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PAPER

Exploring Sex Differences in Numerosity Perception Using Dynamic Visual Stimuli: Insights into Cognitive Processing and STEM

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ABSTRACT

Numerosity perception, the innate ability to estimate the number of objects in a set without counting, plays a crucial role in cognitive science and has implications for addressing sex disparities in science, technology, engineering, and mathematics (STEM) fields. Despite its significance, research on sex differences in numerosity perception, particularly in dynamic visual contexts, is still limited. This study aims to address this gap by investigating sex differences in numerosity perception using 3D dynamic stimuli in a dual-task experiment. We found a significant underestimation of numerosity among females, a phenomenon not previously reported in adults. This suggests sex-based variations in numerosity perception, likely linked to differences in spatial cognition. The study also reveals how increased attentional load can negatively affect numerosity estimation, especially in females. Despite the limitation of a small participant group, this pilot research establishes a framework for more extensive future studies to substantiate these findings and deepen our understanding of sex-specific cognitive processing in dynamic environments.

KEYWORDS

numerosity estimation, science, technology, engineering, and mathematics (STEM), sex differences, cognitive load

1 INTRODUCTION

Numerosity perception, which refers to the spontaneous extraction and mental representation of set size, is a fundamental and universal ability that significantly influences human behavior. We use numerosity as a cue for judging quantity or probability [1, 2] and tend to base our judgments on numbers rather than any of the various other types of information available [3]. The assessment of numerosity perception is commonly based on a subject's ability to compare patterns or estimate object quantity at a glance without physically counting [1].

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Numerosity perception is inherent in the primary biological forms of cognition [4, 5] and emerges universally, irrespective of cultural experience and development. Numerosity perception underlies many life skills, making it important to understand its operating principles. Studies [6, 7, 8] have revealed that preschool and school-aged children with high number acuity tend to achieve higher levels of success in mathematics. While studies [9, 10, 11, 12] have documented a pattern of differences between sexes favoring males, the performance gap increases in line with the complexity of the tasks [12]. This leads to a noticeable sex imbalance in science, technology, engineering, and mathematics (STEM) programs, a matter of concern for educators and scholars globally [13, 14], and contributes to the underrepresentation of women in STEM careers [15, 16]. Therefore, a study on sex differences in numerosity perception is very timely and necessary.

While the functional architecture of numerosity perception remains a topic of debate, a consistent observation guiding the discussion is that there is a difference in how people perceive numerosity for small and large sets. People can identify the number of elements in a set almost without error when the set size is up to four elements. When evaluating larger sets, number acuity decreases linearly with the size of the set [17]. Consequently, most researchers believe that two distinct systems are used for numerosity perception, namely. The object tracking system (OTS), which is responsible for identifying sets of up to four elements, while the approximate numbering system (ANS) is used when the set size exceeds four elements [18]. However, a key research challenge is analyzing the relevant visual tools and sensory features used by the ANS to derive an approximate numerical representation [19]. A distinct ANS trait evidenced in literature is that confidence in the number of objects presented decreases correspondingly with an increase in the actual number [20]. Allik and Tuulmets [21] observed that perceived numerosity diminishes as the spatial and temporal proximity of displayed items increases. Thus, illustrating the interplay between the timing of dynamic visual events and their spatial characteristics, which together impact the overall perception of numerosity [22].

Some circumstantial evidence suggests potential sex-specific differences in the performance of ANS. However, this disparity in numerosity perception remains unstudied, even though some related cognitive mechanisms exhibit a sex difference in performance. In a recent study, Murray et al. [23] found a surprising sex-specific difference in OTS. It is not only responsible for numerosity perception for a small set but also for detecting movement. Murray et al. [23] reported that males detect visual motion significantly faster than females. While object tracking is closely related to numerosity perception for small sets, the observed differences in the performance of OTS between sexes do not directly imply similar inter-sex differences in numerosity perception for larger sets. However, it prompts us to hypothesize that ANS may not perform identically in males and females.

In this exploratory study, we investigate potential intersex differences in numerosity perception using complex visual dynamic stimuli.

2 LITERATURE REVIEW

2.1 Sex differences in mathematics and STEM

The disparity between sexes in science and technology degrees is well documented [13, 14, 15, 24, 25, 26], with numerous studies since 1971 exploring sex equality in

STEM programs [25]. Generally, the proportion of female graduates in these areas is smaller than that of their male counterparts. To bridge the gap between sexes in the professional sphere, fostering diversity and inclusion in educational environments from an early age is essential [15]. Factors such as individual self-perception and confidence, particularly regarding mathematical skills fundamental in STEM disciplines, contribute to this disparity [13, 27].

The close relationship between numerosity perception and mathematical abilities has been the subject of intense debate for decades, as numerosity perception and symbolic numerical skills both involve quantity processing [9, 28]. Nonverbal numerical estimation is a fundamental cognitive ability that spans various human cultures and stages of development [3]. What forms the cognitive basis for number acuity in humans? Recent studies have shown that the ANS, an innate and inexact analogue system, enables humans to rapidly approximate numerical operations such as comparison and addition without explicit counting [29, 30]. The ANS produces numerical representations that increase linearly with the target array; larger quantities are represented less precisely than smaller quantities. The Weber fraction indexes the amount of error in the underlying mental perception of numerosity [6, 31]. For example, Halberda et al. [6], Matthews et al. [7], and Zhang et al. [8] showed that preschool and school-aged children with high ANS acuity tend to have higher achievement in mathematics scores. Several sources have shown that the ANS is the cognitive foundation of numerical acuity skills, including addition, subtraction, and multiplication. Dehaene [32] asserts that the ANS activates automatically in response to Arabic numerals. Even children without formal math instruction seem to utilize the ANS to perform symbolic arithmetic operations [28]. Conversely, Haist et al. [33] found evidence that numerosity comparison occurs in the ventral occipital-temporal cortex and hippocampus, the same areas considered responsible for mathematical performance in adults. In recent studies, Chen [9] conducted a meta-analysis that revealed a moderate but statistically significant cross-sectional correlation between number acuity and math performance. Out of 36 studies, 35 demonstrated a positive relationship between number acuity and mathematical abilities, with statistically significant results in 20 studies. Most of those studies focused on children, and only a few explored the correlation between number acuity and mathematical performance in adults. For example, Guillaume et al. [34], Mazzocco et al. [5], and Szucs et al. [35] found a connection between mathematical performance, arithmetical performance [36], and numerosity comparison in adults. Contrastingly, Inglis et al. [30] reported opposing results for adults. Their findings confirm the hypothesis that non-verbal number acuity correlates with symbolic math performance in children only. However, there is currently no research reviewing intersex differences in numerosity perception in adults. The only study observed children aged 6 months to 8 years, and the results revealed that boys and girls do not differ in early quantitative and mathematical ability [37]. However, the recognized intersex gap becomes more prominent in later years. Willingham and Cole [12] documented that, starting in high school, boys outperformed girls in math tasks. The performance difference increased with the complexity of the tasks. According to Royer et al. [11], mathematical skills are significantly higher in males. Hyde et al. [10] reported that the pattern of differences between sexes changes as a function of grade. In high school, boys outperformed girls, while adult males aged 19 to 25 showed a significant advantage over females of the same age. This leads us to hypothesize the existence of sex-based differences in numerosity perception in adults.

2.2 Numerosity estimation

The performance of the ANS has been predominantly studied in experimental settings focused on numerosity comparison tasks. In these tasks, two arrays of dots are briefly displayed side by side, and the participant is asked to identify the larger set [38]. Existing literature supports the idea that the spatial arrangement of objects (dots) directly influences perceived numerosity [1]. Studies indicate that dots in ordered configurations are more frequently overestimated than dots in a random configuration, while clustered dots are typically underestimated [1]. Therefore, this robust method is commonly used for studies that focus on accurately identifying individual numerosity acuity. This variable can then be utilized as an independent variable to explain observed individual differences in later-learned life skills, such as mathematical abilities.

Everyday life, however, is a diverse and noisy environment full of distractions that may influence the performance of numerosity perception. Leibovich et al. [39] demonstrate that the perception of numerosity is context-driven. Additionally, a growing body of literature indicates that the presence of salient task-irrelevant visual features, such as the spatial arrangement of objects [40], illusory contours of sets [41], and a number of distractors [42, 43], all influence numerosity processing. In real-life situations, there is usually an abundance of task-irrelevant stimuli, which can impose a high attentional load. This high attentional load has been shown to significantly impact numerosity processing [44]. Furthermore, visuospatial processing is a complex task that involves mentally rotating and identifying 3D moving objects.

Previous studies have revealed that various perceptual factors may affect numerosity [20, 45, 46]. For example, reducing the distance between objects leads to overlapping apparent areas, resulting in an underestimation of numerosity [1]. Tokita and Ishiguchi [47] showed that precision deteriorated when the event duration and the total stimulus interval were manipulated. The longer interval led to lower numerosity perception than the shorter interval, affirming that temporal information affects numerosity perception. Based on reference [22], when visual information is presented more quickly than the visual system can process, some of it may not be fully processed, leading to a failure to reach conscious perception. Consequently, the current scene representation can overwrite and replace the previous one, leading to an underestimation of the number of objects.

Given the volume of information that the human senses receive at any given moment and the capacity of the human brain to process higher-level information [48, 49], only a fraction of the incoming information is processed at a specific time. While allocating the available cognitive bandwidth, attention must proactively filter behaviorally relevant stimuli from environmental clutter [50] to ensure that the user's current active goals remain a priority [51]. Recent studies [52] challenge the traditional theory that small numerosity perception, also known as subitizing, would be exempt from the capacity limits of attention. Particularly considering that discrimination ability deteriorates drastically under high attentional load, especially in the subitizing range. Feature detection is also an attention-demanding process in dual-task experiments [53]. Pome et al. [44] investigated numerosity perception under the influence of visual attentional load. Their results support the notion that attentional loads primarily affect the subitizing range of numerosity. The range least impacted by the attentional load is the intermediate object quantity. Au and Watanabe [22] found that in a dual-task experiment, as the attentional load increased, the accuracy of numerosity estimation decreased, with the lowest precision observed in the high-load condition. Similarly, Burr et al. [54, 55] provided evidence showing that increased attentional load results in a reduction in the accuracy of numerosity estimation, leading to greater variability in responses.

The current study has largely focused on numerosity estimation using static displays, where observers are asked to estimate or compare the number of items in the briefly shown stimuli. However, in real-world settings, numerosity judgments often occur within dynamic visual environments, an area that has been relatively underexplored in research. In our study, we measured numerosity estimation by utilizing 3D dynamic stimuli, with each trial lasting approximately one minute. Following Testolin and McClelland's [20] concern about the impact of ecological settings on response distribution, we intentionally kept the task of numerosity perception unknown to participants during the experiment and presented it only once. This approach minimized the likelihood of participants engaging in active counting during the tasks.

To contribute to the limited literature on dynamic display numerosity estimation, our research explored potential differences in numerosity estimations between sexes in dynamic visual contexts. We hypothesized that there would be an underestimation of numerosity in dynamic visual stimuli in a dual-task experiment with a high attentional load. Our results supported this hypothesis and demonstrated a new phenomenon: numerosity underestimation, which varies between sexes in dynamic displays with a large number of objects (far beyond the subitizing range). Further, we demonstrate that the underestimation effect mostly occurs for females but not for males.

3 MATERIAL AND METHODS

3.1 Participants

Given the exploratory nature of this pilot study, we worked with a small cohort of participants. We recruited 22 observers to participate in the experiment: 12 females and 10 males, aged between 20 and 50 years old ($\bar{x} = 29.2$). Considering a within-subject design and two basic cells related to independent variables, the minimum requirement of a sample size is 10 contributing participants for each cell mean [56]. All participants had normal or corrected to normal vision. Participation in the experiment was voluntary. We obtained written consent from all participants before the experiment. The privacy of the participants was protected as personal information was kept confidential in accordance with the code of ethics of the World Medical Association (Declaration of Helsinki). Participants were unaware of the conditions of the experiment before they took part in the study.

3.2 Stimuli

Stimuli were programmed using raw data from the KITTI website [28] and XVIZ v2.0.0 (Uber Technologies, Inc., San Francisco, United States) for access through a browser. We utilized streetscape.gl v1.0.0 (Uber Technologies, Inc., San Francisco, United States) to visualize the XVIZ stream and incorporated a base layer map from Mapbox (Mapbox, San Francisco, United States) to generate a lifelike 3D video simulation of a monitoring platform. This resulted in 22 short video files. The experiment was programmed in ExperimentBuilder version 2.3.38 (SR Research Ltd., Ottawa, Canada). Stimulus presentation and response collection were controlled during the experiment by the EyeLink Portable Duo v6.12 (EYELINK II, SR Research Ltd., Ottawa, Canada). We presented video files to the participants on a monitor with a refresh rate of 240 Hz and a resolution of 1152 × 864 pixels. The viewing distance from the PC display was approximately 70 cm, with a stable overall luminance of the display. We used a head-fixed mount with a chest rest to maintain uniform distance for each participant.

3.3 Procedure

In the experiment, we chose to take a novel approach by using 3D moving objects instead of the 2D objects commonly used in previous studies. Observers performed an attention-demanding task involving object identification as well as a numerosity judgment task. When a target appeared on the screen, it was immediately marked with the respective colored box (orange for pedestrians and pink for bicycles). As an object moved behind the car, its colored box became invisible. A snapshot of one of the routes is shown in Figure 1. The independent variables in our study were sex and quantity of objects. The number of objects varied from 1 to 17. The set of moving objects comprised both targets (a bicycle or a pedestrian) and task-irrelevant distractors. Video files contained three types of visual conditions: 1) absence of targets; 2) presence of one target only; and 3) presence of both targets. The left panel of the screen displayed additional visual data such as acceleration, velocity, camera image, and view mode options. Participants were instructed to detect the appearance of a bicycle or a pedestrian and subsequently press one of two designated keys on the keyboard as quickly as possible following the object's appearance.

The task consisted of two blocks. The first block contained two examples for instructing participants, and the second block comprised twenty-two trials involving approximately one-minute-long video files. All participants were exposed to the same set of videos in the second block. The video files contained different numbers of targets and task-irrelevant objects, such as trucks and other vehicles. A target appeared unpredictably. Out of the 22 video files, 14 contained targets, while the remaining 8 contained only distractors. The minimum number of objects was 1, while the maximum "effective set size" was 17. The "effective set size" refers to the number of objects considered as particular targets in a specific scene [57] or those highlighted with a colored box.

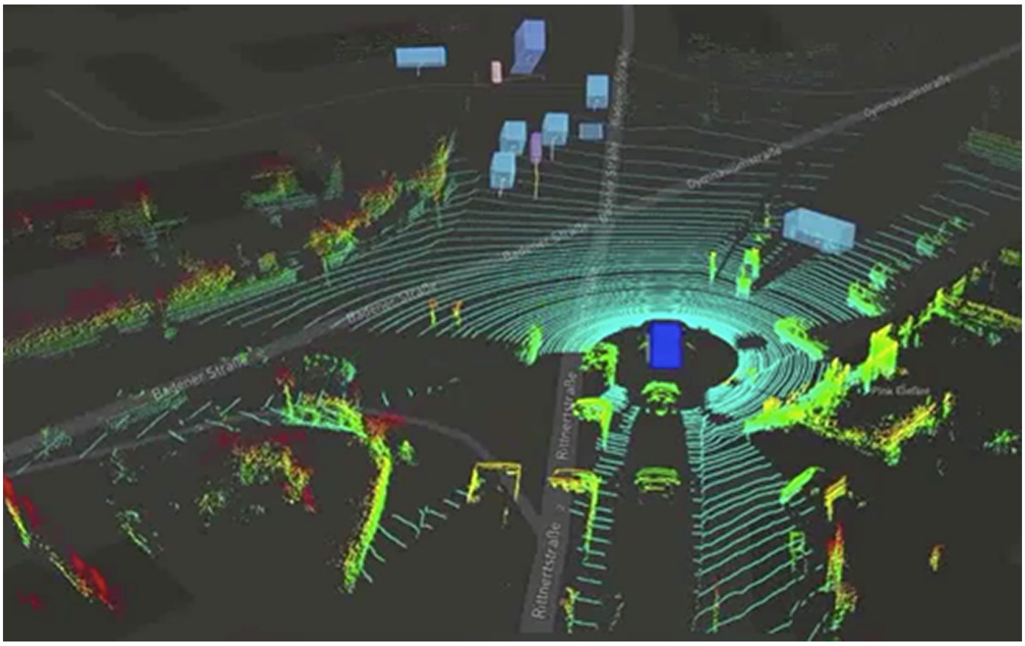

Fig. 1. Depiction of visual stimuli employed in the experiment

Before the experiment, we provided participants with photo instructions on identifying the visual representation of each target. No information was provided regarding the quantity of objects or the visual conditions. Participants were unaware of their upcoming task of identifying the numerosity of objects. Considering the duration of each trial, we intentionally kept the task of numerosity perception undisclosed throughout the experiment and administered it only once to prevent observers from potentially engaging in active counting during the tasks. The photo instruction was followed by two trial videos, during which participants could press a button when they detected the object. The approximate duration of the entire experiment was 25 minutes. Upon completion of the experiment, the participants were asked to assess the maximum number of objects (referred to as the "effective set size") that had appeared on the screen to observe the user's numerosity estimation.

4 RESULTS

4.1 Sex-specific differences in numerosity perception

All the participants (N = 22) obtained more than 40% correct answers when responding to the dynamic stimuli presented on the screen. The average percentage of correct answers was 56.61% for females and 57.34% for males. The suggestion is that all participants were attentive while completing the task. During the data analysis phase for numerosity estimation, we identified outliers in the responses of one male participant. Following the approach recommended by Tabachnick and Fidell [58] and Holmqvist et al. [56], we examined the standardized values and excluded data points that were more than 3.29 standard deviations above or below the mean. As a result, this participant's data was excluded from the final analysis to maintain the integrity and accuracy of our study findings. To test the hypothesis that numerosity estimation differs between women and men, a comparative analysis was conducted using the non-parametric Mann-Whitney U test for independent samples. The decision to use a non-parametric test was based on the unequal number of observations in the subgroups (N = 12 females and N = 9 males), their small sample sizes, and the deviation from a normal distribution. As a result of the analysis, statistically significant differences were observed. The results are presented graphically in Figures 2 and 3 and Table 1.

Table 1. Statistical analysis of numerosity estimation: mean, standard deviation, and mean rank by sex

	Male (N = 9)			Female (N = 12)			U	W	p-Value
	M	SD	R	M	SD	R			
Numerosity estimation	16.333	5.292	14.22	11.833	4.407	8.58	25.000	103.000	0.041
Difference between real numerosity and estimated	–0.667	5.292	14.22	–5.167	4.407	8.58	25.000	103.000	0.041

We also conducted a statistical analysis to compare the estimation of numerosity with the actual numerosity between females and males. The value of real numerosity was 17. Quantitative variables were represented by mean (M), standard deviation (SD), and mean rank (R). The statistical significance threshold used in the analysis of the main effects for the groups was set at $p <= 0.05$. The numerosity estimation for women turned out to be significantly lower than the actual numerosity. Whereas for males, the numerosity estimation did not significantly differ from the actual numerosity (refer to Table 1).

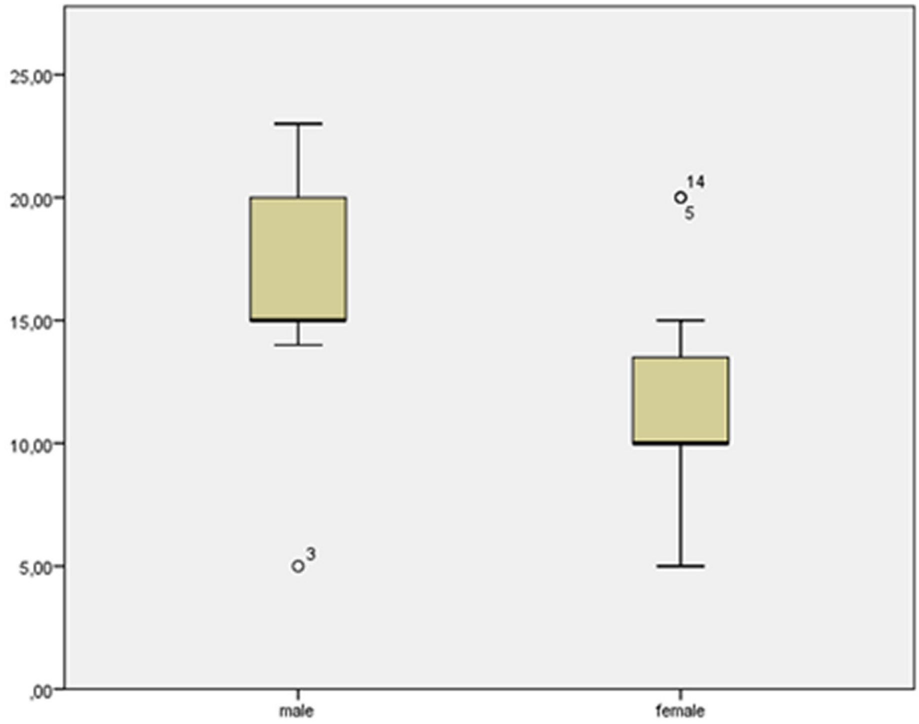

Fig. 2. Sex differences in numerosity estimation

Figure 2 illustrates the relationship between participant sex (x-axis) and perceived numerosity (y-axis). It compares how females and males perceive the quantity of objects, highlighting potential variations in numerosity estimation between sexes.

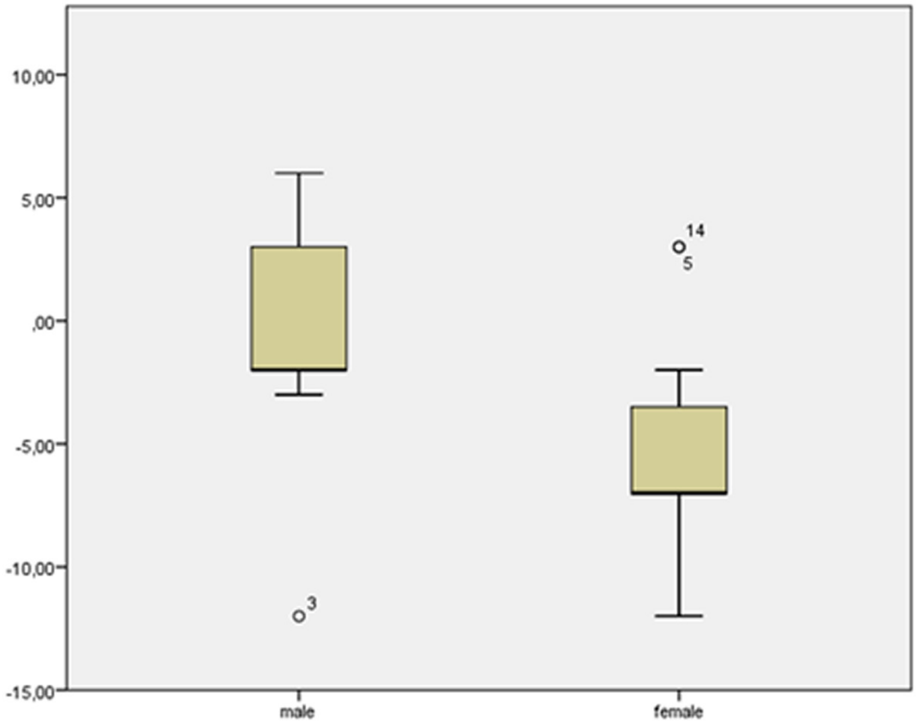

Fig. 3. Sex differences in numerosity estimation accuracy

Figure 3 illustrates the relationship between participant sex (x-axis) and the difference between perceived and actual numerosity (y-axis). It showcases variations in estimation accuracy between male and female participants, reflecting how each sex perceives the number of objects compared to the actual count.

5 DISCUSSION

5.1 Sex differences in perception of numerosity

In this study, we investigated the influence of sex in numerosity estimation and found that sex did influence the participants' estimates. The male participants' estimation of numerosity was significantly higher than that of the female participants, and it was also closer to the actual number of objects. The only study in the existing literature that observes sex-specific differences in numerosity perception analyzes the performance of children between the ages of six months and eight years. The authors found no differences between the sexes [37]. Our pilot study is the first to raise this question and reveal sex differences in numerosity estimation in adults.

Understanding of numerosity perception is crucial, as it underpins many essential life skills. Research [6, 7, 8] has shown a correlation between numerical acuity and mathematics achievement, which may contribute to the imbalance in STEM fields. Disparities in mathematics achievement may result in reduced self-confidence among women in these fields. Additionally, issues related to social belonging also play a role in this disparity, albeit to a lesser extent [59].

Geary [4] found evidence that males outperformed females in tasks that require manipulating images in 3D space and those involving the dynamic measurement of spatial cognition. Therefore, males have an advantage in experiments that require object manipulation or judging the distance or velocity of moving targets [4]. According to studies [60, 61], spatial visualization tasks require complex processing of spatially represented information. Therefore, advanced spatial cognition in males could explain why they outperformed females in numerosity estimation, leading to significant differences in numerosity underestimation for females in our study.

In addition to the attention-demanding task of object identification, participants also performed the numerosity judgment task. The level of task difficulty influenced users' accuracy in the numerosity estimation task. Attentional resources that are still available after reaching the capacity limit are allocated to completing the secondary task. Thus, we assume that a higher cognitive load for females impaired their performance in the secondary task of numerosity estimation. The mental effort did not exceed the available capacity, even for females. Although the remaining capacity was minimal, as suggested by the difference in perceived numerosity. Nonetheless, the proportion of correct responses in identifying moving objects during the experiment was quite similar within the groups (56.61% for females and 57.34% for males). Distinctions are only evident in numerosity estimation, suggesting that these differences may occur due to the nature of the visuospatial task, including mental rotation and object identification.

6 FUTURE WORK AND CONCLUSIONS

In this study, we expanded existing research on numerosity estimation by comparing the data between sexes. To the best of our knowledge, our study is the first to establish intersex differences in numerosity perception in adults. The numerosity estimation of the male participants was notably higher compared to that of the female participants and was closer in accuracy to the actual number of objects. The numerosity underestimation effect remained evident for females, while for males, both underestimation and overestimation were observed. Given the exploratory nature of this pilot study, we worked with a small cohort of participants. We acknowledge that the limited sample size is a constraint and have identified it as a limitation of our current research. Further studies with a complete experiment may be conducted to test the hypothesis regarding inter-sex differences in numerosity perception in adults. Furthermore, different types of experiments with dynamic visual stimuli are required to assess various inter-sex disparities in perception.

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