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Forty Years of Research on Mathematical Cognition: Summing It Up

Jo-Anne LeFevre
Department of Cognitive Science, Carleton University
Department of Psychology, Carleton University

In this article, I describe my academic journey as a Canadian researcher in the field of mathematical cognition. The article is a version of the talk I gave when I was presented with the Donald O. Hebb Award from the Canadian Society for Brain, Behaviour and Cognitive Science in July 2023 at the University of Guelph.

Public Significance Statement
This article describes how my research career has contributed to the cognitive science of how people represent knowledge about numbers. I have also provided a glimpse into the interconnections between personal and scientific growth over the course of a career.

Keywords: cognitive psychology, cognitive science, career overview

I am honoured to be the 2023 recipient of the Donald O. Hebb Distinguished Contribution Award. I thank those who nominated me, although I only know the identity of the ringleader, Erin Maloney. I have taken the opportunity to provide an overview of my research in numerical cognition, which corresponds to exciting developments in that field and in the field of cognitive science more generally.

The 1970s: The Rise of Memory, Language, and Cognition

In the 1970s, a new psychological discipline slowly emerged from the shadow of behaviourism. The shift from a focus on external behaviours to mental processes was reflected in the names of relevant journals. New journals, such as *Cognition* (1972) and *Cognitive Science* (1977), were created. Other journals were renamed. The flagship *Journal of Experimental Psychology* (*JEP*) branched out to include a suite of journals, including *JEP: Human Learning and Memory* (1975), which was renamed *JEP: Learning, Memory, and Cognition* in 1982. However, not until 1984 was the eponymous *Journal of Verbal Learning and Verbal Behavior* relabelled as the *Journal of Memory and Language*. Consistent with the revamped disciplinary focus, an interest in memory, language, and cognition has inspired my research path.

I started my postsecondary education at the University of Calgary in 1978, where I began studying biology. An elective psychology course revealed a more compatible direction. The professor ignited my interest in how people think and learn. Unfortunately, I do not remember her name, but I do remember that the textbook we used in that course was written by Donald O. Hebb! It was a thin green volume which presented his theory of learning in a concise and digestible form. My personal academic journey was launched by Hebb's ideas.

In 1979, I transferred to the University of Alberta, majoring in psychology. I was fortunate to be in a class taught by a brand-new assistant professor, Jeffrey Bisanz. Jeff had just completed a PhD in cognitive development from the University of Pittsburgh. At the end of the term, he invited me to work as a research assistant, creating a foundation for all my subsequent academic experiences (Bisanz et al., 1984). Jeff supervised my honours thesis research (LeFevre & Bisanz, 1986), and we collaborated until his retirement (Sowinski et al., 2015). Critically, Jeff provided unstinting mentorship, showed

Editor's Note. Jo-Anne LeFevre received the 2023 Donald O. Hebb Distinguished Contribution Award from the Canadian Society for Brain, Behaviour and Cognitive Science / Société Canadienne des Sciences du Cerveau, du Comportement, et de la Cognition. In association with this award, LeFevre was invited to submit a manuscript to the *Canadian Journal of Experimental Psychology*, which was peer reviewed.—DT

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Jo-Anne LeFevre https://orcid.org/0000-0002-1927-7734
The author's career has benefitted greatly from support from the Natural Sciences and Engineering Research Council of Canada through scholarships (1981–1986) and with Discovery grant funding since 1988. Other projects and activities have been funded by the Social Sciences and Humanities Research Council of Canada through Operating and Insight grants (1996–1999, 1999–2002, 2003–2006, 2006–2009, 2018–2024, 2022–2028), Connection grants (2019, 2023, 2024), and a Partnership Development grant (2022–2025). The author appreciates the support offered by Carleton University since she started as an assistant professor in 1988. The author also thanks the people who read over this article and provided comments, as well as Taeko Bourque for creating the timeline.

Most critically, the author's husband, Chris Herdman, and her daughters, Jenna Herdman and Brianna Herdman, have provided continued social, intellectual, and emotional support. They have commented on articles, patiently described their solutions to math problems, and given her many examples of entertaining math memes. The author could not do it without them.

Correspondence concerning this article should be addressed to Jo-Anne LeFevre, Department of Cognitive Science, Carleton University, 22nd floor, Dunton Tower, 1125 Colonel By Drive, Ottawa, ON K1S 5B6, Canada. Email: joannelefevre@cunet.carleton.ca

me a model of family life that could include academia, and taught me how to write. I passed along his painstaking editing of my articles to my own students—the tiny version of me in their heads, urging them to "omit needless words", is Jeff's legacy.

I was fortunate to have two important mentors. While finishing my BSc, I applied to graduate programmes in psychology at the University of Toronto, University of British Columbia, McGill University, and the University of Waterloo. However, personal reasons kept me in Edmonton. Jeff very wisely said that he would not supervise my graduate work—but luckily the university had just hired another young expert in cognition, Peter Dixon, from Carnegie Mellon University. I switched my focus (temporarily, it turns out) away from numbers to words and pictures. For my MSc, I explored the preferences and cognitive processing involved in choosing examples over instructions (LeFevre, 1987; LeFevre & Dixon, 1986). This work showed that people mostly ignore written instructions, preferring to use examples, even if those examples are terrible. For my PhD, I focussed on working memory and reading comprehension (Dixon et al., 1988). It surprises my students that my PhD work was not on numerical cognition, and it surprises me that I never tried to publish my thesis research!

I learned many important lessons from Pete and was terrified of disappointing him. In seminars, Pete was always the one to ask the question that drove to the heart of the research and, sometimes, demolished it. His experimental rigour and keen statistical skills set me up for success. More generally, the training I received at the University of Alberta from Jeff, Pete, Gay Bisanz, Alinda Friedman, Fred Morrison, Vince Di Lollo, and other dedicated professors enabled me to navigate a path to a successful career in cognitive psychology.

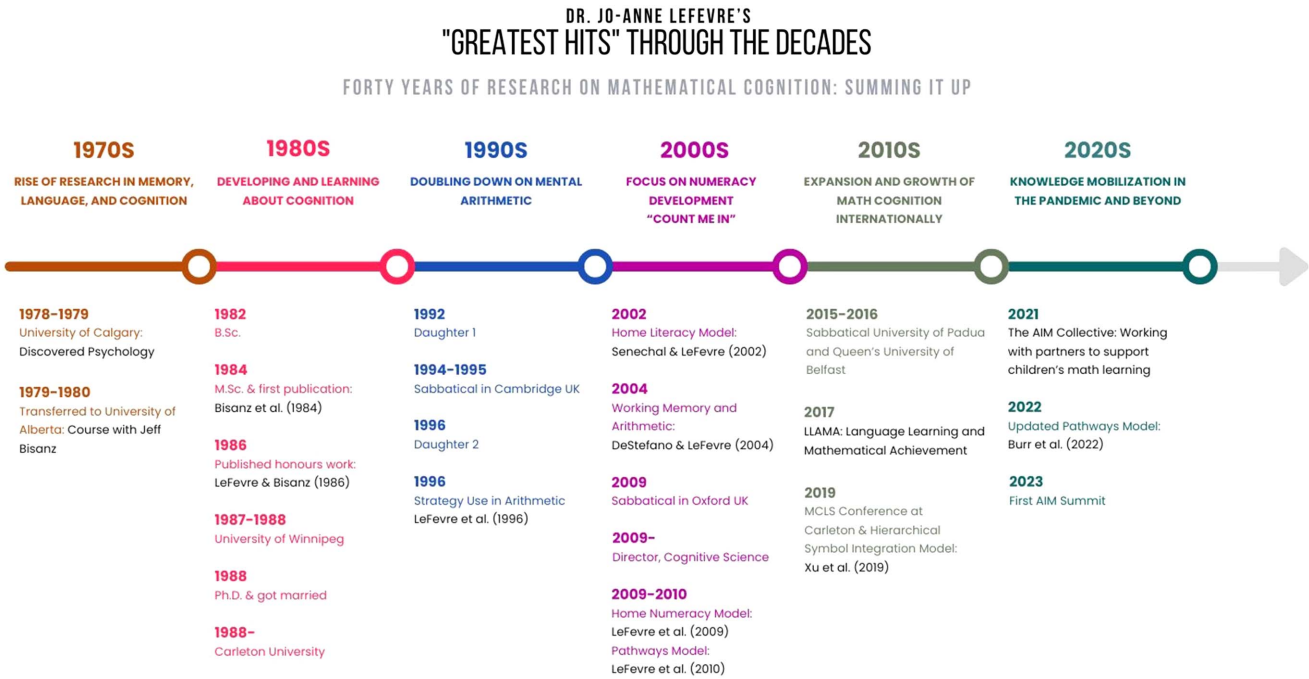
Chris Herdman and I spent our first year as assistant professors at the University of Winnipeg, moving to Carleton in 1988. I also received my first Natural Sciences and Engineering Research Council of Canada (NSERC) grant in 1988. It was titled *The Development of Processing Efficiency in Reading and Arithmetic*, a comfortable merging of several lines of research. Although my focus shifted such that I have mainly published on numerical cognition, I have never lost my interest in research on reading, and I feel that these two foci have been mutually beneficial.

In the remainder of this article, I will discuss my "greatest hits"—those that best capture my academic journey. I will also describe the development of the field of numerical cognition, although a more detailed account can be found in LeFevre (2016). These intersecting timelines and more personal highlights are illustrated in Figure 1. My interests appear diverse, yet, as I was preparing my presentation for the Hebb Award, I realised that they have been quite consistent. In addition to using research on reading and mathematics to mutually inform my own research directions, I have focussed on individual differences in performance, the nature, and consequences of fluency of access to information, working memory, the processing involved in reasoning, and strategy use by children and adults.

The 1980s: Developing Along With Cognitive Psychology

My research career started as the cognitive revolution was gearing up. In 1986, Jeff and I published an article based on my

Figure 1
LeFevre's Greatest Hits



Note. MCLS = Mathematical Cognition and Learning Society; AIM = Mathematical Cognition and Learning Society. See the online article for the color version of this figure.

honours thesis in the journal *Memory & Cognition* (est. 1973). It is titled *A Cognitive Analysis of Number-Series Problems: Sources of Individual Differences in Performance* (emphasis added; LeFevre & Bisanz, 1986). I find it interesting that we highlighted the *cognitive* analysis! Undergraduates judged whether number sequences formed predictable patterns, such as 1 2 3 4 5 and 2 4 6 8 10 versus 1 2 3 4 6 or 2 3 6 8 10. We found that people who were more skilled at solving complex number series completion were also faster and more accurate at identifying simple patterns. Moreover, patterns that incremented by the value of the initial digit were verified faster and more accurately; thus, 3 6 9 12 15 was faster than 2 5 8 11 14, highlighting the importance of familiarity and memory access in this task.

My fascination with numbers and arithmetic relations has continued (LeFevre et al., 1993; Pyke & LeFevre, 2011; Xu, LeFevre, et al., 2023), as has the focus on individual differences (S. M. Di Lonardo Burr et al., 2022). At the time, however, in the absence of a field of numerical (or mathematical) cognition, LeFevre and Bisanz (1986) received very little attention until Ian Lyons started studying ordinal processing 20 years later (Lyons & Beilock, 2009, 2011). Interestingly, when I was preparing my presentation, I realised that I did not have a digital copy of LeFevre and Bisanz (1986). Working from home, I did not have a printed copy available either. I attempted to access the article through our library. No luck! Issues of the journal prior to 1997 are not accessible online through the regular channels. A copy would have cost me $39.95 U.S.! The paywall barrier is real, and it is high.

The University of Alberta provided rich opportunities for graduate students. Many famous or to-be-famous researchers visited and gave seminars. My research on obligatory activation of arithmetic facts (LeFevre et al., 1988) was inspired by a presentation by Mark Ashcraft in 1985, who described his programme of work developing an associative model of arithmetic facts (Ashcraft, 1987). I hypothesised that if arithmetic facts are stored in an associative network as proposed by Ashcraft, then they should show obligatory activation of the sort which leads to interference (as do words in the Stroop task). Accordingly, I devised an interference task in which participants were briefly presented with two digits (e.g., 3 + 2 or 3 2). After a variable delay, they saw a single digit and were required to determine whether it matched one of the first two. They answered "yes" if the single digit was 3 or 2, otherwise "no" (e.g., 5 or 7). In support of the obligatory activation hypothesis, participants were slower and less accurate to respond "no" when the single digit was the sum of the first two (i.e., 5). This obligatory activation declined quickly (LeFevre et al., 1988), occurred sooner and declined more quickly for participants with better arithmetic skill (LeFevre & Kulak, 1994), developed slowly over the elementary school years (LeFevre et al., 1991), and was present for both addition and multiplication facts (Thibodeau et al., 1996).

My work on obligatory activation fit well with other research in the nascent area of numerical cognition. Canada was a relative hotbed of this research, with another Canadian, Jamie Campbell, also studying mental arithmetic (Campbell, 1987). Jamie, who passed away in 2022, and I "grew up" together as junior faculty, reviewing each other's articles and grants. We were often the only people presenting on number processing at conferences. Jamie and I did not collaborate directly because we needed to be at arms-length to review each other's work, but we did exchange students and participated together in symposia at Canadian Society for Brain, Behaviour, and Cognitive Science many times, maintaining two degrees of separation that reflected the very small size of the numerical cognition community in Canada (Campbell & Robert, 2008; Robert & LeFevre, 2013). Happily, we now have tens of math cognition researchers in Canada, an exponential increase.

Technology changed rapidly throughout my career. My first research assistant task was to carry the punch cards which held the data from Jeff's PhD thesis to the computer science building to get "read in." As an undergraduate, I learned to program in Pascal on an Apple II+ computer (with 64 K of memory and external 5-1/4 in floppy drives!). We often had to simplify programs that would not compile because they used too much random access memory. Similarly, word processing was barely accessible in the early 80s. My honours thesis was written with a line editor on the mainframe computer—the formatting was not visible until I printed it and walked to the Computer Science building to pick up the hard copy. We started using email at the University of Winnipeg in 1987 but had to access it from a single dedicated terminal connected to the University of Manitoba system. By 1988, although I had access to a personal computer to format and print my PhD thesis, I had to work on it after hours because this computer was in the main psychology office at the University of Winnipeg. Somehow, we managed to do excellent research without access to smart phones, laptops, universal Wi-Fi or artificial intelligence.

The 1990s: Doubling Down on Mental Arithmetic

I continued to work on mental arithmetic processes (funded by NSERC) during the 1990s. My earlier research on obligatory activation of arithmetic facts presupposed that adults solved simple problems like 3 + 4 by retrieving a stored answer from long-term memory (Ashcraft, 1982). But do they? Children often solve arithmetic problems using strategies such as counting (e.g., 3 + 2 as 3, 4, 5). In a series of studies (LeFevre, Bisanz, et al., 1996; LeFevre, Sadesky, et al., 1996), we found that adults sometimes used counting strategies and sometimes used derived facts strategies where they retrieved an intermediate solution and then calculated (e.g., 9×6 as $10 \times 6 = 60 - 6 = 54$). The patterns of response times were quite different for fully retrieved versus strategically computed solutions, such that the problem-size effect depended on the degree of strategy use. The problem-size effect is the ubiquitous finding that people are slower and make more errors on problems with larger numbers (Zbrodoff & Logan, 2004). I am indebted to my first PhD student, Alison Kulak, who insisted that not all adults used full memory retrieval and forced me to test this assumption empirically. Listen to your students!

The 1990s were busy. Chris Herdman and I cooperated on several joint projects (C. M. Herdman et al., 1994, 1996; C. M. Herdman & LeFevre, 1992; Lichacz et al., 1999). We also had two children, gained tenure and promotion, and did a sabbatical in Cambridge, United Kingdom. Surprisingly, having children enhanced my productivity—I had to learn to use my work time wisely. The excellent maternity benefits available in Canada, generously supplemented by Carleton University, were critical to my ability to keep my career on track. I also appreciated one of the side benefits of parenthood—acquiring two in-house participants for my developmental research. Watching the girls grow and learn led me to various new projects and directions.

Inspired by parenthood, my interest in reading was revived when my older daughter, despite having strong language skills and parents who read to her incessantly, struggled to learn to read in Grade 1. There were no long-term consequences—she overcame this hurdle, graduating with a PhD in English language and literature (J. M. Herdman, 2020, 2021, 2022). At the time, this experience made me curious about the role of home experiences in children's early learning. Carleton colleague Monique Sénéchal and I designed and tested a model of home literacy experiences that helped to explain why children with excellent oral language skills and parents who provided literacy-rich home environments did not spontaneously acquire written language (Sénéchal et al., 1996, 2001; Sénéchal & LeFevre, 2002). We found that home literacy experiences could be categorised into two types, which reflected a focus on written versus oral language. In brief, parents who read a lot to their children had children with stronger vocabulary and other oral language skills, whereas parents who spent time helping their children learn to recognise letters and letter sounds had children with stronger early word reading skills. These home literacy activities were orthogonal and are predictive of different skills in Grade 1. The culminating article is by far my most cited publication (Sénéchal & LeFevre, 2002).

The 2000s: A Focus on Numeracy Development

The field of numerical cognition grew exponentially in the first decade of the new millennium, a trend that was foreshadowed for me when I attended the conference of the European Society for Cognitive Psychology in Ghent, Belgium, in 1999 and discovered a whole country of researchers interested in numerical processing! In 2003, myself and a group of my favourite colleagues (Bisanz, Skwarchuk, Kamawar, Smith-Chant) received an Social Sciences and Humanities Research Council of Canada grant for a longitudinal study of numeracy development. Guided by a fantastic research assistant, Lisa Fast, the *Count Me In* project followed over 600 children across 4 years, making many interesting discoveries along the way.

Continuing the tradition of family involvement in my research, my younger daughter Brianna was conveniently in elementary school during the *Count Me In* grant period. She cheerfully and honestly evaluated the software we developed to collect the data, posed for newsletter pictures, and provided useful insights on why the counting strategies used by our animated frog (Hoppy) were correct but not what she would have done (Kamawar et al., 2010; LeFevre et al., 2006). She continues to respond quickly when I ask her to solve multiplication facts and regularly sends me interesting math-related titbits and memes. You have heard, I imagine, that four out of three people do not understand fractions!

The *Count Me In* research culminated in the pathways model of early numeracy learning (LeFevre et al., 2010; Sowinski et al., 2015). The model has been influential because it helps to organise the domain-general and domain-specific cognitive skills that influence early math learning. The *Count Me In* project also introduced me to the addictive excitement of collaborating with like-minded colleagues to tackle complex problems. Working with these colleagues and, subsequently, with others has greatly expanded my research activities.

Another direction for my research emerged when, at the insistence of Sheri-Lynn Skwarchuk, we asked parents about their activities at home that involved mathematics. This research, conducted as part of the *Count Me In* project, resulted in an article (LeFevre et al., 2009) that helped to develop a now-flourishing but previously obscure area of research on the relations between children's home numeracy experiences and their mathematical development (cf. Hornburg et al., 2021). Despite its subsequent influence, however, LeFevre et al. (2009) almost did not get published. The process was disturbing but fascinating because the parallel field of home literacy research was so well-established (cf. Sénéchal & LeFevre, 2002). Criticisms in the many rounds of reviews of the home numeracy article ranged widely—from "the work was correlational" (it was, but so is most of the work on home literacy) to "it is invalid because fathers were not included" (fathers were welcome to participate but rarely complete questionnaires). Reviewer comments were difficult to reconcile—one reviewer stated that the work was not of interest because children do not learn math at home, whereas another reviewer commented that the work was not of interest because everyone already knows that children learn math at home! No one appeared to value what seemed to be an obvious extension of the role of families in early academic development. After being rejected from three other journals, the article finally found a home in the *Canadian Journal of Behavioural Science* (phew!). It is now the most cited article (ever) in that journal, showing that the topic was, in fact, of interest. In academia, persistence is critical.

In 2009, I became the director of the Institute of Cognitive Science at Carleton, and I have remained at the helm ever since. The (now) Department of Cognitive Science has about 600 undergraduate and 45 graduate students who study cognition through an interdisciplinary lens. We are indebted to Dr. Andrew Brook (another University of Alberta alumnus), who founded Cognitive Science at Carleton and attracted excellent students from across the world. Administrative duties are not for everyone, but this experience has helped me to gain a broader perspective on the disciplines that make up the university and the differential but important roles of staff and faculty.

The 2010s: International Expansion and Growth of Cognitive Science at Carleton

In the 2010s, I continued work on home numeracy, collaborating with other researchers to analyse data from children in several countries, including Chile (Susperreguy et al., 2020), Mexico (Susperreguy et al., 2021), Lithuania (Silinskas et al., 2020), Italy (Tomasetto et al., 2022), and China (Wei et al., 2023). These ongoing collaborations hinge on the contributions of excellent past and current students (Chang Xu, Sabrina Burr, Taeko Bourque). We also initiated a project on language and mathematics (called the LLAMA project for "language learning and math achievement") that included colleagues in Northern Ireland (Victoria Simms and Judith Wylie) as well as collaborators from three provinces in Canada (Erin Maloney, Helena Osana, and Sheri-Lynn Skwarchuk). This project was expertly shepherded by Chang Xu, Anne Lafay, and Sabrina Burr (Xu, Di Lonardo Burr, et al., 2022, 2023; Xu, Lafay, et al., 2022). We also snuck in some home numeracy work (Skwarchuk et al., 2022). This research on language and mathematics has shown that, although math problem solving is harder for second language learners, it is the language that causes

difficulties, not the math (Xu, Di Lonardo Burr, et al., 2022; Xu, Lafay, et al., 2022).

Also in the 2010s, after receiving an NSERC equipment grant and buying a locally sourced eye tracker (SR-Research), we explored numerical cognition using the extra information provided by eye movements for arithmetic (Curtis et al., 2016; Huebner & LeFevre, 2018) and number line tasks (S. Di Lonardo Burr & LeFevre, 2021; Di Lonardo et al., 2020). Post pandemic, we are tackling questions about order judgements using the eye tracker, thanks to keen students including James Vellan, Liza Kahwaji, Jules Lavoie, Seyeon Kim, and Alexander Kirby. My fundamental research on basic numerical processes has been funded continuously by NSERC since 1988. The Canadian system of funding researchers throughout their career is an outstanding way to support scientific progress, minimising overhead and maximising the involvement of highly qualified personnel. We do need, however, to increase the funding available for graduate scholarships and postdoctoral fellows, amounts that have not changed for over 15 years.

The field of mathematical cognition grew dramatically throughout the 2010s. Mathematical cognition is highly interdisciplinary, and topics range from the very basic (counting in goldfish) to the very applied (math anxiety in children). The *Journal of Numerical Cognition* started publishing online in 2015. From three articles in the first year, it has grown to include 25 articles in 2023. The *Journal of Numerical Cognition* is a completely free and open access journal—thus, there are no monetary barriers to either authors or readers. In 2017, the Mathematical Cognition and Learning Society was founded by Dan Berch; I served as its first secretary (from 2017 to 2022). I cohosted the second Mathematical Cognition and Learning Society conference at Carleton in 2019 with Rebecca Merkley, Heather Douglas, and Chang Xu, supported by a legion of students. The weather in early June was perfect, and much math cognition research was shared among 250 participants from across the world. Helping at the registration desk, my daughter Brianna was amused when an attendee (who assumed she was a graduate student of mine) remarked that students were looking a lot like their supervisors these days! I am very happy that my career has spanned the creation of a dynamic area of cognitive research.

The 2020s: Knowledge Mobilisation in the Pandemic and Beyond

Knowledge mobilisation is critical to science, but as a researcher studying basic cognitive processes, I have often felt that we have little impact on the world beyond the few readers of our refereed journal articles. In contrast, one of our current projects takes collaboration outside of academia to engage with math educators. To address the gap between research and practice, we initiated the Assessment and Instruction in Mathematics (AIM) Collective, which is partially funded by a Social Sciences and Humanities Research Council of Canada Partnership Development Grant. The vision of the AIM Collective is to support the development of evidence-based tools to support math assessment and instruction in the early grades that will increase equity by providing all students with the support they need to learn math.

The impetus for the AIM Collective draws heavily on the passion and diverse skills of two colleagues: Rebecca Merkley and Heather Douglas. Rebecca honed her knowledge mobilisation skills by collaborating with school board personnel as a postdoc with Daniel Ansari (McDonald et al., 2021). Heather Douglas was an elementary school teacher who completed a PhD with me at Carleton so she could understand how children learn math. AIM also draws in colleagues who are based in faculties of education: Helena Osana (Concordia), Zachary Hawes (Ontario Institute for Studies in Education at the University of Toronto), and Sheri-Lynn Skwarchuk (Winnipeg), as well as practitioners embedded in the school system, including Julie Houle (Lester B. Pearson School Board, Quebec), Jennifer McDonald (Halton Catholic District School Board, Ontario) and Tracie Anthony (Grande Prairie Public School District, Alberta).

In part, the AIM Collective was inspired when Heather and I created a math assessment tool called the Early Math Assessment at School (EMA@School) that is currently licenced to the Alberta Ministry of Education. Students Jenna Rice and Peyton Nault have also contributed to developing the EMA@School. Through AIM, we became involved in several projects that use the EMA@School to evaluate the impact of math interventions on children's foundational skills (Youmans et al., 2023). I never imagined that my research on the cognitive processes involved in number processing would lead to such direct practical applications. Over 50,000 students have been assessed using the EMA@School. In part, the growth in interest in mathematical cognition reflects a larger concern across the world about the importance of mathematics, along with declines in math performance as shown by international studies such as Programme for International Student Assessment. The evidence about mathematical cognition that has accumulated in the past 20 years is critical to our ability to provide evidence-based solutions to educators' concerns.

Through the AIM Collective, I have connected with an impressive cadre of math educators who are dedicated to ensuring that children get the opportunity to acquire the core math and reading skills they need to succeed. It has been inspiring to work with superintendents and math leaders, such as Mike McMann and Gil Morris in Fort Vermilion (the most northernly school district in Alberta), who are passionate about using evidence to improve math instruction. In May 2023, we hosted a forum for educators and researchers from four provinces (i.e., the AIM Summit), who came together to discuss their concerns about AIM. It was thrilling to see how research could influence practice—and exciting to learn how practice could influence research. Two amazing students, Liza Kahwaji and Ayushi Chitranshi, have built on the AIM Summit momentum by hosting a podcast and creating a newsletter to further promote educator–researcher connections.

Final Thoughts

I can sum up my experience as a researcher over the last 40-plus years in four words: support, collaboration, mentorship, and cooperation. I have received support from Carleton, NSERC, Social Sciences and Humanities Research Council of Canada, and other agencies, enabling my research. I have collaborated with former mentors, current students, former students, and colleagues at Carleton and across the world. In my experience, such collaboration leads to more and better research. I have benefitted from excellent mentors and tried to pay it forward. Finally, I have learned that cooperation is central to research productivity. Even though we sometimes get frustrated or have differences of opinion, research is always better and more fun when we do it together. Moreover,

competition is unnecessary—there are always more questions to be answered. On this note, I have not had a chance to mention other areas of research, including the importance of working memory to mathematics (DeStefano & LeFevre, 2004; Kalaman & LeFevre, 2007), my uneasy but nevertheless persistent relationship with math anxiety (LeFevre et al., 1992; Song et al., 2021), or my occasional distraction into topics such as cognitive load while reading in hypertext (DeStefano & LeFevre, 2007). So many questions—so little time.

In summary, it has been a privilege to be a researcher in Canada over the last 40 years—and I am not done yet—and to share my knowledge with a vast and diverse group of colleagues and students from around the world. Thanks to all of you who have been cheerleaders and companions on my academic and personal journey.

Résumé

Dans cet article, je décris mon parcours académique en tant que chercheuse canadienne dans le domaine de la cognition mathématique. L'article est une version du discours que j'ai prononcé lorsque j'ai reçu le prix Donald O. Hebb de la Société canadienne des sciences du cerveau, du comportement, et de la cognition (SCSCCC) en juillet 2023 à l'Université de Guelph.

Mots-clés : psychologie cognitive, sciences cognitives, survol de carrière

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