number-analogies that were progressive in difficulty. Feedback was provided on each question. Once a question was answered, participants were able to review an explanation and solution for it. Similarly, in the structural priming condition, participants were presented a series of 12 number sequences that were progressive in difficulty. Participants were given no feedback on their responses. In the no-training control condition, participants received no mathematical training and were directed to the test phase. Following the same training criterion, participants who received a score of eight or more on either of the mathematical training paradigms – mathematical reasoning or structural priming – were considered trained.

In the test phase, all participants answered 12 alphabetical sequencing questions that were progressive in difficulty. Participants had one minute to answer each question, and received no feedback on their responses.

Results

A One-Way Analysis of Variance (ANOVA) was conducted to analyse the effectiveness of the three different types of mathematical training – mathematical reasoning, structural priming, and no-training – on linguistic performance. Results indicated a significant difference between training conditions $F(2, 142) = 3.86$, $p = .02$, $\eta 2 = .05$. on participants' linguistic performance (Figure 1).

Figure 1. *Line Graph Depicting the Three Different Types of Mathematical Training (i.e., Mathematical Reasoning, Structural Priming, and No Training) on the x-axis, and Participants' Subsequent Linguistic Performance on a scale of 0 to 12 on the y-axis.*



A Tukey post-hoc test showed a significant difference between the structural priming (*M* = 9.37, *SD* = 1.99) and no-training conditions (*M* =8.04, *SD*=2.66). However, no significant difference was found between the mathematical reasoning (*M* = 8.37, *SD* = 2.65) and no-training conditions (*M* =8.04, *SD*=2.66). Similarly, there was no significant difference in mathematical performance between the mathematical reasoning (*M* = 8.37, *SD* = 2.65) and structural priming (*M* = 9.37, *SD* = 1.99) conditions.

Discussion

The current study examined whether training in language would facilitate performance in mathematics, and vice versa. Moreover, it investigated whether the nature of training – either highlighting commonalities in relational reasoning or priming symbolic representations – in one domain would impact performance in the other. The results of the first experiment showed that linguistic training did not facilitate performance in mathematics. By contrast, the results of the second experiment demonstrate that structural priming of mathematical symbols elicited better performance in corresponding linguistic problems, compared to mathematical reasoning and no-training.

These results lend insight into the nature of the cross-modal relationship between language and mathematics. The first question asked in this study was whether this cross-modal relationship was pathway-dependent or shared. Pathway models of mathematical development, such as the multiple pathways model (LeFevre et al., 2010) and the triple-code model (Dehaene, 1992; Dehaene & Cohen, 1995) propose that language facilitates access to numerical representations, and that linguistic competencies are recruited during mathematical performance. These pathways models are supported by existing evidence from cross-linguistic studies, which suggest that that domain-specific featural cues of language, such as morphology, word-meaning, and syntax, are recruited during number development and mathematical problem-solving. If language serves as a pathway to mathematics, then presumably, linguistic training in this study would have enhanced mathematical performance compared to no-training, but presumably, mathematical training would not have any impact on linguistic performance. Given that there was no significant effect of linguistic training on mathematical performance, it seems that linguistic representations may not be a pathway or means to mathematical representations.

Contrary to the results of the first experiment, the second experiment showed that mathematical training did facilitate linguistic performance, such that participants who were structurally primed to answer number sequences performed better on linguistic sequences than those in the no-training control condition. However, participants who trained in mathematical reasoning did perform differently than the control group. There is little research examining whether mathematical development and experience impacts linguistic performance. The current literature does not provide evidence for a mathematical pathway to linguistic representations. In this absence of this research, it is hard to determine the ways in mathematical representations or processing impacts linguistic performance. Presumably, results showing that the mathematical reasoning condition did not facilitate linguistic problem solving, indicate that there may not be a mathematical pathway to language. However, a positive effect of mathematical structural priming on linguistic performance is in line with evidence from structural priming studies (e.g., Scheepers & Sturt, 2014) that suggest that language and mathematics draw on shared representations. These results suggest that language and mathematics might draw on shared representations or deep structures that facilitate a cross-modal relationship between the two domains.

One challenge posed by the results of Experiments 1 and 2 around a model of shared representations or deep structure is that the data do not show a bi-directional transfer: while mathematical training facilitated cross-modal transfer, linguistic training did not. This may be because domain-specific symbolic cues in mathematics may make corresponding symbolic representations easier to access during linguistic problem-solving. In comparison, participants may not have drawn on linguistic featural cues during mathematical problem-solving, because mathematical symbolic representations may be easily accessible through other domain-general mechanisms, such as working memory which is involved in arithmetic fact retrieval (DeSmedt et al., 2010). Moreover, it is possible that the domain-specific featural cues in language and/or mathematics may work to elicit domain-general mechanisms, such that they are easier to access during linguistic and mathematical problem-solving. For instance, symbolic mapping – a shared deep structure outlined by Collins and Laski (2019), which refers ability to identify and map different symbols and make phonological letter-sound and number-sound connections – may be recruited while engaging in domain-general processes, such as analogical reasoning, pattern extrapolation, and part-whole thinking, involved in problem-solving across both domains. Overall, the salience of these specific featural cues in one domain may make domain-general processes easier to access when acting in the other domain.

Limitations

There are a few open questions to consider in interpreting these results. The first of these is around participant recruitment and task performance. Data were collected on Amazon Mechanical Turk (M-Turk). Research participants on M-Turk are unsupervised and motivated by financial incentives. Given this, there are some concerns around participants' attentiveness to instructions and tasks, and its possible impact on data quality (e.g., Chandler et al., 2014). To mitigate possible issues around data quality, response time on individual questions and time-to-completion were monitored in this study. This was done to ensure that participants spent time working through the problems presented to them, and did not skip through the study only for the financial incentive associated with their participation. While response time did not seem to confound performance in either domain, these M-Turk data should be understood relative to data collected using more traditional recruitment methods in order to truly assess data quality, and discuss possible opportunities and challenges related to using crowdsourcing platforms for participant recruitment.

Another consideration is around the level of participant engagement in these tasks. Given that these experiments are not conducted in a controlled environment, it is hard to determine impact of possible environmental confounds, as well as the salience of different featural cues on participants' performance. Participants may be drawing on other task-specific or external cues to solve problems. Differences in engagement might impact the explicitness of specific featural cues or deep structures during training, which in turn, might impact participants' performance on test. Synchronous participation might create more controlled conditions and increase task engagement for participants. These limitations are addressed in the next experiment.

Conclusion

Understanding whether domain-specific featural cues, such as symbolic representations, plays a central role in linguistic and numerical systems requires an understanding the extent to which participants draw on symbolic processes while performing a task. While it seems that symbolic mapping may be important for both linguistic and mathematical cognition, it is not entirely possible to dissociate this shared deep structure from a specific task effect. This is especially true given that structurally priming participants to mathematics elicited better linguistic performance, but priming participants to language did not lead to better performance in mathematics. It is possible that the degree of explicitness of symbolic featural cues in the given task might also impact performance. These mechanisms may need to be understood better to conclusively understand the role of shared deep structures in the cross-modal relationship between language and mathematics.

While the impact of explicitness of different featural cues in facilitating the cross-modal interactions remains an open question, the results of this study demonstrate that individuals broadly draw on some shared representations or deep structures when performing linguistic and mathematical tasks. Although they may not always support each other in direct ways, the cross-modal relationship between language and mathematics may be supported through domain-specific features, as well as domain-general mechanisms.

Chapter 3: Introduction

Language and mathematics may rely on some shared representation or deep structures during problem-solving across the two domains. One such deep structure is symbolic mapping (Collins & Laski, 2019). This refers to the ability to make sound-symbol connections to identify and recognize letters in language (e.g., Aa, Bb, Cc, etc.), numbers in mathematics (e.g., 2, 3, 4, etc.), as well as other relational symbols that might represent some linguistic-semantic meaning (e.g., &, $, etc.) or mathematical operation (e.g., +, -, =). Symbolic representations are considered instrumental to language and mathematics. One example of the role of symbolic representations in language is in prior research on reading and literacy. Letter identification is a strong predictor of reading performance (Foulin, 2005; Snow et al., 1998). Moderate to high correlations have been found between letter identification prior to formal schooling and later reading abilities (Snow et al., 1998; Stuart, 1995). Similarly, numerical identification is correlated to numerical magnitude estimation (Berteletti et al., 2010; Kolkman et al., 2013), showing that symbolic representations may be important for understanding number representations and mathematical processing.

Given that symbolic mapping facilitates domain-specific performance, it is possible that symbolic mapping may also facilitate cross-domain interaction, i.e., the process of identifying and mapping symbols in one domain might facilitate performance in the other. This is supported by the results of previous study (see Chapter 2) which shows that structurally priming participants to solve symbolic numerical problems facilitated their performance on corresponding symbolic problems in language, compared to no priming. These results suggest that the domain-specific features of mathematics may be accessed during linguistic problem-solving, such that structural priming participants to symbols in mathematics might have made the deep structures shared between the two domains more accessible during linguistic problem-solving. An open question remains about whether increased access to these deep structures – in this case symbolic mapping – might facilitate performance across language and mathematics. There are two lines of evidence that suggest that greater access to domain-specific features and domain-general mechanisms might support cross-modal training and transfer. Some research suggests that the explicitness of domain-specific features of language, such as vocabulary, syntax, and structure, might facilitate numerical development and mathematical performance. Moreover, research on mathematical instruction (e.g., Chow & Jacobs, 2016; Fuchs et al., 2020) suggests that highlighting different linguistic features during mathematics might facilitate the development of mathematical concepts, and positively impact mathematics performance.

The Role of Domain-Specific Featural Cues

Prior research suggests that explicitly directing individuals' attention to similarities between different tasks leads to improvement on more abstract reasoning-based tasks, such as equivalence problems and search tasks (e.g., Cook et al., 2013; DeLoache et al., 1999). Increased awareness of, and reduced errors in syntactic and semantic reasoning, could enhance learning outcomes in mathematics (Easdown, 2009). This may be true for studies examining the relationship between language and mathematics.

Prior research shows that domain-specific featural cues in language facilitate performance in mathematics. The explicitness of specific semantic cues, such as vocabulary or word-meaning might play into this cross-modal relationship. For example, Purpura and colleagues (2011) investigated the unique relationship between early literacy (vocabulary, phonological awareness, and print knowledge) in preschool-aged children's numeracy development one year later. The researchers found that vocabulary and print knowledge accounted for variance in numerical development. Vocabulary was a significant predictor of young children's early numeracy skills. Prior research suggests that mathematics-specific vocabulary or mathematics language – which consists of specific-vocabulary used to refer to quantitative relations, such as ‘more than’, ‘less than’, ‘fewer’, etc., and spatial relations, such as ‘below’, ‘above’, ‘near, ‘far,’ etc. – facilitates performance in both language and mathematics (see Purpura et al., 2019 for review). These studies support the idea that linguistic aptitude/knowledge can facilitate mathematics performance.

Extensive examples of the role of different domain-specific features in facilitating cross-modal performance across language and mathematics come from the literature on word problems. Variations in semantic structures affect the ease with which word problems are solved by young children. According to Kintsch (1986), two factors influence the level of difficulty of word problems for children. First, the closer the linguistic structure to the underlying calculation structure, the easier the problem is to solve. Second, the more indirect or imprecise the language signalling the calculation structure, the harder the problem is to solve. Familiarity with diction and syntax also influence the relative difficulty of a problem (Kintsch, 1986). For instance, addictive structures can be easier to solve than multiplicative structures, relational statements, and quantitative comparisons (Kintsch & Greeno, 1985).

Abedi and Lord (2001) examined the differences in performance on mathematical word problems between English language learners (ELL) and native English speakers. Students were presented items from a standardized mathematics assessment, as well as revised items which used simplified language. Revisions included changes of verb voice from passive to active voice and shortened nominals. Conditional clauses were replaced with separate sentences, and relative clauses were removed or recast. Finally, unfamiliar and infrequent words were changed. The authors reported that although ELL speakers scored significantly lower than proficient English speakers on mathematical word problems, modifying language structures to make them linguistically simpler led to improvements in performance. The modifications benefitted ELL speakers and students from low SES families more in comparison to proficient English speakers, and students from higher SES families.

The results of these studies suggest that highlighting different features of language and number might impact performance across the two domains. If these studies are considered in conjunction with the findings on symbolic representations, it may be possible that further highlighting the symbolic cues elicited during structural priming in the previous study might further improve performance in the two domains.

The Role of Instruction

Some evidence for the role of explicit instruction in facilitating performance across the two domains comes from literature on mathematics instruction. Stocco and Prat (2014) examined differences between monolingual and bilingual speakers on mathematical operations, such as “subtract one from y” and “multiply x by two”. No significant differences in performance were found on trials where mathematical operations were repeated from the previous problem. However, bilingual participants had faster response times on problems with novel operations, compared to their monolingual counterparts. Planas (2014) observed interactions between Catalan language learners and native language speakers, while solving algebraic problems in small groups. Catalan language learners attempted to solve the problems using different strategies, such as using geometric approaches to understand algebraic functions, since they lacked the mathematics-specific terminology required to describe the problems. Additionally, the language learners focused more on the meaning of mathematical terms than native speakers.

Chow and Wehby (2019) found a significant interaction between language and symbolic instructional representations in an equal-sign instructional classroom intervention. The authors suggest that the linguistic abilities of young children might involve individuals’ understanding of systems of symbolic representations that are instrumental to the development of mathematics concepts.

Prior research suggests that instruction and intervention in mathematics-specific language benefits children's literacy and numeracy skills, that are important components of early linguistic and mathematical development. Purpura, Logan et al. (2017) investigated how and why early mathematics is a significant predictor of early literacy development in 3-to-5-year-old children. The results suggest that the relations between early mathematics and early literacy were mediated by mathematics language skills. In the same year, Purpura, Napoli et al. (2017) examined the relationship between mathematics language and mathematics skills and knowledge using an eight-week-long dialogic reading intervention. Children were either assigned to a mathematical language intervention, in which dialogic reading focused on quantitative and spatial mathematical language, or a control group. Students in the intervention group performed significantly better than those in the control group on both mathematics language and mathematics knowledge assessments. These studies suggest that mathematics-specific language instruction may be crucial for young children's mathematical reasoning skills.

Fuchs et al. (2020) tested the efficacy of embedded language-instruction intervention on word-problem solving in first-grade children who demonstrated low mathematics accuracy. Participants were assigned to one of four intervention conditions: first, schema-based word-problem intervention with embedded language comprehension, second, the same intervention without embedded language comprehension instruction, third, a number knowledge intervention with a word-problem component, and fourth, a control group. Children in the schema-based intervention with embedded language instruction performed significantly better than children who did not receive embedded language comprehension instruction. No significant difference was found between the number knowledge and control groups. Children in all three intervention conditions performed better than those in the control group. These results suggest that language instruction facilitates young children's mathematical problem-solving skills.

From this research on mathematics instruction, it seems that explicit instruction about specific features of language and number, such as symbolic representations, vocabulary, and syntax, might facilitate performance in the two modalities. Instruction may be an important tool for eliciting common deep structures in both language and mathematics, in turn facilitating pattern recognition, reasoning, and problem solving across two the domains.

Emerging Questions

The previous study described in Chapter 2 showed that symbolic mapping was recruited for both language and mathematics. However, the extent to which participants rely on symbolic mapping to solve linguistic and mathematical problems remains unclear. The existing literature demonstrates that explicit instruction on the different features (e.g., symbolic representations, word meanings, etc.) and rules (e.g., grammar, sentence structure, order of operations, etc.) governing language and mathematics may facilitate performance across the two domains. Therefore, the current study examines whether increasing the salience of symbolic featural cues or representations impacts the cross-modal relationship between language and mathematics by asking the following questions:

1. Does explicit instruction about symbolic mathematical patterns facilitate better performance on corresponding linguistic problems compared to implicit structural priming?
2. Does explicit instruction about symbolic mathematical patterns facilitate better performance on corresponding linguistic problems compared to no exposure or training to mathematical symbols?

Method

Participants

Participants were 75 undergraduate students at Huron University College, a small liberal arts college in southwestern Ontario. All participants, aged 18 to 23 years, were fluent in the English language. Participants were randomly assigned to one of three language training conditions: explicit instruction, structural priming, and a no-training control condition. A total of 25 participants were assigned to each training group.

Materials

The materials used in this study were the same as the previous one. Number sequences were used as training stimuli in both training conditions: explicit instruction and structural priming. Alphabetical sequences were used as test items in all three conditions.

Procedure

Participants were randomly assigned to one of three training conditions: explicit instruction, structural priming, or a no-training control condition.

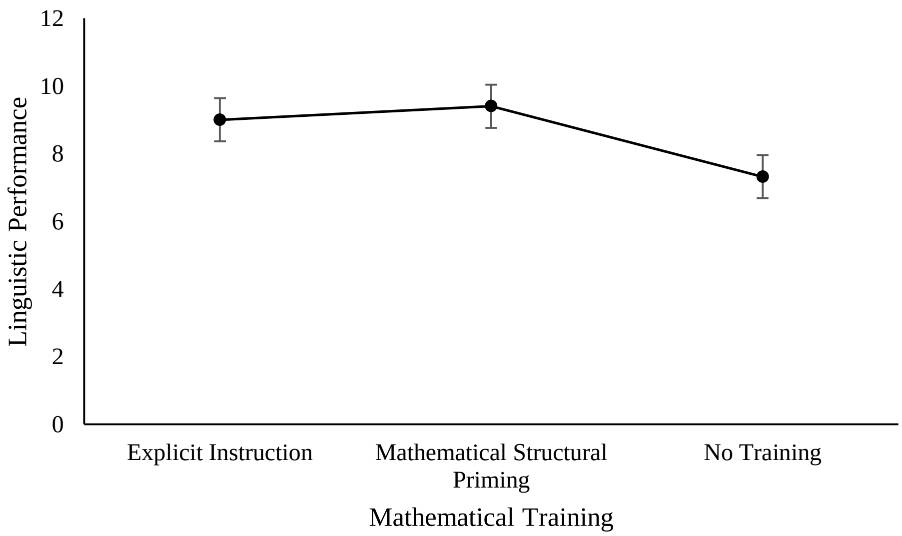
The mathematical structural priming and no-training conditions were the same as the first study. In the structural priming condition, participants were presented a series of 12 number sequences that were progressive in difficulty. Participants were given no feedback on their responses. In the no-training control condition, participants received no mathematical training and were directed to the test phase. By contrast, in the new explicit instruction condition, participants were presented the same series of 12 number sequences and given feedback after each question. Once a question was answered, the experimenter highlighted the pattern of numbers in each sequence and also revealed the correct answer. This meant that participants had an explanation and solution to each question before moving on to the next. For both training conditions, training criterion was set at eight correct responses, i.e., participants who received a score of eight or more on either of the mathematical training paradigms – explicit instruction or structural priming – were considered trained. In contrast to the first study, participants were trained through live-synchronous interaction.

In the test phase, all participants answered 12 alphabetical sequencing questions that were progressive in difficulty. Participants had one minute to answer each question, and received no feedback on their responses.

Results

A One-Way Analysis of Variance (ANOVA) was conducted to analyse the effectiveness of different levels of explicitness in mathematical training – explicit instruction, structural priming, and no-training – on linguistic performance. Results indicated a significant difference between training conditions $F(2, 72) = 5.40$, $p = .006$, $\eta 2 = .13$. on participants' linguistic performance (Figure 2).

Figure 2. *Line Graph Depicting Three Different Types of Mathematical Training (i.e., Explicit Training, Structural Priming, and No Training) on the x-axis, and Participants' Subsequent Linguistic Performance on a scale of 0 to 12 on the y-axis.*



A Tukey post-hoc test showed a significant difference between the explicit instruction (M = 9.00, SD = 2.61) and no-training conditions (M =7.32, SD=2.88). In addition, a significant difference was found between structural priming (M = 9.40, SD = 1.32) and no training (*M* =7.32, *SD*=2.88). However, no significant difference was found between two training conditions: explicit instruction (*M* = 9.00, *SD* = 2.61) and structural priming condition (*M* = 9.40, *SD* = 1.32).

Discussion

This study investigated whether increasing the salience of symbolic featural cues in mathematics problems facilitates performance on corresponding linguistic problems. Explicit instructional training in mathematics was compared to implicit structural priming and no-training. Results indicate that training participants in mathematics – either through explicit instruction or structural priming – facilitated performance on corresponding linguistic problems compared to no mathematical training. There was no difference in linguistic performance between the two training conditions. Overall, these results suggest that mathematical training facilitated performance in linguistic problem solving, but the type of mathematical training participants received did not differently impact linguistic performance.

In line with the results of the Experiments 1 and 2 (Chapter 2), structurally priming participants to numerical symbols facilitated their performance in linguistic problems involving alphabetical symbols. Similarly, explicit instruction to highlight symbolic representations in mathematics facilitated performance in linguistic problems, compared to no mathematical training. These results align with Collins and Laski's (2019) proposal that language and mathematics shared common deep structures. Moreover, it supports the idea that domain-specific featural cues in mathematics (i.e., symbolic numerical representations) make corresponding linguistic representations more accessible for solving linguistic problems.

This study also examined whether explicit instruction about symbolic mathematical patterns facilitated better performance on corresponding linguistic problems compared to implicit structural priming or no exposure. Presumably, explicit instruction would draw attention to symbols in mathematics in a manner that implicit structural prime could not, as suggested in the literature on mathematics instruction and intervention. Explicit instruction would increase the salience of symbolic featural cues in the mathematical problems, thereby facilitating better performance in language compared to an implicit structural prime. However, the lack of difference in linguistic performance between the two training conditions – explicit instruction and implicit structural priming –suggests that explicit instruction may not increase the salience of symbols. It is possible that structural priming in mathematics sufficiently elicits the deep structure required to solve similar linguistic problems. Explicit instruction may not add value by further directing attention to the underlying deep structure (i.e., symbolic mapping) as anticipated. The facilitation effect seen in the implicit structural priming condition may suggest that simple exposure to mathematical problems may be enough to facilitate better linguistic performance. Despite this, mathematical training does yield better linguistic performance than no training.

Addressing Limitations

The training and transfer experiments discussed in Chapter 2 left open questions related to the efficacy of mathematical training in supporting linguistic transfer. A specific concern was around the use of Amazon M-Turk participants as the sample of the study, given previously expressed concerns about participants' attentiveness and motivations for participation, and its possible impact on task performance. However, the results of this study might alleviate that concern: the results of the structural priming condition in this study were the same as the one used previously. Average performance on linguistic problems after being structurally primed to mathematical problems remained consistent across the two studies. Undergraduate students performed at par with M-Turk workers, confirming the efficacy of the mathematical training.

Another open question in previous study was around task engagement. One concern was that asynchronous, self-directed training might negatively impact performance, posing possible challenges to participants' attentiveness to the task at hand. To address this, training for this study took place synchronously in the presence of an experimenter. Once again, consistent performance and no difference between the common training conditions in the two studies suggests that the lack of synchronous engagement may not have been a barrier to task performance. Moreover, possible differences in attention as a result of differential modes of engagement did not confound the results of either study.

Conclusion

These results lend valuable insight into the deep structures underlying the cross-modal relationship between language and mathematics, and address important questions left unanswered in the previous study. However, these data also generate new questions about the strengths and limits of explicit instruction in supporting cross-modal training and transfer.

In this study, instruction was conceptualized as a way to make symbolic cues more explicit for participants, thereby facilitating greater cross-modal transfer than an implicit structural prime. Although there was no significant difference explicit and implicit training, explicit instruction did not negatively impact performance either. It is possible that explicit instruction facilitates performance, but does so by relying on other deep structures or cognitive processes other than symbolic mapping. For instance, instruction might facilitate arithmetic fact retrieval without relying on symbolic featural cues.

Moreover, the ability to identify numerical patterns to solve linguistic problems might draw on other domain-specific and domain-general skills and processes. For instance, phonological skills, random automatized naming, and working memory might impact the ways in which instruction is received, comprehended, and applied to problem-solving. Alternatively, explicit instruction might only serve as a means to communicate and clarify task requirements and directions. Perhaps the competencies employed for instruction may not be competing with symbolic mapping, but drawing on other features or skills to support the cross-domain interactions between language and mathematics.

Ultimately, it seems that mathematical training facilitates linguistic processing and problem-solving overall compared to no mathematical training, but explicit instruction about the patterns connecting mathematical symbols may not serve an additional, or even the same purpose as simple exposure or priming to symbolic featural cues, both within and between language and mathematics.

Chapter 4: General Discussion

The present set of studies described in this thesis investigated the relationship between language and mathematics. Chapter 2 explored whether training participants in one domain would facilitate performance in the other domain through two different training and transfer experiments. The first experiment examined whether different types of training in language – i.e., linguistic reasoning, structural priming, and no-training – would facilitate performance on corresponding mathematical problems. Results suggested that training participants in language did not impact their mathematical performance compared to no-training controls. Neither linguistic reasoning, nor linguistic structural priming supported mathematical performance. The second experiment investigated whether training participants in mathematics – i.e., mathematical reasoning, structural priming or no-training – would facilitate performance on corresponding linguistic problems. Results suggested that training participants in mathematical problem-solving yielded better results on participants' linguistic performance than those who received no mathematical training. Although mathematical reasoning did not impact linguistic performance, participants who received mathematical structural priming performed better on corresponding linguistic problems compared to the other groups.

Chapter 3 expanded on the results of this experiment (Experiment 2, Chapter 2), by examining whether the nature of mathematical training – i.e., explicit instruction and feedback compared to the implicit structural prime used in the previous experiment – would impact linguistic performance in comparison to no mathematical training. Results indicated that participants who received mathematical training – either explicit instruction or structural priming – performed better on linguistic problems than those who received no training. No difference in participants' linguistic performance was found between the two training conditions, but overall, mathematical training elicited better linguistic performance than no training. In addition, participants' scores on linguistic problems were replicated: participants' scores after receiving mathematical structural priming were consistent across the two studies. There are a few possible explanations for these results and a few different ways to take this research forward.

Implications

Experimental evidence for the cross-domain interaction between language and mathematics is limited. A majority of the evidence linking the two domains comes from from research conducted with different linguistic populations, which show that variations in linguistic skills impact mathematical development and performance. Studies comparing children with linguistic difficulties to typically-developing counterparts show differences in mathematical performance between the two linguistic groups (e.g., Archibald et al., 2013; Cross et al., 2019). Similarly, cross-linguistic studies comparing individuals who speak different or multiple languages show cognitive costs in mathematical performance (e.g., Grabner et al., 2012; Spelke & Tsivkin, 2001). This evidence predominantly connects the process of language acquisition to numerical development. However, the prevalence of a cross-modal relationship between language and mathematics is debated (see Peng et al., 2020). The results of this thesis demonstrate that the two domains do interact with each other and share some kind of cross-modal connection.

Moreover, the nature of the relationship between linguistic and mathematics is unclear. Evidence from cross-linguistic developmental research suggests that the relationship between language and mathematics is pathway-dependent (i.e., language is a means to mathematics). This line of research is explained in pathway models of cognitive development (e.g., Dehaene, 1992; Dehaene & Cohen, 1995; LeFevre et al., 2010), which propose that individuals draw on their linguistic knowledge to perform mathematical tasks. By contrast, research conducted with clinical populations suggests that language and mathematics may rely on some domain-general mechanisms, such as attention, working memory, and intelligence. A third line of experimental research has hinted at the relationship between language and mathematics as relying on shared representations, i.e., both draw on some common cognitive resource (e.g., Collins & Laski, 2019). In comparison to the pathway-model, proponents of the shared representation model argue that rather than language facilitating mathematics, the two domains draw on some common or shared deep structure. As discussed in Chapter 2, the results of Experiment 1 show that linguistic training did not facilitate mathematical performance, which suggests that language is not a pathway to mathematics. However, mathematical structural priming did support linguistic performance, which supports the idea that language and mathematics may be connected competencies.

An open question remains about whether language and mathematics rely on shared deep structures or representations, and if mathematics serves as a pathway to language. One explanation is that the domain-specific featural (i.e., symbolic) cues in linguistic training might not be as salient as those in the mathematical training, given that participants may have relied on other domain-specific linguistic skills, such phonological and grammar cues, rather than relying on symbolic cues to solve linguistic problems during training. As a result, participants completing the mathematical problems during test might rely on other domain-specific cues (including number word-learning. numerical syntax, etc.) or other domain-general mechanisms (such as working memory for arithmetic fact retrieval and counting) to engage in mathematical problem-solving. By contrast, participants completing the mathematical training might have found the salient symbolic cues easily accessible to complete mathematical problems, and may have used the same strategy of symbolic mapping to complete linguistic problems at test. It may then be possible that language and mathematics do rely on common or shared representations, such that easier access to shared featural cues or deep structures in one domain might facilitate performance in the other.

However, to better understand the domain-specific and domain-general cognitive processes underlying the cross-modal transfer between language and mathematics, it is important to understand whether the salience of this featural cue (i.e., symbolic mapping) matters during cross-modal training and transfer from mathematics to language. As such, Chapter 3 explored whether the explicitness of the deep structure in mathematics would facilitate corresponding linguistic performance. The results demonstrate that training participants in mathematics facilitates performance in linguistic problems overall, compared to no mathematical training, but explicitly pointing towards certain featural cues might not add any additional value to the training, that isn't already provided by the structural prime. Understanding the meaning and connection between different numerical symbols may be sufficient to support participants' ability to identify and make connections between different alphabetical symbols. From these results, it seems that language and mathematics might rely on some common or shared cognitive resources (such as shared symbolic representations, part-whole thinking skills, etc) that facilitate domain-specific and domain-general competence.

The current research is successful in providing evidence for the existence of a cross-modal relationship between language and mathematics, and discuss the ways in which the two processes or abilities might interact. It seems that the two domains draw on each other for reasoning and problem solving, and are not entirely separate cognitive processes. Contrary to existing evidence suggesting a pathway-dependent relationship from language to mathematics, the results of the current research show that the relationship between these two abilities is not unidirectional, such that mathematical competencies also support linguistic skills.

Limitations and Future Directions

The current research provides experimental evidence of a cross-modal relationship between language and mathematics, but many questions remain unanswered in this research. One of these questions is about the role of linguistic experience in facilitating cross-modal transfer. Both studies recruited participants from western, predominantly English-speaking populations. In the first two experiments (Chapter 2), all participants were recruited from the United States and Canada via M-Turk. Similarly, participants in the third experiment (Chapter 3) were Canadian university students. All participants reported English as their first language across the three experiments. Therefore, it is possible that differences in linguistic experience (e.g., monolingual versus multilingual speakers) and even geographical diversity (e.g., recruiting from countries with different emphases on language) might lead to differences in performance across the two domains, which could lead to different conclusions.

Another issue related to linguistic experience is one of unequal exposure to both modalities throughout the lifetime. People not only have earlier exposure to language than mathematics, it is also a regular and irreplaceable part of communication and cognitive performance. Future research should consider this disproportionate advantage in language over mathematics and examine the strength of these cross-modal relationships at different stages of language acquisition and development.

Moreover, a central question only partially addressed in this study is related to the potential influence of domain-general factors on the cross-modal relationship between language and mathematics. Participants' age was not related to their performance in either domain, and attention checks in the form of easy questions were interspersed throughout training and test. However, no measures of domain-general skills, such as general intelligence, attention, and working memory were included in the current research. This is because pilot data showed no relationship between participants' general intelligence and working memory and their language and mathematics skills. Despite these measures, deliberate measurement of these skills is required to better understand the ways in which domain-general mechanisms underpin the cross-modal relationship between language and mathematics.

These studies bring several different areas of research together – including literature on language acquisition, numerical development, cross-linguistic variations, and cognitive delays and disorders – to provide strong evidence for the prevalence cross-modal transfer between language and mathematics. However, the potential impacts of socio-cultural factors, such as economic status, educational attainment, and mathematics-anxiety on linguistic and mathematical processes are not addressed. Parental vocabulary, caregiver-child interactions, and formal instruction in both language and mathematics could all impact the ways in which language interacts with other cognitive capacities.

The literature exploring cross-modal language and mathematics interaction is disparate and disconnected. This research is a way to bridge some of those gaps and understand the ways in which language and mathematics not only interact with, but also draw from each other.

The current research was an attempt to bring together different literature offering descriptions of the cross-modal relationship between language and mathematics through studies with different linguistic populations, i.e., monolingual vs bilingual people, clinical vs. typically-developing populations, and children at different stages of their linguistic and mathematical development. The results of this thesis successfully establish the existence of a cross-modal transfer relationship, however the results of a short one-time training and transfer study should be treated cautiously. It remains for future research to explore the ways in which different domain-specific features, domain-general mechanisms, and external factors impact the cross-modal relationship between language and mathematics.

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