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Original Research

Explanatory model of South Asian newcomer mother and Canadian-born mother comprehension: A cross-sectional

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Abstract: Maternal health literacy refers to the skills mothers use to manage their own health and their family's health in healthcare settings. Newcomer mothers face unique barriers to healthcare access, which can be reduced through health education to improve comprehension. An applied, cross-sectional design was used to recruit 20 English-speaking South Asian newcomer mothers (SANMs) and 20 English-speaking Canadian-born mothers (CANMs). This cross-sectional study utilized fuzzy-trace theory to develop an explanatory model for how mothers comprehend health information, with a focus on gist understanding. A digital survey collected data on the ability to comprehend the main idea of pregnancy health information. Additionally, three validated psychometric instruments were administered to measure differences in functional health literacy. Descriptive statistics were conducted on responses to a questionnaire, and accuracy scores were calculated using observation oriented modelling. Data analysis examined the accuracy of models in explaining patterns of observations, supplemented by a visual "eye test" using a histogram to describe observed events. Results indicate that both samples of mothers self-reported adequate numeracy abilities, but performed poorly on functional assessments. In Experiment 1, CANMs who engaged more frequently in numerical reasoning showed a meaningful, non-random pattern of comprehension regarding the chance of viral infection. In Experiment 2, SANMs who more frequently counted or read numbers demonstrated a meaningful pattern of correctly identifying medication timing. These results suggest that gist-based processing supports comprehension in both samples, but the causal patterns linking numerical engagement and comprehension differ. Numerical reasoning relates to comprehension differently across SANMs and CANMs, and therefore health education must be ethno-culturally responsive. Ultimately, this research highlights the need for 'kind' learning environments to help ethno-culturally diverse mothers practice and improve their comprehension in healthcare settings and recommends health numeracy education and medication literacy programs to improve numerical reasoning.

Keywords: Health literacy, Health education, Information literacy, Mathematics, Maternal health services, Canada, South Asian

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Introduction

Maternal health literacy (MHL) refers to the skills mothers use to make health decisions for themselves and their families [1,2]. MHL is important for newcomer mothers who face language, cultural, and gender barriers [3], particularly when preparing for medical appointments, comprehending health risks, and participating in decision-making [4]. Health literacy (HL) is the ability to access, understand, evaluate, and communicate health information (HI) to promote well-being [5], and includes basic, interactive, and critical skills [6]. In Canada, 55% of adults aged 16-65 years old have inadequate HL [5], which suggests Canadians may lack the critical HL to advocate for themselves to impact health at broader social, cultural, and policy levels [7]. While Canadians generally score above average on literacy and numeracy (NUM) assessments according to the results of the 2019 Program for International Assessment of Adult Competencies [8], newcomers perform worse [9]. NUM refers to the ability to understand and manage numbers [10], while health numeracy (HN) is about using numbers in healthcare settings and contexts to make informed decisions [11]. HN is also influenced by information, social behaviors, and technology [12]. Online health information (OHI) is sought by mothers in the first trimester of pregnancy to change health behaviors related to diet and nutrition [13]. Digital technologies are used to access trustworthy OHI as new parents [14], and virtual prenatal appointments and telemedicine have been used to enhance patient satisfaction [15]. Ultimately, MHL is vital for newcomer mothers to confidently navigate the healthcare system and access and use OHI to ensure satisfaction and quality care.

The rationale for this research on MHL is to foster a deeper understanding of the language, language competencies, and comprehension challenges Canadian and newcomer mothers face to improve future health education. Comprehension is the process of understanding information in a specific healthcare setting or context to function successfully [16] and is a component of functional health literacy (FHL) (Figure 1) [16,17]. Therefore, comprehension represents the cumulation of prior knowledge and experience with perception and incoming sensory information as a mental activity to correctly respond to questions, make decisions, and change behaviours, for example (Figure 1). Refugee and newcomer women with inadequate FHL appear to lack comprehension and consequently underutilize health programs, interventions, diagnostics, and treatments [18-20]. Furthermore, newcomer women have difficulty comprehending written HI [21] and have lower NUM scores than newcomer men [18]. Thus, presenting clear and concise HI can be achieved by shaping and framing written HI texts to improve FHL [9]. As such, the aim of this research was to develop an explanatory model explaining the comprehension depth of a sample of South Asian newcomer mothers (SANMs) and a sample of Canadian-born mothers (CANMs). SANMs were selected as they represent the largest visible/racialized minority sample in Canada at 5.4% of the total population [22]. Additionally, the research evidence suggests SANMs have inadequate HL, thus impeding healthcare access [23,24]; prefer written HI over numbers, to assist with learning [25]; and experience barriers to social integration related to language, communication, and information [26-28]. CANMs were included as a comparison to help generalize results across different samples of mothers [29,30]. The objectives of this research were to examine the socio-demographic factors associated with inadequate FHL and to apply fuzzy-trace theory (FTT) to identify specific patterns based on efficient and final cause pairs to provide interpretations for future health education practice. The results of this research are intended for health communication specialists, health educators, and public health practitioners who design HI to improve learning. The originality of this research lies in applying observation oriented modeling (OOM) to MHL—shifting from traditional statistical methods to a person-centred, explanatory approach. In doing so, OOM uncovers individual patterns and causal processes related to MHL as a system, offering deeper insights than group averages and a more context-sensitive understanding, which is especially valuable in public health. The research tests the following hypotheses:

- We hypothesize that SANMs and CANMs who engage more frequently in probabilistic and statistical reasoning will correspond to accurate comprehension of the chance of viral infection, with observable differences in the causal process between the two samples.
- We hypothesize that frequent engagement with numerical information—through counting or reading numbers—will correspond to accurate comprehension of medication timing instructions, and that this causal process differs between SANMs and CANMs based on the functional application of mathematics skills.

Background

This cross-sectional study applies FTT, which suggests people distinguish between verbatim information and the gist of HI to aid comprehension [31-33]. FTT is relevant because it explains how mothers with inadequate HL use gist to comprehend complex HI texts. By investigating MHL processes in a dynamic system, the unit of analysis is the individual rather than aggregates as seen in traditional null hypothesis significance testing (NHST) allowing for the assessment of gist [34-36]. FTT includes three assumptions: (i) people prefer frequency values over probabilities; (ii) individuals' personalities influence whether they rely on intuitive or rational thinking, affecting how they remember information; and (iii) people remember the summary of a text rather than

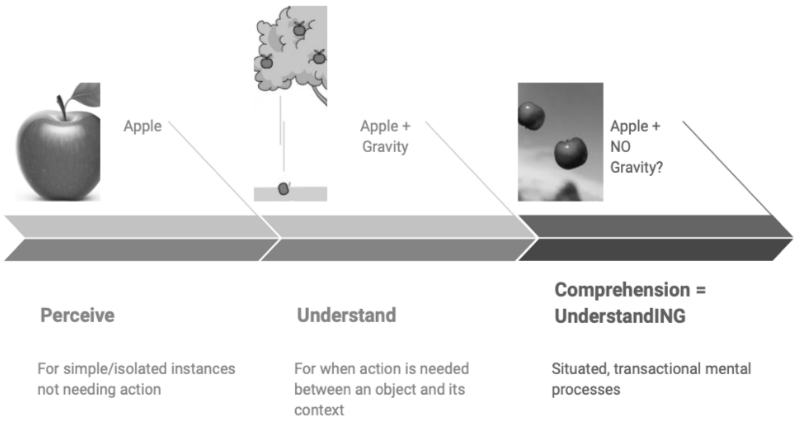


Figure 1. The relationship between perception and comprehension

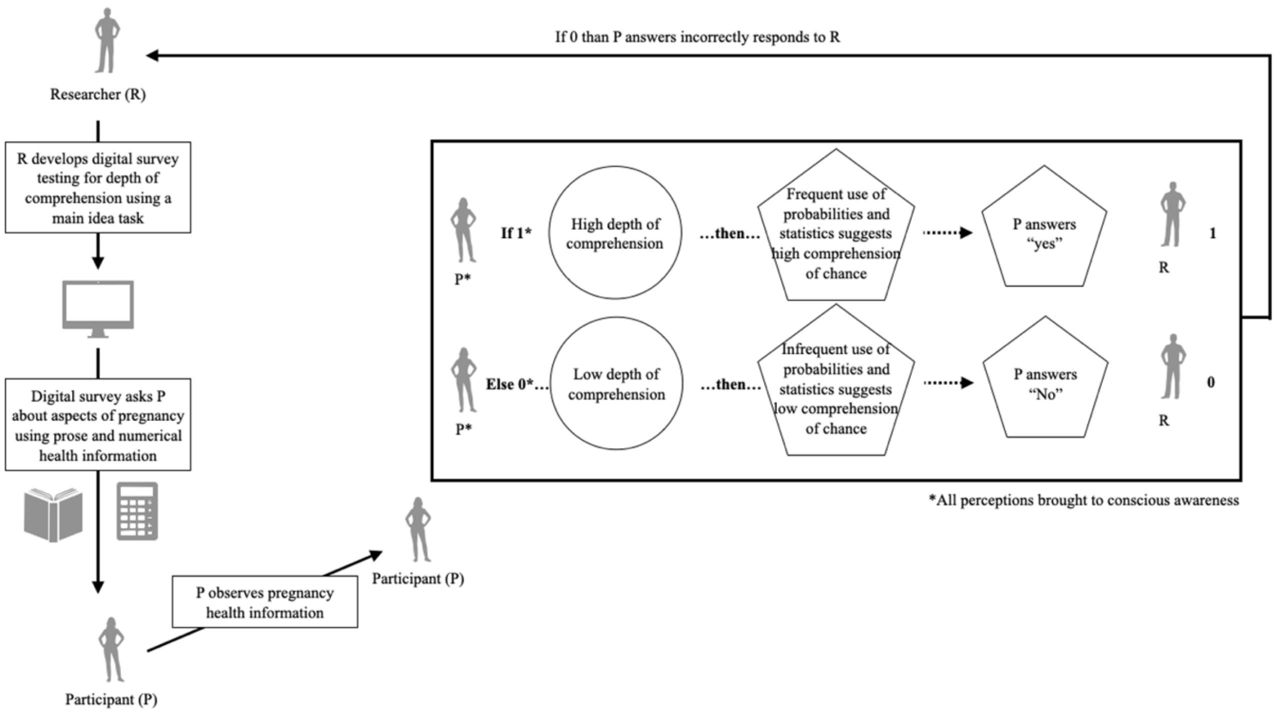


Figure 2. Integrated model for the comprehension of the chance of viral infection based on the frequency of using probabilities and statistics [40]

exact details [32,35-37]. To develop the integrated model for this research, pairs of efficient and final causes (based on Aristotle's four causes—that are, material, formal, efficient, and final) related to the perception of OHI were graphed to explain the causal process between exposure to information and its behavioral outcome (Figure 2) [38]. Figure 2 organizes the discrete structures and time-dependent processes in a system involved in a mother's comprehension of HI to clearly distinguish between different causal processes; this serves as an analogue for the natural world, and the data collected is entered into OOM software for analysis, producing accuracy scores [39,40]. The efficient cause is the direct mechanism or trigger that produces a change or behaviour in a specific person. The final cause refers to the purpose, goal, or motivation behind a behaviour. The final cause also comprises of the researcher's hypothesis about the goal, such as determining whether a passage is correct or a correct behavior is performed, which becomes clear when the mother provides her response to the digital survey question.

Materials and methods

Ethics approval was obtained from the University of Waterloo Ethics Review Board (REB #43128) prior to launching the research, and the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) Statement was used as a guideline to ensure quality reporting [41]. Mothers were recruited through Facebook mom communities and with help from local community organizations in Ontario, Canada. Non-probability, judgement sampling was used to recruit n = 20 English-speaking SANMs and n = 20 English-speaking CANMs (N = 40) [42]. The sample size was based on a study by Grice et al. [43], which recruited 30 participants in total for experimental and control groups. OOM does not require large sample sizes like NHST, but relies on the primacy of observations, randomization, and the entities and qualities of objects or things underlying the processes within a system [40]. In fact, OOM is designed to work well with small samples (theoretically, as few as two participants), depending on the complexity of the model and the research question [40]. The key idea is that OOM focuses on pattern detection and individual level analysis rather than group-level inference, thus making it suitable for pilot research or for working with hard-to-reach populations such as newcomers, refugees, and asylum seekers [40]. Participant recruitment took place from January 2020 to December 2020. Participants were required to be (i) mothers, (ii) born in Canada or South Asia, (iii) 18 years or older, and (iv) living in Ontario. Exclusion criteria included (i) self-reporting as unhealthy, (ii) living outside Ontario, (iii) being under 18 years old, and (iv) being an adoptive mother. All mothers identified as women, and the SANMs spoke Punjabi, Hindi, Urdu, Tamil, or Gujarati. CANMs came from any ethnocultural background but were born in Canada. All mothers were informed that their participation was voluntary through an information letter, and an oral consent script was used to engage mothers in the research after being informed about what it entailed. A secure survey link was emailed to consenting mothers, and pseudonyms were used to protect their privacy and ensure anonymity. Anonymity helps reduce social desirability bias, in which respondents may alter their answers to align with perceived social norms or expectations [42]. A post-research information sheet was provided to debrief mothers and to correct answers. Mothers received a $10 gift card for completing the digital survey and were informed they could withdraw at any time without penalty.

Relying on a single data source can introduce bias; therefore, multiple data collection methods were used to validate assessments of FHL with observational data in this cross-sectional study. To reduce bias related to how questions were perceived or interpreted, (i) clear, simple, and culturally appropriate language was used to avoid ambiguity; (ii) both subjective and objective questions were included to reduce the chance of forcing answers into predetermined categories; and (iii) leading questions were avoided to prevent steering mothers toward a particular response. To ensure the digital survey's accuracy, a panel of experts reviewed the questions to ensure the currency of pregnancy HI, the digital survey was pilot-tested, and changes were made based on feedback.

The digital survey was integrated with a socio-demographic questionnaire and FHL instruments. It included 20 questions about pregnancy, presenting the information in both prose and numeric formats using a main idea task, and took 30 minutes to complete. Two types of pregnancy texts (literal and paraphrased) were shown randomly for up to 15 seconds each to assess gist and test basic pregnancy knowledge related to medical examination preparation, health risk information, and shared decision making [4]. Questions also included distractor information to test if mothers could distinguish between conflicting details [29]. Descriptive statistics were then used to profile the social, cultural, and economic characteristics of the mothers using IBM Statistical Package for the Social Sciences (SPSS) software (Version 26) by collecting information such as age [44], education [45], and socioeconomic status [46]. Figure 3 illustrates one’s information processing involving long-term memory, perceptual, visual interaction, and problem-solving processes necessary for the comprehension of HI, similarly OHI [47]. At a high level, (i) samples of information (or objects) from the natural world are perceived and modified to form internal representations; (ii) these abstract and internal representations are continually attuned to, thus forming hypotheses or plans regarding the handling of said information; (iii) a test then becomes the basis for a decision directing the solution of a problem when presented; and (iv) the perceptual, visual interaction, and problem-solving processes overlap via buffers to refine these abstractions with experience [47]. This incoming information forms semantic hierarchies in the mind, reflects comprehension of the natural world, and is retained in short- and long-term memory for continual consolidation (Figure 3) [16]. As such, this research helps "restore the subject-object dialectic…[by] acknowledging that the process of understanding is rooted in the senses" (p.220) [40]. Ultimately, the digital survey helped analyze how mothers perceived, attuned to, and responded to digital survey questions, demonstrating their comprehension, measured using data from observation pairs entered OOM software.

OOM software (Version 5.27.2020) uses binary Procrustes rotation to align two observations, called the target variable (efficient cause) and the conforming variable (final cause), into conformity using the "Build/Test Model" option. The observations are aligned by (i) comparing the frequency of different patterns, (ii) assigning each observation to the most common pattern, and (iii) evaluating each observation against the common pattern as correctly, incorrectly, or ambiguously classified [39,40]. OOM is a method grounded in moderate realism

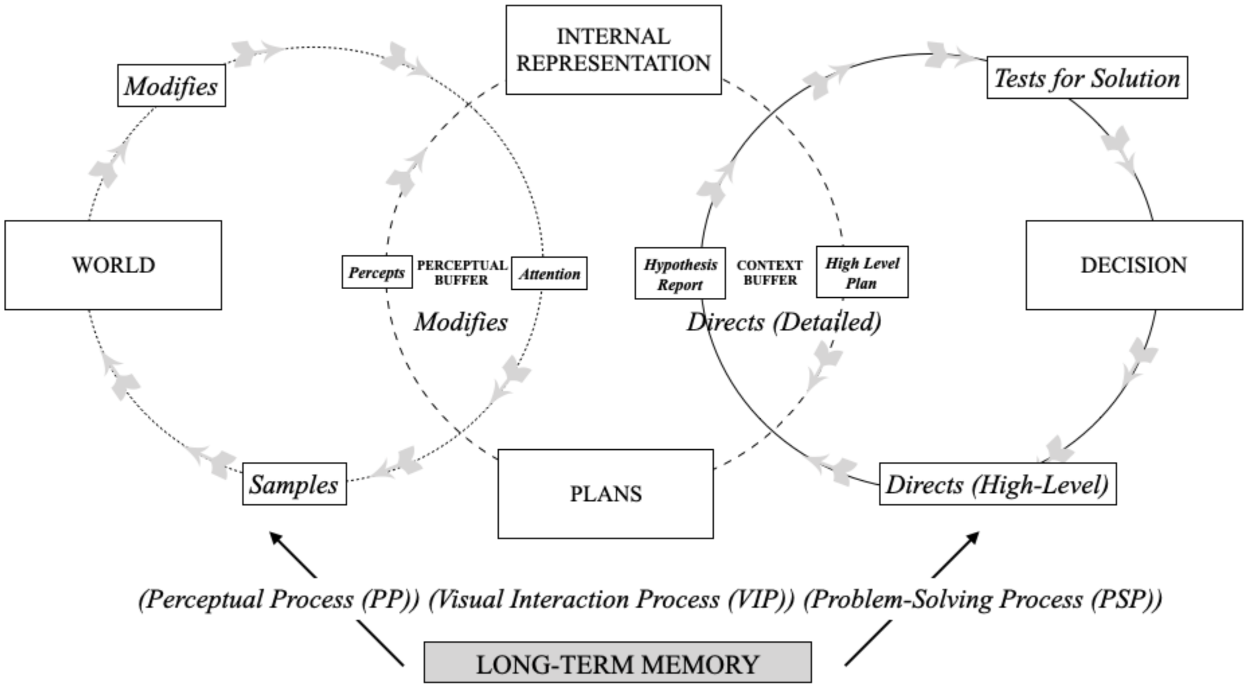


Figure 3. Adaptation of perceptual process (PP), visual interaction process (VIP), and problem-solving process (PSP) to illustrate health information (HI) processing at the individual level [47]

used to assess the accuracy of a theory or hypothesis based on patterns of observations in the causal system, using the individual as the unit of analysis rather than aggregates as seen in NHST [40]. Two key accuracy measures referred to as the percent correct classification (PCC) and the chance value (c value), are calculated [39,40]. The PCC shows how well the observations for the target variable match those of the conforming variable—also referred to as "orderings," given that the assumptions of OOM suggest natural events are integrated and ordered [48]. This indicates the proportion of observations that match the expected pattern (i.e., a relational hypothesis). A higher percent classification suggests the model fits the data well, indicating more individual observations conform to the expected pattern. A high PCC and a low c value suggest that the pattern is rare and relevant to the hypothesis, with a PCC of 70% -100% considered important [48]. The c value shows how often a random shuffle of the paired orderings results in a PCC equal to or higher than the observed PCC (usually, after shuffling 1,000 times)—it represents the proportion of random data shuffles (permutations) that produce equal or higher PCCs than the actual data. A c value of 1.00 means the PCC is 100% every time the data is shuffled [48]. Essentially, the c value shows whether the observed pattern fits the hypothesis in a common or uncommon way and represents the probability of achieving the observed percent classification by chance under a randomization test. A low c value (typically below 0.05) indicates that the observed classification is unlikely to be due to random variation, supporting the meaningfulness of the pattern found and the alternative hypothesis. The null hypothesis is that the pattern occurred randomly. The former combination suggests the model fits the data better than what would be expected by chance, aligning with the core goal of OOM, which is to assess whether patterns in the data reflect meaningful causal structures. The latter indicates randomness. Finally, a histogram was graphed for each hypothesis to allow for a visual inspection of responses for further interpretation.

Health literacy skills instrument-short form

The Health Literacy Skills Instrument-Short Form (HLSI-SF) is a ten-question instrument used to assess HL and covers health promotion, prevention, and treatment [49]. Before using the HLSI-SF in this research, a user agreement was signed with Research Triangle Institute (RTI) International. The HLSI-SF includes four components: (i) print literacy, (ii) NUM, (iii) oral literacy, and (iv) the ability to find OHI. The HLSI-SF takes 5-10 minutes to complete and is scored based on the percentage of correct answers, with 1 point for each correct and 0 for each incorrect response [49]. A score of 0-6 indicates 'inadequate' HL, while a score of 7-10 indicates 'adequate' HL [49]. The HLSI-SF has an internal consistency of Cronbach's alpha = 0.70 and a small to moderate correlation with the Test of Functional Health Literacy in Adults (TOFHLA) [49].

Lipkus numeracy scale

The Lipkus Numeracy Scale (LNS) assesses mathematics skills such as converting values and estimating health risks [50]. The LNS includes multiple-choice and open-ended questions, with a total of ten items—three general and seven more detailed questions. The LNS evaluates a person's ability to: (i) understand risk magnitude, (ii) use percentages and proportions for calculations, (iii) convert percentages to proportions, and (iv) convert probabilities to proportions. Scores range from 1-5 indicate 'inadequate' NUM, and scores from 6-11 indicate 'adequate' NUM [50]. The scale's advantage is that it evaluates global NUM; however, the results cannot be generalized across diverse ethnic groups. The scale's alpha coefficient, which measures reliability, is 0.78 [50].

eHealth literacy scale

The eHealth Literacy Scale (eHEALS) assesses electronic health literacy (eHL) and can be administered either in-person or digitally. It is an instrument measuring the ability to find and apply OHI [51]. The scale covers six areas including: (i) traditional, (ii) health, (iii) information, (iv) scientific, (v) media, and (vi) computer literacy. eHEALS consists of eight items assessing perceived skills, each scored on a five-point scale (1 = strongly disagree, 5 = strongly agree). Total scores range from 8 (inadequate eHL) to 40 (adequate eHL), with higher scores indicating higher self-reported eHL [51]. The Swedish eHEALS thresholds are: (i) inadequate = 8-20, (ii) problematic = 21-26, and (iii) sufficient = 27-40 [52]. eHEALS has a Pearson's r = 0.40-0.68, item scale correlations from 0.51-0.76, and high item fit (α = 0.88) [51].

Results

The sample included 20 SANMs and 20 CANMs (N = 40) (Table 1). All mothers had received English language instruction from elementary through high school. The majority of mothers were married or in a domestic partnership (n = 39, 97.5%), which reflects national marriage rates in Canada [53]. The mothers' ages ranged from 23-43 years old, and the majority had a bachelor's degree or higher (n = 29, 72.5%), which aligns with educational trends for women in Organisation for Economic Co-operation and Development (OECD) countries [54]. The mothers also rated their knowledge of various pregnancy topics on a Likert scale (5 = very high; 1 = very low), with the majority reporting average to high knowledge in prenatal care, ultrasound, pregnancy, labour, postnatal care, and the Canadian healthcare system.

Mothers then self-reported their reading and writing habits in daily life, excluding work or school, using a Likert scale (5 = daily; 1 = never). The majority of mothers (n = 39, 97.5%) use a computer, Internet, or social media daily. Of the total sample, 18 mothers (45.0%) read books, newspapers, or magazines daily, and seven mothers (17.5%) read HI and resources or talk to health professionals daily. In the total sample, two mothers (5.0%) never read books, newspapers, or magazines. The mothers also self-reported their mathematics skills on a Likert scale (5 = very good; 1 = very poor). In the total sample, 14 mothers (35.0%) rated their mathematics skills as very good, 13 mothers (32.5%) as good, and 12 mothers (30.0%) as okay. Notably none self-reported "poor" or "very poor" mathematics skills. To further explore specific mathematics skills, mothers were asked to self-report their engagement in mathematics activities, such as measuring or estimating the size and weight of objects; calculating prices, costs, and budgets, or handling money; counting or reading numbers to keep track of things; managing time or preparing timetables and schedules; giving or following directions or using maps or street directories; and using probabilities and statistics to reach conclusions using a Likert scale (5 = at least once a week; 1 = never). Here, only data from the total sample of mothers who self-reported "rarely" or "never" will be shared, as these responses relate closely to our discussion and interpretations of FHL.

In the total sample, 13 (32.5%) and two (5.0%) mothers self-reported "rarely" and "never" using probabilities and statistics to reach conclusions, respectively; three (7.5%) mothers "rarely" give or follow directions or use maps or street directories; two (5.0%) and one (2.5%) mother "rarely" and "never" manage time or prepare timetables and schedules, respectively; one (2.5%) mother "rarely" counts or reads numbers to keep track of things; two (5.0%) mothers "rarely" calculate prices, costs budgets, or handle money; and nine (22.5%) and one (2.5%) mother "rarely" and "never" measure or estimate the size or weight of objects, respectively. After administering the validated HL, NUM, and eHL instruments to compare performance with the self-reports, the results generally showed the SANMs scored lower than CANMs on the FHL instruments.

The results from the HL, NUM, and eHL instruments were scored to determine the adequacy of functional skills in the sample of mothers. Analyzing the results of the HLSI-SF allowed us to assess the FHL of mothers related to topics such as signs of stroke, hospital navigation, medication dosage, and food portion sizes. The collective mean HL score for the entire sample of mothers is 79.0, with a standard deviation of HL = ± 18.6 (Table 2). The mean HL score for the sample of SANMs is 73.0, and

Table 1. Self-reported characteristics of mothers (N = 40)

	Count (n)	Percent (%)
Marital status		
Married or in a domestic partnership	39	97.5
Separated	1	2.5
Age (years)		
23-27	3	7.5
28-32	12	30.0
33-37	17	42.5
38-42	6	15.0
43+	2	5.0
Employment		
Employed full time for wage (40 or more hours per week)	24	60.0
Employed part time for wage (up to 30 hours per week)	6	15.0
Self-employed	2	5.0
A homemaker	4	10.0
Out of work, but not currently looking for work	3	7.5
A student	1	2.5
Religion		
Christianity	6	15.0
Catholicism	3	7.5
Protestant	1	2.5
Judaism	1	2.5
Islam	10	25.0
Buddhism	2	5.0
Hinduism	8	20.0
Sikhism	3	7.5
Spiritual, but not religious	4	10.0
Not spiritual nor religious	2	5.0
Time in Canada (years)		
1-10	14	35.0
11-20	1	2.5
21-30	8	20.0
31-40	14	35.0
40+	3	7.5
Highest degree or level of school completed in Canada		
No education	4	10.0
High school	1	2.5
Some college, no degree	5	12.5
Trade/technical/vocational training	1	2.5
Bachelor's degree	15	37.5
Master's degree	13	32.5
Doctorate	1	2.5
Engage in physical activity		
Yes	30	75.0
No	10	25.0
Eat foods low in salt, fat, and sugar		
Yes	36	90.0
No	4	10.0
Drink alcohol		
Yes	16	40.0
No	24	60.0
Smoke cigarettes		
Yes	2	5.0
No	38	95.0

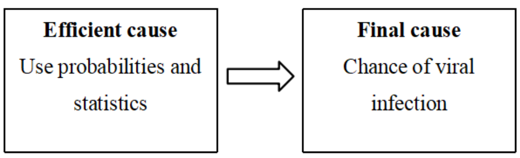
the mean HL score for the sample of CANMs is 85.0 (Table 2). In the sample, seven (17.5%) of the SANMs have inadequate HL and 13 (32.5%) have adequate HL. Two (5.0%) of the CANMs have inadequate HL and 18 (45.0%) have adequate HL. Analyzing the results of the LNS allowed us to assess the factors associated with comprehension of basic mathematical concepts such as probabilities and chance. Based on these results, a comparative analysis of SANMs and CANMs was performed. The collective mean NUM score for the entire sample of mothers is 8.8, with a standard deviation of NUM = ± 2.0 (Table 2). The mean NUM score for SANMs is 8.4, and the mean NUM score for CANMs is 9.1 (Table 2). In the sample, two (5.0%) SANMs and CANMs in each group have inadequate NUM, and 18 (45.0%) SANMs and CANMs in each group have adequate NUM. These results are as expected with measures of central tendency reporting the mean, suggesting the presence of outliers in the sample of SANMs (in contrast to reporting the median). Analyzing the results of the eHEALS instrument allows us to assess the factors associated with engaging electronic tools to promote health through a self-report of eHL skills by the sample of mothers. The collective mean eHEALS score for the entire sample of mothers is 34.4, with a standard deviation of eHL = ± 4.7 (Table 2). The mean eHEALS score for the sample of SANMs is 33.4, and the mean eHEALS score for the sample of CANMs is 35.5 (Table 2). Using the results from the self-reports and validated FHL instruments, we then tested our hypotheses using OOM.

Table 2. Functional health literacy (FHL) scores of mothers (N = 40)

Sample	Mean HL score	Mean NUM score	Mean eHEALS score
SANMs (n = 20)	73.0	8.4	33.4
CANMs (n = 20)	85.0	9.1	35.5
Total (N = 40)	79.0, SD = ± 18.6	8.8, SD = ± 2.0	34.4, SD = ± 4.7

Experiment 1: Comprehension of chance of viral infection

In Experiment 1, we hypothesized that SANMs and CANMs who engage more frequently in probabilistic and statistical reasoning will correspond to more accurate comprehension of the chance of viral infection, with observable differences in the causal process between the two samples. The null hypothesis (H_0) suggests any observed pattern of classifications can be explained by random processes (i.e., no meaningful causal process exists). The alternative hypothesis (H_A) suggests the causal process will yield a pattern of classifications (i.e., correct comprehension of viral infection chance) that is unlikely to occur under random data shuffling. The digital survey asked, *"How often do you do each of the following in everyday life?—Use probabilities and statistics to reach conclusions."* This was paired with the following responses, *"At least once a week," "Less than once a week," "Rarely," "Never,"* and, *"I do not know."* The LNS then posed the following vignette, which required the mothers perform a mathematical calculation, "The chance of getting a viral infection is 0.0005. Out of 10,000 people, about how many of them are expected to get infected?" [50].



For the SANMs, the analysis showed 70.0% correct classifications with a c value of 0.15, when compared to 1,000 random data shuffles (Figure 4). Of the 20 total observations, 14 were correctly classified, and six were incorrectly classified in the sample of SANMs. There were no ambiguously classified observations. Notably, nine SANMs who used probabilities "less than once a week" correctly classified the number of people who would get infected. Although the model correctly classifies 70.0% of the observations, the c value of 0.15 indicates that such a high level of accuracy is not rare under random conditions. This means the pattern could reasonably occur by chance, and therefore the SANM pattern does not appear meaningfully different from random expectations. No meaningful causal pattern is supported. For the CANMs, the analysis also showed 70.0% correct classifications with a c value of 0.04, when compared to 1,000 random data shuffles (Figure 4). The analysis showed 14 correctly classified observations, six incorrectly classified observations, and no ambiguous classifications of the observations in the sample of CANMs. It is noteworthy that eight CANMs who used probabilities "rarely" correctly classified the number of people who would get infected. The model correctly classifies 70.0% of the observations, and the c value of 0.04 indicates that such a pattern is unlikely to have occurred by chance. This provides reasonable support for the presence of a meaningful, non-random causal process in the data, consistent with the theoretical expectations. This indicates moderate-to-strong empirical support for our hypothesis among CANMs. Lastly, in partial support of the hypothesis, only the CANMs showed a meaningful causal process between frequent use of probabilistic and statistical reasoning and correct comprehension of viral infection chance, while the pattern observed among SANMs could plausibly be due to chance. Only the CANMs showed a non-random causal pattern linking everyday probabilistic and statistical reasoning to correct comprehension of viral infection chance. In contrast, the SANMs pattern could plausibly arise by chance and therefore does not support the hypothesized causal process. In summary, CANMs who report more frequent use of probabilistic and statistical reasoning are classified into the state showing higher classification accuracy; this is the only sample that showed a distinct or stronger causal process, and the pattern observed between the samples differs.

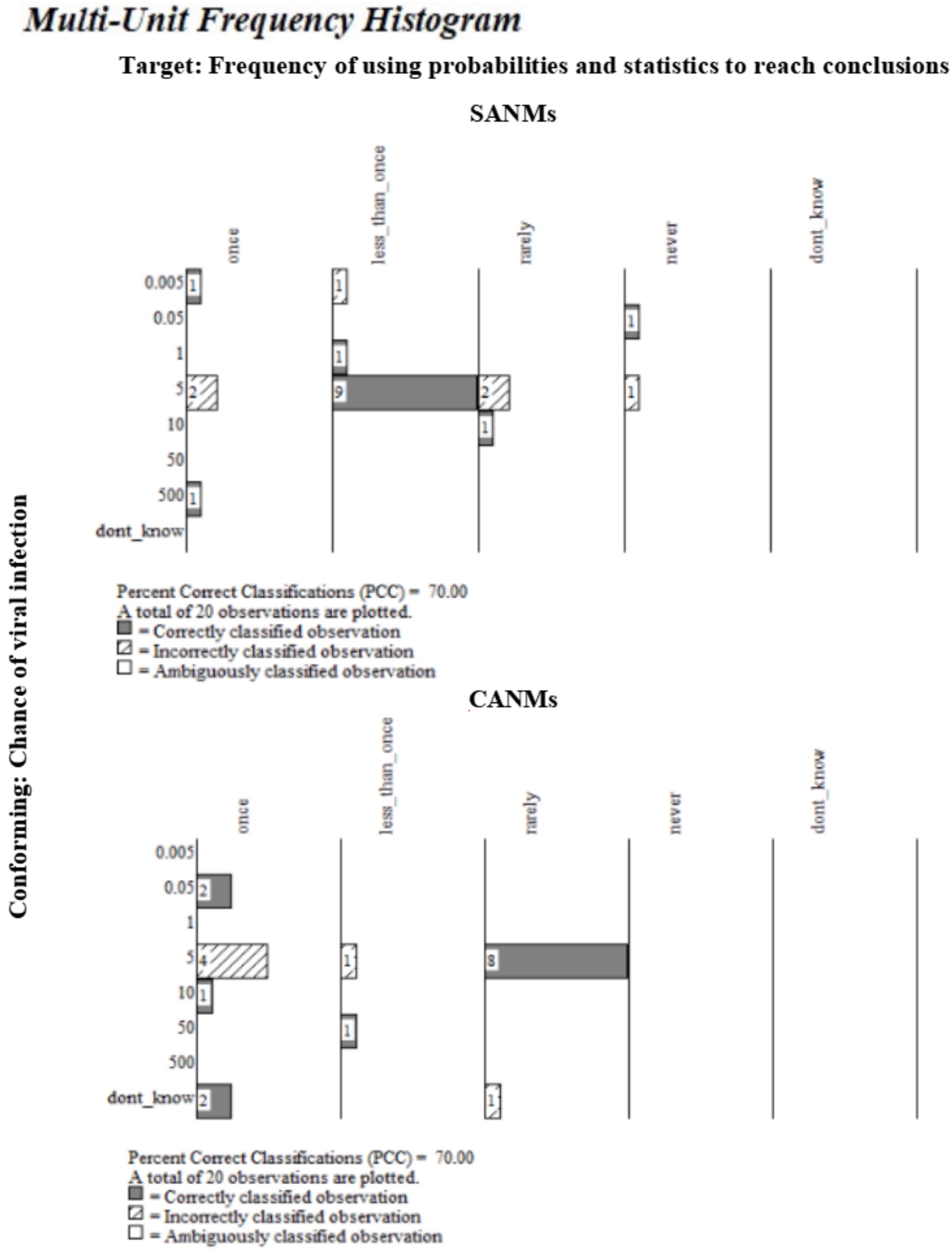
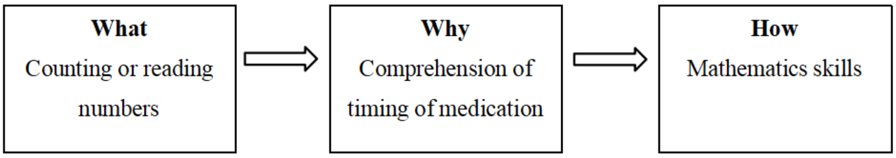


Figure 4. Histogram of classification results for SANMs and CANMs knowledge of using probabilities and statistics to reach conclusions, and the ability to calculate the chance of viral infection

Experiment 2: Comprehension of when to take medication

In Experiment 2, we hypothesized that the frequency of numerical engagement—such as counting or reading numbers—corresponds to accurate comprehension of medication timing, and that this causal process differs between SANMs and CANMs based on the functional application of mathematics skills. This explanatory model consists of three-variables and was developed using a What>Why>How framework. In a three-variable model (classification mapping: X = What (predictor), M = Why (mechanism or moderator), and Y = How (outcome)), which in traditional path analysis often explores direct and indirect effects (mediation), OOM shifts the focus to how well a theoretical model accounts for the specific outcome pattern for each individual case. Thus, the explanatory three-variable model defines how the states of X and M jointly determine the state of Y for a given observation. We presented this as a stepwise progression from Experiment 1 and as a good demonstration of the applied nature of OOM and its capabilities. The goal is to provide a rich, substantive explanation for the pattern of observations, focusing on how and why cases deviate from the pattern, which can inform model revision and theory development. This hypothesis tests whether numerical engagement behaviours (i.e., counting, reading numbers) are classified into the state representing accurate comprehension of medication timing based on functional mathematical skills, and whether this causal process differs between SANMs and CANMs.

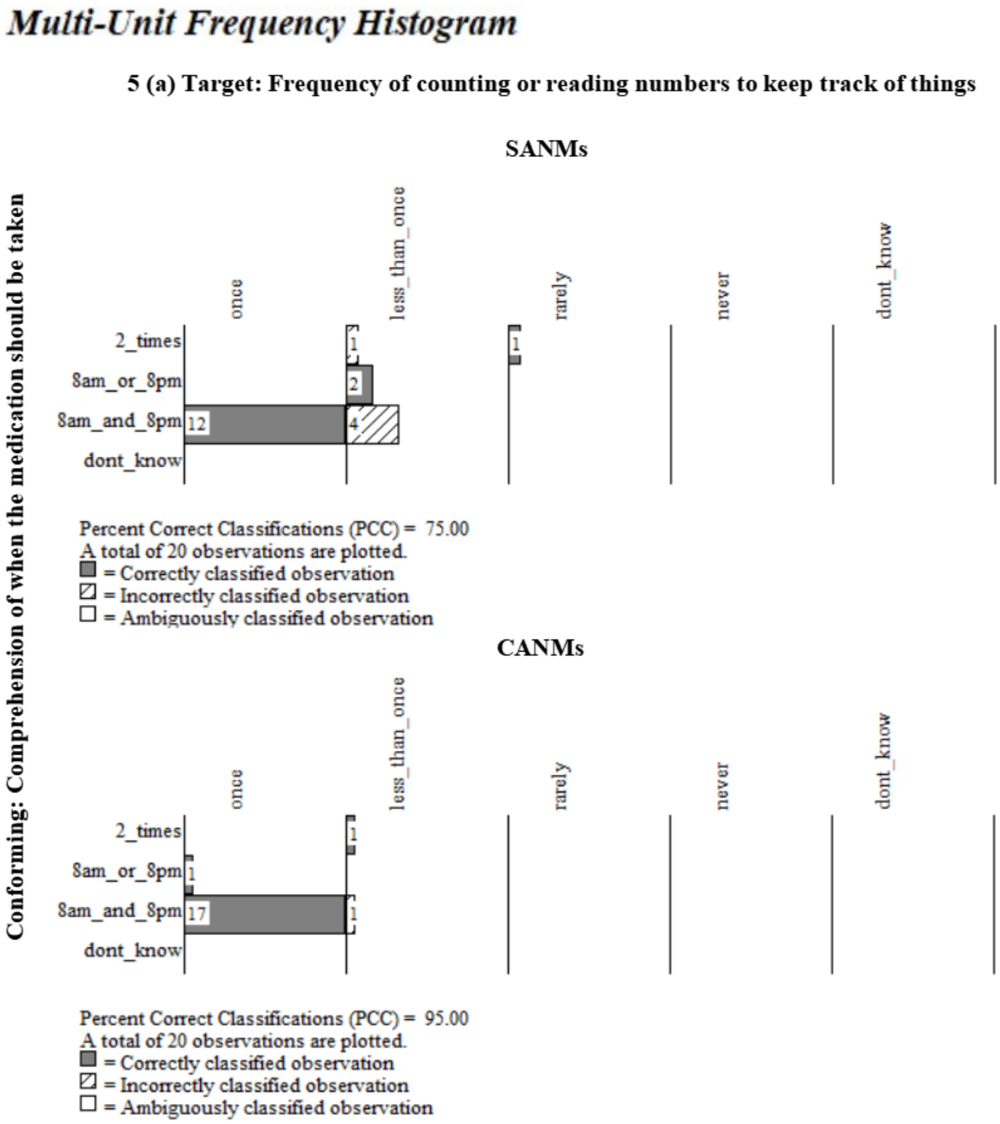


Similarly to Experiment 1, the null hypothesis (H_0) suggests the observed classification pattern is not meaningfully different from what would occur under random data shuffling. The alternative hypothesis (H_A) suggests the observed pattern is meaningfully structured (i.e., unlikely to occur under random shuffling), consistent with the theorized causal process. The digital survey asked, *"How often do you do each of the following in everyday life—Count or read numbers to keep track of things."* This was paired with the following responses, *"At least once a week," "Less than once a week," "Rarely," "Never," and "I do not know."* The HLSI-SF then posed the following question, requiring the mother to interpret OHI from a chart entitled, "My Medicine Record" [49]. The question reads, "In the example listed in the first row of the table, when should the medicine be taken?" The multiple choice responses include: a.Two times a day anytime between 8 am and 8 pm; b. At 8 am or 8 pm each day; c. At 8 am and 8 pm each day; d. Don't know [49]. The digital survey then asked, *"How would you rate your mathematical skills?"* This was paired with the following responses, *"Very good," "Good," "Okay," "Poor," and "Very Poor."*

This explanatory three-variable model was analyzed in two parts. Firstly, we began with analysis of patterns within SANMs only. For the SANMs, the results of the first pair of variables (what and why) showed 75.0% correct classifications (PCC) with a c value of 0.01, after comparing it with 1,000 random data shuffles (Figure 5a). Of the 20 total observations, the analysis revealed 15 correctly classified and five incorrectly classified observations in the sample of SANMs. Here, 12 SANMs who reported counting or reading numbers "at least once a week" correctly responded that 8 am and 8 pm were when the medication should be taken. This model correctly classifies 75.0% of the cases, and the c value of 0.01 indicates that such a pattern is unlikely to occur by chance. This provides strong evidence for a meaningful, non-random causal process between the variables in the model. OOM emphasizes model refinement with real cases. Adding the third variable (why and how), the results showed 70.0% correct classifications with a c value of 0.06, after comparing it with 1,000 random data shuffles (Figure 5b). Of the 20 total observations, the analysis revealed 14 correctly classified and six incorrectly classified observations, with no ambiguously classified observations. Here, seven SANMs who self-reported "very good" mathematics skills correctly responded that medication should be taken at 8 am and 8 pm. There appears to be moderate evidence for a meaningful directional pattern between the timing of medication and self-reported mathematics skills, introducing some variability into the pattern as 70.0% of observations fit the expected pattern, with a relatively low c value of 0.06. Adding in the third variable introduces variability into the predicted pattern, suggesting that self-reported mathematical skill does not correspond as consistently to the expected medication-timing responses in this sample. The strength of the pattern here is not overwhelming. Thus, including the third variable introduces inconsistency, and this is less strong than the first pair of variables alone.

Secondly, we completed an analysis of patterns within CANMs only. For the CANMs, the results of the first pair of variables (what and why) showed 95.0% correct classifications (PCC) with a c value of 0.18, after comparing it with 1,000 random data shuffles (Figure 5a). Of the 20 total observations, the analysis indicated 19 correctly classified observations, with only one incorrectly classified observation in the sample of CANMs. Here, 17 CANMs who reported counting or reading numbers "at least once a week" correctly responded that 8 am and 8 pm were the appropriate times to take the medication. Although the model correctly classifies 95.0% of the observations, the c value of 0.18 indicates that such a high level of accuracy is not distinguishable from patterns produced by random assignment. This means the pattern could reasonably occur by chance and, therefore, the result does not provide strong evidence for a meaningful non-random pattern. In this case, the pattern is not unique enough to be clearly distinguished from chance. OOM emphasizes model refinement with real cases. Adding in the third variable (why and how), the results showed 45.0% correct classifications with a c value of 0.69, after comparing it with 1,000 random data shuffles (Figure 5b). Of the 20 total observations, the analysis revealed nine correctly classified and 11 incorrectly classified observations. There were no ambiguously classified observations. Here too, there is no support for a meaningful or directional causal process between timing of medication and self-reported mathematics skills. Only 45.0% of classifications matched the hypothesized pattern, and the high c value of 0.69 suggests this result is highly likely due to chance. Therefore, the theorized explanatory pattern does not correspond well to the observed individual level outcomes among CANMs.

In summary, consistent with the hypothesis, the results for SANMs provide strong evidence of a meaningful and non-random pattern that frequent numerical engagement is associated with correct medication timing comprehension, and moderate evidence for a meaningful pattern involving self-reported mathematical skills, although this pattern



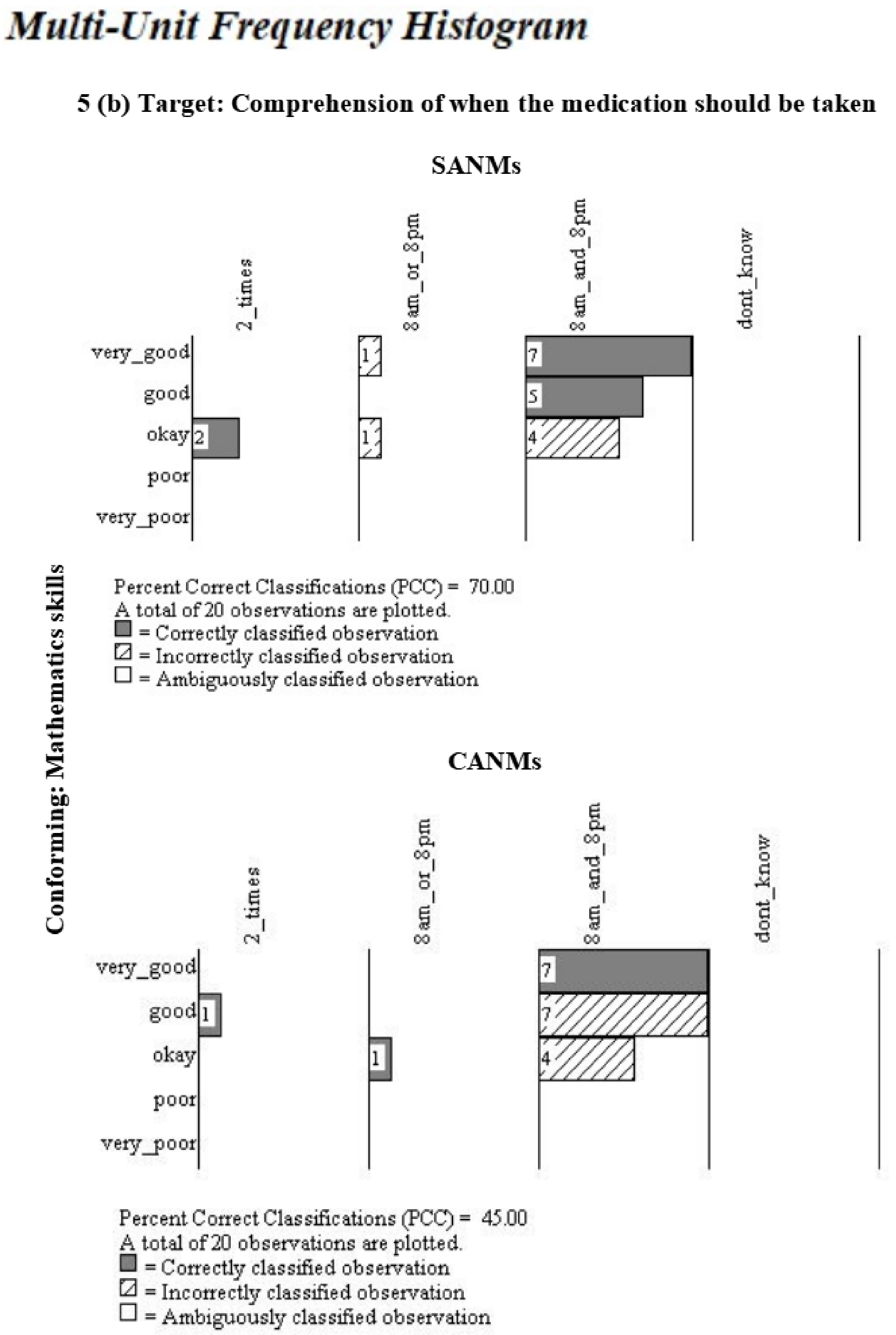


Figure 5. Histogram of classification results for SANMs and CANMs knowledge of frequency of counting or reading numbers to keep track of things, comprehension of timing of medications, and mathematics skills. (a) What>Why model and (b) Why>How model

is weaker and less consistent. However, for CANMs, the high classification lacks strong evidence for a meaningful non-random pattern, suggesting the observed pattern may be solely due to chance. For SANMs, the two-variable model showed strong evidence of a meaningful, non-random pattern linking numerical engagement to correct medication-timing comprehension, while the three-variable model received moderate support. In contrast, for CANMs, neither model was meaningfully distinct from chance. Thus, the hypothesized explanatory process appears supported for SANMs, but not for CANMs.

Discussion

This research examined the MHL of SANMs and CANMs by assessing individual learning processes to develop an explanatory model of comprehension depth. This research focuses on SANMs, the largest racialized/visible minority population in Canada, and compares their sociocultural cognitive processing with that of CANMs. In doing so, we offered suggestions for future health education, wherein creating effective HI and OHI is required. These recommendations are based on the results of FHL assessments in two samples of mothers [55]. The purpose of this research is to understand the language, language competencies, and comprehension opportunities and challenges faced by all mothers to improve health education, with a specific focus on FHL implications in healthcare settings and the use of gist. In summary, both the SANMs and CANMs self-reported adequate NUM abilities, but failed to perform functionally on assessments, which is aligned with much of the existing research evidence.

The research evidence suggests numerical language affects how people solve problems and retrieve numbers, which influences learning [56-58]. Although only one mother in the total sample reported "poor" or "very poor" mathematics skills, both SANMs and CANMs samples struggled with understanding numeric print when assessed functionally, according to the results of the HLSI-SF and the LNS. Notably, the metric system represents a different numerical language that is more difficult for older South Asian mothers, who engage with the imperial system, to grasp. In Experiment 1, the analysis showed a meaningful pattern between frequent use of probabilities and statistics and correct comprehension of chance of viral infection in the sample of CANMs, while the pattern observed among SANMs could plausibly be due to chance. In terms of gist, the result suggests SANMs who engage in more numerical reasoning might have better comprehension of the gist (e.g., the main idea of viral infection chance), but there is less confidence that they are systematically engaging in deeper, more refined probabilistic and statistical understanding (verbatim processing). Therefore, for the SANMs, one can cautiously conclude that there is some evidence for gist-level comprehension improvement with increased numerical reasoning, but less strong evidence of deeper comprehension. In contrast, the meaningful pattern among CANMs may reflect greater familiarity with Canadian number conventions, customs, or other sociocultural exposures, but this study did not directly test the metric system hypothesis in either sample of mothers. These customs are formed in elementary school and throughout the entirety of their course in the education system as well as through general practice at work or in the community (e.g., paying with cash and calculating tips). Consequently, CANMs may be drawing on numerical conventions familiar within Canadian schooling and daily contexts. In terms of gist, the pattern appears uncommon (c value = 0.04), suggesting not only that CANMs show gist (main comprehension of chance), but also that their numerical reasoning may effectively contribute to this comprehension in a meaningful way. While this is not direct evidence of full verbatim comprehension, CANMs likely benefit more strongly from increased numerical reasoning compared to SANMs. Thus, for CANMs, the data show a meaningful pattern consistent with the idea that more frequent probabilistic and statistical reasoning corresponds with correct comprehension of the chance of viral infection (likely at the gist level, maybe approaching deeper processing) than for SANMs (given the lower c value). Therefore, information recall and experience depend on how well information is connected to other ideas and activities—reinforced through practice in situated contexts and contributing to gist [59]. In summary, this provides reasonable support for the presence of a meaningful, non-random causal process according to the data, consistent with the theoretical expectations in Experiment 1 for CANMs.

However, the aforementioned does not apply to SANMs who showed weaker evidence for a non-random pattern or had shallower uptake of HI. According to the results of Experiment 1, SANMs did not show a meaningful pattern linking the frequency of their numerical reasoning to accuracy of comprehension. In terms of MHL implications, CANMs showed stronger gist but had difficulty with two-step mathematical calculations and in converting decimals compared to SANMs, possibly due to less practice with these tasks, which can also be reflected in their child's learning challenges [58,60,61]. The OOM pattern among CANMs indicates stronger accuracy between probabilistic and statistical reasoning and comprehension, but their raw performance on multi-step NUM items remained inconsistent, highlighting that comprehension does not necessarily imply overall superior global NUM skills. Both samples of mothers experienced difficulties with functional NUM abilities, contrary to their self-reports. Health educators may need to provide additional scaffolding (e.g., more contextualization, culturally relevant examples) to ensure that numerical reasoning leads to comprehension. According to the results of the HLSI-SF, both samples of mothers struggled with reading numerical values from nutrition labels and following oral instructions in English related to numbers, consistent with previous research findings [62,63]. Therefore, health education materials should be designed to engage numerical reasoning (such as presenting likelihood data, statistical information and interactive reasoning tasks in context) rather than contain purely descriptive text. Evidence is seen in the sample of CANMs, who had difficulty in understanding data from stacked bar charts on prostate cancer (perhaps because of lower awareness and context of men's health issues) [64]. The format and content of educational materials must be improved for better comprehension; otherwise, decision-making may be affected [65]. People who struggle with probabilities often overestimate health risks as well [50,66,67]. Of the total sample, 26 mothers (65.0%) answered correctly to the LNS question about the chance of getting a viral infection—six (15.0%) SANMs and eight (20.0%) CANMs answered incorrectly. This is the second of two NUM scale items of which there was a greater number and percentage of CANMs in the sample who responded incorrectly compared to SANMs (here, CANMs had higher incorrect responses on the raw LNS items involving advanced probability tasks). Since differences emerged in the evidence for a meaningful non-random pattern between samples, educational programs should anticipate that different populations may respond differently to numerical reasoning interventions; thus, adaptability is key.

In Experiment 2, the explanatory model accurately found SANMs who engage more frequently in counting or reading numbers are more likely to correctly comprehend information regarding when to take medication by functionally applying mathematics skills, according to the explanatory three-variable model, which provided strong and moderate evidence for the pattern, respectively. This was not the case for the sample of CANMs, wherein the pattern was not rare and likely due to chance. According to the raw results of the HLSI-SF item performance, SANMs had difficulty interpreting tables and documents, as four (10.0%) SANMs incorrectly identified the timing of medications. In contrast, CANMs were better at understanding quantitative medication records presented in tables. Although CANMs scored higher on the raw medication-table item, their responses did not align with the predicted multi-variable pattern, suggesting greater variability in how they applied NUM. According to the general research evidence, learning new language and number customs improves newcomers' experiences of healthcare access in Canada (e.g., navigation of the healthcare system, comprehension of OHI) [20]. In effect, we may cautiously conclude that in Experiment 2, SANMs showed a relatively stable and meaningful pattern (at the gist level), whereas CANMs did not. This does not generalize across all tasks; the pattern differs by context. The pattern for SANMs suggests gist-level comprehension may be relatively robust within the medication-timing task, although we cannot infer deep verbatim understanding from OOM alone. The stronger results for SANMs with two variables (and the moderate drop when adding the third) suggest their comprehension of the relationship (What>Why) is reasonably deep—enough that a majority adhere to the hypothesized structure. The drop in fit when adding the third variable (Why>How) indicates that adding detail (how the process works) requires deeper processing, which may reduce uniformity. This is typical when one shifts from gist to more detailed comprehension. The implication of this result is that language and number customs affect how information is accessed, and behaviors impact learning over time based on individual characteristics.

We may summarize that in the case of SANMs, the gist model is strong and less robust for CANMs; when complexity increases, the pattern is less consistent, indicating typical difficulties in moving from gist to deeper relational understanding, which may be attributable to individual characteristics. Individual characteristics, including age, gender, education, and previous use of electronic health tools, affect FHL [68]. There may be differences in prior knowledge, cultural frameworks, learning experiences, or metacognitive strategy use as well. Therefore, health educators should ensure that newcomer mothers can reliably grasp and articulate the gist of health directives before introducing more complex "how" details. It is also noteworthy that the HLSI-SF was administered digitally. According to the results of the eHEALS assessment, more SANMs had difficulties in accessing, understanding, and using electronic HI compared to CANMs in the sample. Previous research has also confirmed that SANMs have difficulty in using the Internet, possibly due to limited access to online technologies [69,70]. In contrast, CANMs have more experience with digital tools such as the Internet, search engines, and healthcare websites [12,71]. The difference between SANMs and CANMs suggests that one size may not fit all. Ultimately, medication literacy may be improved by enhancing skills to understand print documents containing numbers, such as identifying and integrating information, making inferences, and searching through dense information [72]. Addressing different levels of medication literacy through interventions has been recognized as a need in both newcomer and domestic populations [73,74].

In summary, the research suggests that OOM can be used to validate an explanatory model of MHL by analyzing how specific combinations of orderings align with observed individual patterns. This research identifies consistent causal processes, pattern classifications, and mismatches across cases, allowing for refinement in future research that develops multivariable, explanatory models based on efficient and final cause pairs. This approach emphasizes explanation over correlation, providing a more accurate, context-sensitive validation of how multiple, psyche-based orderings interact to shape comprehension in real-world settings. Across both samples, similarities are that English language alone is not associated with greater comprehension of health conditions, and that information access and use depend on quality, breadth, depth, range, and information context. Differences across both samples include variation in knowledge of key pregnancy and obstetric terminology, as well as how the influence of personal characteristics, psychosocial factors, cultural and religious beliefs, and social relationships result in differences in comprehension. Ultimately, the outcomes of this research illustrate that comprehension of numbers is shaped by a multi-step information-seeking process involving perception, visual interaction, and problem-solving, and consolidation in the memory. HI must be tailored (shaping and framing), as many mothers struggle to apply written and numerical advice, and context-based oral or interactive health interventions are needed for those with lower FHL.

Strengths and limitations

This research has both strengths and limitations. One limitation is that the non-probability judgement sample is homogeneous, which means the results may not be generalizable [42]. Since the sample is homogeneous, future research should include more diverse participant groups to test whether similar explanatory patterns emerge across different contexts to enhance population validity. For instance, future research may recruit different populations of newcomer mothers to track individual changes before and after a MHL intervention that combines health education with basic HL and HN skills (such as reading prescriptions, understanding nutrition labels, and interpreting risk of infection), or conduct research using oration, word recognition, and reading comprehension. OOM would identify which patterns of improvement emerge across participants and how the different literacies interact in real-world contexts. This approach refines the explanatory model and supports the development of more effective, personalized public health education strategies to facilitate learning. A strength of the research is that the majority of the mothers engaged in English-language instruction at school, which allows for more consistent comparisons between the two samples. Similarly, a strength of OOM is that it considers MHL as a whole system of orderings of psyche-based qualities, rather than as a set of separate variables, providing valuable insights at the individual level [40]. Multiple data collection methods were employed by means of data triangulation, thus providing a comprehensive interpretation of the phenomenon investigated. To improve the overall methodological framework, increasing the sample size, collecting more data on a wider range of MHL events and psyche-based orderings, and refining the response scales could enhance the relevance of the results [40,42]. OOM relies heavily on finding similar patterns across different samples and settings. As such, future research can focus on replication, where the same research is conducted with different populations, settings, or over time to help determine if the results hold true across varied contexts.

Conclusions

The research explores how perception is linked to behaviour by explaining MHL processes in a system using a sample of SANMs and CANMs. This contributes to MHL research by using OOM to develop an explanatory model that reveals individual level patterns in two samples of mothers. Unlike traditional variable-based methods, OOM highlights how specific factors interact within real-world contexts, enabling a more personalized understanding of behaviours. This person-centred approach supports the design of more effective, context-specific health education interventions. Additionally, it advances methodological innovation in public health research by demonstrating the value of explanatory, pattern-based analysis over predictive, group-based statistics. In this research, the implication for health education practice is to create 'kind' learning environments where success criteria are clear, enabling all mothers to use their knowledge to make better health decisions in real-world contexts. For ethno-culturally diverse mothers, this can be achieved by consistently referring to health concepts in the same way, avoiding synonyms, providing explanations for unfamiliar topics, marking topics, and using sentence conjunctions to improve flow. Ultimately, the explanatory model highlights the importance of shaping and framing OHI to improve comprehension.

Abbreviations

CANMs – Canadian-born mothers
c value – chance value
eHEALS – eHealth literacy scale
eHL – electronic health literacy
FHL – functional health literacy
FTT – fuzzy-trace theory
HI – health information
HL – health literacy
HLSI-SF – health literacy skills instrument-short form
HN – health numeracy
LNS – lipkus numeracy scale
MHL – maternal health literacy
NHST – null hypothesis significance testing
NUM – numeracy
OECD – organisation for economic cooperation and development
OHI – online health information
OOM – observation oriented modelling
PCC – percent correct classification
PP – perceptual process
PSP – problem-solving process
REB – research ethics board
RTI – research triangle institute
SANMs – South Asian newcomer mothers
SPSS – statistical package for the social sciences
STEM – science, technology, engineering, and mathematics
STROBE – strengthening the reporting of observational studies in epidemiology statement
TOFHLA – test of functional health literacy in adults
VIP – visual interaction process

Availability of data and materials

The supplementary files, codebook, and datasets that support the results of this research are available on request from the corresponding author upon reasonable request.

Authors' contributions

DK, HTN, LD, and EN contributed equally to the conceptualization of this research and the formulation of the aims of this research. DK, HTN, and LD developed the design of the research and DK executed the creation of the explanatory model and application of the methodology. DK and MP were involved in the exploratory data analysis, with MP assisting in project administration. IS provided scholarly review and feedback of the final draft and assisted with manuscript writing. All authors contributed equally to the investigation and validation of the research. DK was responsible for the original draft writing of this manuscript; however, all authors were responsible for the review, feedback, and editing of the final copy of this manuscript. HTN and LD are the principal investigators, serving as supervisors for the oversight and leadership responsibility of all research activity.

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Institutional review board statement

This research follows the guidelines of the Declaration of Helsinki and has been approved by the University of Waterloo Ethics Review Board (REB #43128). Oral consent has been obtained from all mothers participating in the research.

Conflict of interest

All authors declared there are no conflicts of interest for this research.

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