Breastfeeding Reimagined: Examining Augmented Reality, Maternal Support, and Breast Pumping Experiences in a Randomized Mixed-Methods Study

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Abstract

Background

Pump-dependent milk expression frequently occurs in environments that lack the sensory and emotional cues associated with direct breastfeeding, which may interfere with relaxation and milk let-down. Emerging digital technologies such as augmented reality (AR) may help recreate visual and emotional cues that support the physiological processes associated with milk expression.

Objective

This study examined whether AR technology may reduce stress, enhance maternal satisfaction, and influence emotional and physiological experiences associated with breast pumping.

Methods

This mixed-methods study examined whether an immersive AR environment influenced maternal experience, attentional focus, and physiological responses during breast pumping. Secondary quantitative data were analyzed from the parent iPUMP randomized two-sequence repeated measures pilot study, which compared pumping sessions using a tablet-based visual condition and an AR environment. Quantitative measures included heart rate, blood pressure, and perceived stress. Qualitative data were collected through follow-up semi-structured interviews with a subset of participants who completed the parent study.

Results

Quantitative findings indicated modest and variable differences in physiological measures across conditions. However, qualitative findings revealed meaningful experiential differences. In addition to expressing increased emotional engagement, perceived maternal support during pumping, improved focus, and increased support for milk let-down, participants consistently described AR as more immersive and less distracting.

Conclusions

These findings suggest that immersive visual technologies may influence the attentional and emotional context of pumping rather than directly increasing milk output. By reducing environmental distractions and promoting focused engagement with infant imagery, AR environments may help create conditions that support the neuroendocrine processes associated with milk ejection. Future research with larger samples and longer intervention periods is needed to examine whether immersive technologies can support sustained pumping engagement and longer-term breastfeeding outcomes.

Introduction

Breastfeeding is commonly advocated as the ideal source of newborn nutrition and is linked to several advantages for both mothers and infants [1-3]. However, the actual experience of nursing is frequently more complicated than the idealized narratives that portray it as something that is effortless and instinctive [4-6]. In the United States, approximately 84% of mothers initiate breastfeeding, yet duration declines substantially over time, with about 58% of infants receiving any breast milk at six months and 35% at twelve months, both below Healthy People 2030 targets of 42.4% [1-3,7,8].

When broken down by race and ethnicity, breastfeeding rates are even lower than they should be. The lower rates experienced by non-Hispanic Black mothers relative to their counterparts reflect larger structural and contextual discrepancies in access to breastfeeding support [9,10]. National estimates indicate breastfeeding initiation rates of approximately 75.4% among non-Hispanic Black mothers, compared with 86.2% among non-Hispanic White mothers and 83.4% among Hispanic mothers [1-3, 9,10,].

For mothers who work outside the home or whose infants require medical care, pumping introduces additional physical, emotional, and logistical demands [11,12]. Unlike direct breastfeeding, pumping often occurs in environments lacking sensory cues associated with the infant and may involve distractions, time pressure, or limited privacy [11-15]. These conditions can interfere with maternal relaxation and attentional focus, both of which are critical for effective milk ejection [15,16]. As a result, pumping can shift from an experience associated with maternal infant bonding to one characterized by persistence and effort [4, 5,15,17,18].

Emerging digital technologies offer potential strategies to address these challenges. Augmented reality (AR) systems overlay digital visual content onto the user's real-world environment, creating immersive experiences that may enhance attentional focus and emotional engagement [19]. By presenting infant-related imagery in a more immersive context, AR may help recreate sensory conditions that support the physiological processes underlying milk ejection [16].

This study was guided by the Biopsychosocial Model and psychoneuroendocrine perspectives on lactation, which suggest that biological processes, psychological experiences, and environmental influences interact to shape breastfeeding and pumping outcomes [20-22]. In the present study, these domains were reflected through physiological responses, emotional engagement, attentional focus, and exposure to infant-related visual cues.

This mixed-methods study examined whether immersive visual technology influences physiological responses and the experiential context of pumping. Using secondary quantitative data from its parent iPUMP study, and primary qualitative data from follow-up interviews, this study integrates physiological measures with participant experiences to better understand how immersive visual technologies may shape both measurable and experiential dimensions of breast pumping.

Literature Review

Successful milk expression during pumping is influenced not only by mechanical pump function but also by maternal psychological state and physiological regulation [20-24]. The milk ejection reflex is mediated by oxytocin release, which can be inhibited by stress, distraction, and negative emotional states [24,25]. Research has shown that maternal anxiety and psychological distress are associated with challenges in milk let-down and breastfeeding outcomes [24-28]. Conversely, relaxation and emotional connection with the infant can facilitate oxytocin release and support effective milk expression [27]. Sensory cues such as visual, tactile, and auditory interaction with the infant play an important role in stimulating this response [24-26] .

However, mothers who rely on pumping are often separated from their infants and may express milk in environments or other settings where distractions and time pressures are common [14-18,21]. The absence of infant-related sensory cues, combined with environmental stressors, may disrupt the neuroendocrine processes that support milk ejection [21,26]. Consistent with these challenges, studies of pump-dependent feeding report that mothers frequently experience stress, performance pressure, and difficulty maintaining focus during pumping sessions [12,15, 16,28, 29]. Recent advances in digital health technologies have created new opportunities to support patient experiences across healthcare settings [31,32]. Notably, augmented reality (AR) has emerged as a promising digital technology, with applications in healthcare settings including mental health, ophthalmology, rehabilitation, telemedicine, and clinical practice [31].

AR works by overlaying digital visual content onto the user's real-world environment, creating immersive experiences that can enhance attention, engagement, and emotional connection [17,35]. From the clinical perspective, research suggests that immersive visual technologies can improve focus, reduce anxiety, and enhance emotional engagement during medical procedures [30,31,33]. For instance, AR-assisted training has enhanced medical students' understanding of complex physiological processes such as pulmonary mechanics and wound care [37,38]. Similarly, among nursing students, AR has been shown to improve medication preparation accuracy by visually reducing potential errors [33,34,38]. These applications demonstrate how immersive technologies can influence attention, learning, and emotional engagement, mechanisms that may also be relevant for supporting maternal experiences during breast pumping.

The potential relevance of AR for breastfeeding support lies in its ability to recreate sensory experiences associated with maternal–infant interaction. Immersive visual environments may help restore infant-related cues that support oxytocin-mediated milk ejection while simultaneously reducing environmental distractions [39,40]. Prior studies have explored alternative digital technologies such as virtual reality (VR) to support the breastfeeding parent. For example, Tang et al. (2022) developed *Virtual Feed*, an immersive VR simulation designed to represent aspects of the lived breastfeeding experience and expose users to common breastfeeding challenges [41]. Evaluation of the simulation suggested that immersive technology may promote user engagement, curiosity, and reflection regarding breastfeeding experiences. Although this application focused primarily on antenatal education rather than milk expression, it demonstrates the potential for immersive environments to address experiential dimensions of breastfeeding that may be difficult to reproduce through conventional educational approaches [39-45].

However, because VR replaces the user's real-world environment with a fully simulated one, it may limit situational awareness, which is often necessary for mothers pumping in workplaces or clinical settings [17]. In contrast, AR provides immersive visual engagement while maintaining awareness of the surrounding environment, making it potentially more suitable for pump-based milk expression [17,40,42,44].

Despite the growing use of immersive technologies in healthcare, research examining the use of AR specifically during breast pumping remains limited. Most breastfeeding interventions focus on education, counseling, or workplace accommodations rather than addressing the emotional and attentional context of pump-based milk expression [9,11-13]. Understanding how immersive technologies influence these conditions may therefore help identify new strategies to support mothers who rely on pumping during periods of separation from their infants.

Guided by the biopsychosocial and psychoneuroendocrine perspectives on lactation, the present mixed-methods study examined whether an immersive environment may influence maternal focus, perceived stress, and physiological responses during breast pumping [19-21].To that aim, this study addressed the following research questions:

1. What is the impact of AR-based visual support on physiological markers?
2. What factors influence the usability and feasibility of AR technology in lactation environments?
3. How do mothers describe their emotional experience when using AR versus standard digital media?

Reflexivity Statement

The primary researcher is a public health professional, lactation educator, and maternal-child health advocate with experience supporting breastfeeding families. Given this professional background, ongoing reflexive practices were used throughout data collection and analysis to acknowledge potential assumptions related to breastfeeding, pumping experiences, and technology-based support interventions. Reflexive memoing, analytic documentation, and regular peer debriefing with the research team were employed to enhance transparency, credibility, and trustworthiness of the findings.

Methods

Study Design

This study used an explanatory mixed-methods design, integrating secondary quantitative data from the parent iPUMP randomized pilot study with primary qualitative data from follow-up interviews. The parent IPUMP study used a randomized, two-sequence repeated-measure design in which participants were assigned to either a tablet/tablet (iPad/iPad) sequence or a tablet/augmented reality (iPad/AR) sequence across two laboratory pumping sessions[49]. The present study analyzed physiological and feasibility outcomes from the parent study alongside qualitative data collected from a subset of participants who completed follow-up interviews. Quantitative analyses focused on physiological responses, while the qualitative component explored participants' perceptions and experiences with visually supported pumping through thematic analysis. A qualitative descriptive design was selected because it allowed for direct examination and description of participant experiences while aligning with their perspectives and language. These approaches provided complementary insight into both measurable and experiential aspects of breast pumping.

Parent iPUMP Study Intervention

Participants were randomized to one of two sequences across the two laboratory pumping sessions: tablet/tablet (iPad/iPad) or tablet (iPad) followed by augmented reality [49]. Participants attended an enrollment visit followed by two laboratory pumping sessions spaced approximately one week apart. During the enrollment visit, baseline physiological measurements, including heart rate and blood pressure, were obtained using a clinic-grade automated blood pressure monitor. The comprehensive list of quantitative measurement tools is presented in the Supplementary Material section (Table S1).

Participants received study materials, including a milk volume log sheet, hands-free breast pump, collection bottles, and a digital scale, and were instructed on procedures for at-home data collection . Between laboratory visits, participants completed four consecutive days of at-home study activities as outlined in the parent protocol. During the laboratory visits (approximately 60 minutes each), participants completed pumping sessions while viewing either tablet-based images or an immersive augmented reality environment, depending on the assigned grouping. Pumping duration was self-selected to reflect participants' usual routines and was replicated across sessions. Immediately before and after each pumping session, heart rate and blood pressure were recorded, and expressed milk was collected from each breast and weighed separately using digital scales. Participants also completed brief surveys assessing perceived pumping stress and device feasibility following each session.

Quantitative Measures

Quantitative outcomes included physiological measures (heart rate, systolic blood pressure, and diastolic blood pressure) collected during in-laboratory sessions. Milk output data were collected as part of the parent iPUMP study and are analyzed in detail elsewhere [49]. Consistent with the parent study findings, milk output demonstrated substantial inter-individual variability across sessions. As the primary focus of the present analysis was participant experience, physiological responses, and feasibility of immersive visual support, milk output findings are not presented further.

Qualitative Participants and Recruitment

A subset of participants who completed the parent study was invited to participate in follow-up interviews [49]. This approach is consistent with mixed methods designs, allowing for in-depth exploration of participant experiences while complementing quantitative findings [50]. Eligibility included completion of the parent study, prior consent to be contacted for future research, and willingness to participate in an interview. Of the 29 participants who completed the parent study, 25 (86.2%) had agreed to be contacted for future research and were invited to participate in the qualitative phase via email. Sixteen of the 25 invited participants (64.0%) agreed to participate and completed a qualitative interview, comprising the final qualitative analytic sample (n = 16).

The qualitative sample included participants from both parent-study sequences: nine participants had been assigned to the tablet/AR intervention sequence and seven had been assigned to the tablet/tablet control sequence. Thus, nine qualitative participants had direct exposure to AR during the parent study, while seven had experiences with tablet-based visual support only.

Among the nine qualitative participants assigned to the intervention sequence, AR exposure occurred once during the second laboratory pumping session, approximately one week after the initial tablet-based session. Laboratory visits lasted approximately 60 minutes; however, actual AR exposure corresponded to each participant's self-selected pumping duration rather than the full laboratory visit. Pumping duration was based on the participant's usual pumping routine and was replicated across the two laboratory sessions. AR exposure occurred in the laboratory setting while participants pumped and viewed infant-related visual content within the immersive environment. The seven qualitative participants assigned to the control sequence completed tablet-based visual support during both laboratory sessions and did not receive AR exposure.

The remaining nine invited participants did not complete a follow-up interview and therefore were not included in the qualitative analysis. Participants received a $25 e-Visa gift card as compensation for their time. Recruitment continued until thematic saturation was reached.

Qualitative Interviews

Semi-structured interviews were conducted by the first author (WCC), who has formal training in qualitative and quantitative research methods, as well as prior experience conducting semi-structured interviews in maternal and public health research. The interviewer is a public health researcher, lactation educator, and maternal health advocate. Reflexive memoing and peer debriefing were used throughout analysis to enhance transparency and reduce potential researcher bias [50].

Interviews were conducted between September and October 2025 via Zoom and lasted approximately 30–45 minutes. Participants provided informed consent for the Zoom recording prior to the interview. The interview guide included open-ended questions informed by constructs from the biopsychosocial and psychoneuroendocrine models and focused on participants' experiences using tablet-based and augmented reality environments during pumping. Example questions included: "What thoughts or feelings stood out to you while combining AR with pumping?" and "How would you describe your experience with milk let-down or pumping during this study?" and ""How would you describe the way technology impacts your ability to concentrate and your overall mood?" Additional questions explored perceived focus and distraction, emotional responses, relaxation, physiological sensations related to milk let-down, and perceptions of augmented reality feasibility. The full interview protocol is provided in Supplementary Material (Table S2). All interviews were audio-recorded and transcribed verbatim. Following transcription verification, audio recordings were permanently deleted to protect participant confidentiality.

Ethical Approval

This study received approval from the Institutional Review Boards (IRB-FY20-215) and (IRB-5250304). All participants provided informed consent prior to participation in the parent study and consented to follow-up interviews for the qualitative phase.

Data Analysis

Quantitative Data

Quantitative outcomes were summarized using descriptive statistics, including means and standard deviations. Because the analysis included within-participant repeated measures and several outcome variables demonstrated non-normal distributions, differences between augmented reality (AR) and tablet-based conditions were examined using Wilcoxon signed-rank tests. This nonparametric test was selected due to the small sample size and its suitability for paired comparisons when normality assumptions are not met [51]. Analysis were conducted using available complete paired observations for each outcome. Participants with a missing value for either condition on a specific measure were excluded from that paired comparison only; no missing values were imputed. Consequently, analytic sample sizes varied slightly across physiological and feasibility outcomes. Statistical analyses were conducted using SPSS version 30 (IBM Corp., Armonk, NY) [52]. Given the exploratory and feasibility-focused nature of the study, quantitative findings were interpreted descriptively and used to complement the qualitative findings rather than serve as stand-alone tests of intervention effectiveness.

Qualitative Data

Qualitative data were analyzed using thematic analysis with a hybrid deductive and inductive approach aligned with the study aims. The transcripts from the interviews were meticulously compared with the audio recordings, and they were read and re-read several times to ensure familiarity. An initial coding framework was developed based on the interview domains and was refined through repeated review of the transcripts. Coding and data organization were conducted using MAXQDA software (VERBI Software, Berlin, Germany) [53].To support analytic rigor and transparency, strategies such as, iterative code refinement, development of a structured codebook, and the use of analytic memos to document coding decisions and emerging patterns throughout the analytic process were employed.

Themes were examined across participants to identify patterns of similarity and variation in experiences [54-56]. Regular peer debriefing sessions with the research team allowed for discussions on themes and coding interpretations. During these meetings, emergent themes, interpretations, and representative quotations were reviewed and refined to maintain consistency and credibility in the thematic interpretations [55]. Analytic notes recorded coding decisions, fresh interpretations, and theme development reasons. Thematic sufficiency was evident after 14 interviews, with no new themes. A final sample of 16 individuals was obtained after two further interviews to verify data stability. Representative participant quotations were selected to illustrate key themes and can be seen in table 4 to allow readers to assess the relevance of the findings to similar contexts.

Results

Results are presented in alignment with the study research questions, including quantitative findings related to physiological responses, followed by qualitative findings describing participant experiences.

Participant Characteristics

A total of 29 participants completed the parent iPUMP study [48]. Of these, 17 participants (58.6%) were assigned to the intervention sequence (Tablet followed by AR) and 12 (41.4%) were assigned to the control sequence (Tablet/Tablet). When evaluating the baseline characteristics of the sample, the data showed a consistent demographic profile across both the parent study and the qualitative subsample. Participants ranged in age from 18 to 49 years, with the largest proportion between 30–39 years. The sample was racially and ethnically diverse and represented a range of educational backgrounds and employment statuses. A subset of 16 participants completed follow-up interviews and comprised the qualitative sample for the Breastfeeding Reimagined analysis. Demographic characteristics for the full study sample and qualitative subsample are presented below, in Table 1.

Table 1. Participant Characteristics for the Parent Study and Qualitative Subsample

Characteristic	**Parent Study (n=29)**		**Qualitative Subsample (n=16)**	
	(n)	**(%)**	**(n)**	**(%)**
Age (years)				
18–24	1	(3.4%)	1	(6.25%)
25–29	3	(10.3%)	3	(18.75%)
30–34	7	(24.1%)	5	(31.25%)
35–39	8	(27.6%)	5	(31.25%)
40–44	7	(24.1%)	2	(12.5%)

45–49	1	(3.4%)	0	-
Education				
Graduate degree	6	(21%)	4	(25%)
Bachelor's degree	15	(51%)	8	(50%)
Associate's degree	4	(14%)	2	(12.5%)
Some college	4	(14%)	2	(12.5%)
Race/Ethnicity				
White	7	(24.1%)	4	(25%)
Black/African American	6	(20.7%)	3	(18.8%)
Hispanic/Latina	7	(24.1%)	3	(18.8%)
More than one ethnicity	9	(31.0%)	6	(37.5%)

Quantitative Findings

Physiological Measures (Full Sample)

Mean heart rate showed a small increase across sessions, while systolic and diastolic blood pressure remained relatively stable. Overall biometric changes were modest and variable across participants, with no consistent pattern indicating a uniform physiological response between sessions. Descriptive biometric measures are presented below in Table 2.

Table 2. Mean changes in physiological measures (post minus pre) by study condition (Full Sample)

Outcome	**Session**	**n**	**Mean Change (Post–Pre)**	**SD**	**Interpretation**
Heart rate (bpm)	Session 1 (Tablet)	29	-3.44	6.24	Mean decreases observed
	Session 2 (Tablet/AR)	29	-4.18	6.11	Mean decreases observed
Systolic BP (mmHg)	Session 1 (Tablet)	29	-3.80	7.17	Mean decreases observed
	Session 2 (Tablet/AR)	29	-4.55	6.92	Mean decreases observed
Diastolic BP (mmHg)	Session 1 (Tablet)	29	-1.73	7.14	Mean decreases observed
	Session 2 (Tablet/AR)	29	-1.12	6.84	Mean decreases observed

Note. *Values represent mean within-session change (post minus pre). Positive values indicate increases and negative values indicate decreases in physiological measures during the pumping session. Session 1 included tablet-based visual support for all participants. In Session 2, control participants used tablet-based visual support and intervention participants used augmented reality. Findings are presented descriptively due to the feasibility-focused design.*

Table 3. Within-participant comparison of tablet and AR conditions

Outcome	n	Tablet Mean (SD)	AR Mean (SD)	Wilcoxon p
Heart rate change (post–pre), bpm	16	−3.44 (6.24)	−6.12 (6.16)	0.13
Systolic BP change (post–pre), mmHg	15	−3.80 (7.17)	−6.00 (6.00)	0.17
Diastolic BP change (post–pre), mmHg	15	−1.73 (7.14)	−1.33 (6.04)	0.86
Feasibility score (1–5)	14	4.76 (0.35)	3.85 (1.13)	**0.007**

Note. *Negative values indicate decreases from pre- to post-session.* ***Session 1*** *represented the tablet condition, and* ***Session 2*** *represented the AR condition for intervention participants. Analyses were conducted using Wilcoxon signed-rank tests due to non-normal distributions and small sample sizes.*

Within-Participant Comparison: Intervention Group (Tablet vs AR)

Within-participant comparisons were conducted among intervention participants who completed both pumping sessions and are presented below in Table 3. For the participants, Session 1 represented the tablet condition and Session 2 represented the augmented reality (AR) condition. Heart rate and systolic blood pressure demonstrated modest decreases during AR sessions relative to tablet sessions, although these differences were not statistically significant. Diastolic blood pressure remained relatively stable across conditions. Feasibility ratings differed significantly between conditions ($p = .007$), indicating differences in participant perceptions of device usability and practicality. Overall, physiological responses were modest and variable across participants, consistent with the exploratory and feasibility-focused nature of the study.

Although physiological measures were modest and variable across participants, the qualitative interviews provided additional context for understanding these findings [56]. Participants frequently described differences in attention, emotional engagement, and perceived relaxation when using augmented reality compared with tablet-based viewing. These experiential insights help explain how immersive visual environments may influence pumping experiences even when measurable physiological changes are small.

Qualitative Findings

Semi-structured interviews were guided by broad, open-ended questions designed to explore participants' experiences with visually supported pumping. Follow-up probes were used to encourage elaboration and clarification while minimizing interviewer influence. Example probes included "Can you tell me more about that?", "What was that experience like for you?", and "Can you provide an example?"

Participants described their experiences with visually supported pumping during the interviews. Among the nine participants who had direct exposure to both tablet and AR conditions, participants described clear differences between the two technologies particularly in immersion, distraction, emotional engagement, and perceived relaxation. Participants from the tablet/tablet control sequence contributed perspectives regarding tablet-based visual support, pumping experiences, environmental context, and technology acceptability. Five major themes were identified across the qualitative data: (1) immersive engagement and reduced distraction, (2) emotional connection through visual cues, (3) relaxation and mindful pumping, (4) perceived support for pumping, and (5) practical considerations

Table 4. Major themes describing participant experiences with visually supported pumping (n = 16)

Major Theme	Summary	Example Quote
Greater immersion and reduced distraction with AR	Participants described AR as a 360-degree experience that limited external distractions and supported sustained focus. In contrast, the tablet condition was often described as similar to a phone or tablet and allowed multitasking or interruptions.	*"I normally stay distracted on purpose"(BF13, Primiparous).* *I don't like pumping and would rather have my baby with me, but the AR device made it easier to pump, like she was right there with me" (BF11, Multiparous).*
Emotional connection through visual cues	Viewing infant images helped participants feel emotionally connected and reminded them of the purpose of pumping. This was reported for both technologies but was described as more immersive with AR.	*"The pictures reminded me why I was pumping" (BF06, Primiparous).* *"Seeing the photos reminded me that she is okay and in good hands" (BF09, Multiparous).*
Relaxation and mindful pumping	Participants reported feeling calmer and more present when using visual support, particularly during AR sessions, which helped them slow down and focus on the pumping experience.	*"It made me feel more relaxed and mindful" (BF08, Primiparous).* *"There was no room for distractions" (BF15, Primiparous).*
Perceived support for pumping	Many participants believed that relaxation and visual focus helped milk flow more easily compared with their usual pumping routines.	*"The milk seemed to come faster than when I'm distracted" (BF06, Primiparous).* *"For the first time I wasn't concentrating on what I had to do, I concentrated more on my baby and pumped more milk than I ever have" (BF08, Primiparous).*
Practical considerations and usability	Although AR was viewed as engaging, some participants noted concerns about comfort, portability, and setup. The tablet was viewed as easier to use in everyday settings.	*"I would need a smaller case, something more convenient" (BF11, Multiparous).* *"Adding time to my pumping schedule just to set everything up would be hard" (BF07, Multiparous).*

and usability. The narrative below highlights the most salient findings, while additional supporting quotations and theme summaries are presented in Table 4.

Theme 1. Greater Immersion and Reduced Distraction with AR

Participants consistently reported that the augmented reality (AR) environment was more immersive and less distracting compared to the tablet condition. The tablet was frequently compared to a smartphone, enabling multitasking, while the 360-degree AR environment minimized external distractions and facilitated sustained attention. For instance, participant BF08, a first-time mother, explained when comparing the two modalities:

"With the Tablet, I found myself checking things or getting distracted, but with the headset everything was around me, so I stayed focused on pumping"(BF08).

Similarly, participant BF11, a second-time parent, observed that the AR device facilitated mindfulness during pumping, whereas the tablet experience resembled routine technology usage.

"With the AR device, I could stay focused, especially with the photos being everywhere, but with the

tablet I couldn't, or at least not for long. For me, the tablet was like my phone, only bigger" BF11).

Other participants indicated that while the tablet enabled them to view infant images, it did not entirely eliminate distractions. For instance, participant BF04, a parent of two, explained:

"Even with the pictures, I still found myself thinking about all the other things I

needed to do when I left"(BF04).

Theme 2. Emotional Connection Through Visual Cues

While both technologies seemingly facilitated an emotional connection through viewing infant images, participants in the intervention group reported that the augmented reality experience was more immersive and emotionally engaging. For example, participant BF06, a first-time parent, described using the AR device:

"Seeing her pictures all around me made it feel more real,

like I was with her"(BF06).

Participant BF08, also a first-time parent, shared a similar sentiment regarding using the AR device:

"Seeing all of his pictures everywhere helped me feel closer to him"(BF08).

Participants also described how visual cues reinforced the emotional significance of pumping. For instance, participant BF07, a parent of her second child, explained:

"It reminded me of our journey and how far we've come" (BF07).

Theme 3. Relaxation and Mindful Pumping

Participants frequently associated AR use with enhanced relaxation and sustained focus during breastfeeding. Several participants reported perceiving faster or more effortless milk flow when using AR, although experiences varied among individuals. One participant, BF16, a multiparous parent, explained:

"I normally don't produce much when pumping, or if I do it takes a long time.

When I used the headset, I felt and heard my milk flowing before I even saw it.

I was like, wow… it actually works" (BF16).

Another participant, BF04, a first-time parent, reported that due to the heightened mindfulness she experienced during the study, she incorporated the learned insights and continued utilizing visual cues even after the study concluded:

"After the study, seeing how much milk I pumped while using the devices, how much it helped, I started watching photos and videos of my daughter while pumping" (BF04).

Other participants underscored the significance of diminished distractions in facilitating mindful pumping. For instance, participant BF03, a first-time parent, shared the following perspective:

"With the AR, there was no room for distractions.

I could just focus on pumping and thinking about my baby" (BF03).

Theme 4. Perceived Support for Pumping

Participants also described how environmental context influenced pumping experiences. Several participants noted that the laboratory environment provided fewer interruptions and greater privacy compared with their usual pumping environments. As observed in the case of participant BF09, a parent who was breastfeeding her second child provided the following explanation:

"At home, trying to pump can be challenging.

You have other things on your mind and sitting still isn't always possible" (BF09).

Participant BF02 also a second-time parent, reflected on the tranquility experienced during the study sessions.

"Here I was able to be mindful of pumping, relax, and focus

on what I was supposed to be doing instead of a thousand other things" (BF02).

These experiences suggested that reduced distraction and focused environments may support perceived milk let-down during pumping.

Theme 5. Practical Considerations and Usability

Although AR was generally described as engaging and supportive of focus, participants also noted practical challenges related to comfort, portability, and setup. The AR device was described as similar in design to a Meta-style headset but smaller, comparable to wearing safety glasses or a visor. However, participants noted that the protective case and associated equipment could add bulk when transporting pumping supplies. Participants also described the initial setup process as potentially time-consuming. Consequently, the tablet was frequently perceived as more advantageous for daily routines due to its diminutive design, portability, and familiarity. Participant BF11, who was breastfeeding her second child, elucidated:

"I liked the AR experience, but the Tablet would probably be easier to use

quickly at home" (BF11).

Another participant, BF03, a first-time parent, underscored the significant burden associated with the additional equipment stating:

"I already have enough to carry with my pump and cooler,

so, adding another thing could increase stress" (BF03).

Participants suggested AR could be beneficial in secure or private settings where they can prepare and use the device comfortably. The findings, combining quantitative and qualitative data, provide a foundation for understanding how immersive visual environments affect both the quantitative and experiential aspects of breast pumping. Table 4 below, presents the themes, summary of findings, and additional participant quotes.

Discussion

The current mixed-methods study examined the influence of immersive visual technology, specifically augmented reality (AR), on physiological responses and the experiential context of breast pumping. Quantitative findings demonstrated modest and variable changes in heart rate and blood pressure across conditions, with no statistically significant differences observed between tablet and AR sessions. However, feasibility ratings differed significantly between conditions, suggesting that participants perceived meaningful differences in the usability and practicality of the technologies. Qualitative findings further revealed that AR enhanced focus, immersion, emotional engagement, and perceived support during pumping. Together, these findings suggest that immersive visual technologies may influence the pumping experience primarily through emotional and attentional pathways rather than through immediate physiological changes.

The qualitative findings provide important insight into the potential mechanisms underlying these experiences. Participants consistently described AR as more immersive and less distracting than tablet-based viewing, allowing them to focus more fully on pumping and infant imagery. These findings align with biopsychosocial and psychoneuroendocrine perspectives, which recognize that emotional state, environmental context, attentional focus, and physiological regulation may interact during lactation-related processes [19,20]. Prior research has shown that maternal psychological state, stress, and relaxation can influence milk ejection during breast pumping [25-27]. Similarly, studies examining immersive technologies have reported that increased presence and attentional engagement may enhance emotional involvement while reducing awareness of external distractions [57,58]. The current findings extend this literature by suggesting that AR may provide a uniquely immersive environment that supports maternal focus during pumping.

Participants frequently reported feeling calmer, more present, and more emotionally connected to their infants while using AR. These findings are consistent with evidence demonstrating that maternal relaxation and reduced psychological distress can positively influence lactation outcomes and maternal well-being [21,23-27]. Relaxation-based interventions have been associated with reductions in stress and anxiety as well as improvements in milk production, suggesting that emotional and psychological states play an important role in breastfeeding and pumping experiences [59]. However, unlike some studies that have reported measurable physiological benefits associated with stress-reduction interventions, the present study did not observe statistically significant physiological differences between conditions. This discrepancy may reflect the complex and multifactorial nature of lactation physiology, in which subjective experiences do not always correspond to immediately detectable physiological changes. The variability observed in the present findings is also consistent with emerging evidence regarding immersive technologies in breastfeeding support. In a recent systematic review and meta-analysis, Raghav et al. (2026) found that VR-based interventions demonstrated potential benefits for selected outcomes, including prenatal breastfeeding self-efficacy, motivation, breastfeeding technique, and earlier breastfeeding initiation; however, significant effects were not observed for postnatal self-efficacy, exclusive breastfeeding, or maternal anxiety [57]. The authors further noted low to very low certainty of evidence across outcomes, highlighting the preliminary and inconsistent nature of the current evidence base. These findings parallel the present study, in which participants described meaningful experiential benefits despite the absence of statistically significant differences in immediate physiological responses. Together, this emerging literature suggests that immersive technologies may initially influence experiential, attentional, or behavioral dimensions of breastfeeding support more readily than measurable physiological or longer-term breastfeeding outcomes.

Environmental context emerged as a crucial factor. Participants contrasted the calm laboratory environment with the competing demands and distractions of home or work. This aligns with previous research showing that interruptions, lack of privacy, and competing responsibilities negatively impact pumping experiences [6,9,12,13,28]. Mental visualization and infant-related imagery trigger or support milk ejection reflexes, especially when physically separated from infants [28]. Workplace and home-based barriers to pumping hinder lactation goals, especially for individuals juggling caregiving, employment, and household responsibilities [28,29]. This may be particularly relevant for individuals pumping while separated from their infants, as visual imagery and mental visualization can facilitate milk ejection responses even without direct infant contact [40-44].

The qualitative findings suggest that immersive visual technologies may help reduce environmental distractions and promote focused engagement, even when direct physiological effects are not readily detectable.

Practical considerations should also be considered when interpreting these findings. Although participants generally viewed AR as engaging and supportive, concerns regarding portability, convenience, and setup time were frequently discussed. In comparison, tablet-based viewing was often perceived as more practical for everyday use due to its familiarity and ease of access. Similar concerns have been reported in broader immersive technology research, where usability, accessibility, and convenience are important determinants of sustained adoption despite positive user experiences [42,44].These findings mirror broader technology adoption literature, which suggests that perceived usefulness must be balanced with convenience and ease of implementation for sustained use [30,35,58]. Future technological advancements that improve portability and reduce setup burden may increase the feasibility of immersive technologies for routine pumping support.

Taken together, our findings suggest that the primary value of immersive visual support may lie in improving the quality of the pumping experience rather than producing immediate physiological changes. By enhancing focus, emotional connection, and perceived support during pumping, immersive technologies may contribute to a more positive and sustainable pumping experience. Given that stress, frustration, and perceived inefficiency are commonly cited reasons for discontinuing pumping, interventions that improve the overall pumping experience may have important implications for breastfeeding continuation and maternal well-being. Existing evidence suggests that maternal psychological distress may adversely affect lactation outcomes, while relaxation-based interventions may improve both milk production and maternal well-being [58,59]. Therefore, technologies that support relaxation, emotional connection, and sustained engagement may represent a valuable adjunct to breastfeeding support strategies.

Strengths and Limitations

This study has several notable strengths. First, the mixed-methods design allowed quantitative findings to be interpreted alongside participant experiences, providing a more comprehensive understanding of visually supported pumping. The integration of physiological measures, feasibility data, and qualitative interviews allowed for triangulation of findings across multiple sources of evidence. In addition, the use of both laboratory and home-based data collection enhanced ecological relevance and provided insight into the variability of real-world pumping experiences. The repeated-measures design reduced the influence of individual differences by allowing within-participant comparisons across study sessions.

Several limitations should also be considered. The parent iPUMP study was designed as a pilot feasibility study and therefore included a modest sample size, limiting statistical power to detect small intervention effects. In addition, session order was not counterbalanced: all participants completed the tablet condition during the first laboratory session, while participants assigned to the intervention sequence completed the AR condition during the second session. Consequently, potential session-order effects, including increased familiarity with the pumping protocol, study environment, or equipment during the second visit, cannot be fully distinguished from effects associated with AR exposure. Although pumping duration was replicated across sessions to improve within-participant consistency, the possibility of learning or carryover effects should be considered when interpreting differences between the tablet and AR conditions.

Additionally, physiological responses to pumping are influenced by numerous factors, including feeding schedules, hydration status, fatigue, stress, and individual differences in lactation physiology.

These factors may have contributed to variability across participants and reduced the likelihood of detecting measurable differences between conditions. Repeated stress survey data were incomplete for some participants, limiting the ability to examine changes in perceived stress over time. A small number of observations were also missing for individual physiological and feasibility measures; therefore, paired analyses were conducted using available complete observations for each outcome without imputation. This resulted in slight variation in analytic sample size across outcomes.

The intervention was also limited to a single AR exposure during one laboratory pumping session. Accordingly, the present findings reflect participants' immediate responses to AR rather than the effects of repeated or sustained use. A single exposure may not be sufficient to determine whether the experiential benefits described by participants persist over time or translate into measurable changes in physiological responses, pumping behaviors, or longer-term breastfeeding outcomes. Future studies should evaluate repeated AR exposure across multiple pumping sessions and settings and incorporate longer follow-up periods to assess the durability and potential cumulative effects of immersive visual support.

Furthermore, qualitative interviews were conducted following completion of the parent study, and in some cases several months had elapsed between study participation and interview completion. As a result, participant recollections may have been influenced by recall bias.

Finally, practical concerns related to device portability, setup requirements, and convenience may affect the real-world adoption of immersive technologies in pumping contexts. Despite these limitations, the study provides valuable insight into both the measurable and experiential dimensions of technology-assisted pumping.

Conclusion

This mixed-methods study explored the role of immersive visual technology in shaping the breast pumping experience. Quantitative findings demonstrated modest and variable physiological responses across conditions, while qualitative findings consistently highlighted meaningful differences in participant experiences. Participants described augmented reality as more immersive, less distracting, and more emotionally engaging than tablet-based viewing. Many participants also reported increased focus, relaxation, and perceived support during pumping sessions.

These findings suggest that immersive visual technologies may influence pumping experiences through emotional and attentional mechanisms rather than through immediate physiological changes. By reducing environmental distractions and promoting focused engagement with infant imagery, AR environments may help create conditions that support maternal focus, relaxation, and engagement during pumping. Although additional research with larger samples, repeated AR exposure, and longer follow-up periods is needed, the findings provide preliminary evidence that immersive technologies may represent a promising approach for supporting individuals who rely on breast pumps during periods of separation from their infants.

Future research should continue to examine how immersive technologies can be integrated into maternal health interventions, including whether repeated use across diverse pumping environments produces sustained experiential or physiological effects and whether improvements in pumping experiences contribute to longer-term outcomes such as pumping adherence, breastfeeding continuation, and maternal well-being.

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Supplementary Materials

Supplementary Data

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