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Research Note

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RESEARCH NOTE

Virtual Baby: 3D Model of the Anatomy and Physiology of Sucking and Swallowing in Infants as an Educational Tool

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Objective: This project aimed to develop and update a dynamic three-dimensional (3D) graphic video learning object demonstrating a current knowledge of the anatomy and physiology of sucking and swallowing in newborns during breastfeeding.

Method: To build and update the 3D computer graphics iconographies of the "Virtual Baby," we defined objectives for the learning object, created a literature review-based script, and organized a guide for structural (static) and functional (dynamic) graphical modeling for the designer.

Results: Using 3D computer graphics, we produced a video with static images (anatomical structural) and dynamic sequences (most significant physiological and functional aspects and application of transparency to visualize the anatomical correlations between both). The video showed the anatomy and physiology of sucking and swallowing during breastfeeding. Its updates reflected additional scientific evidence as studies were published.

Conclusion: Creation of the Virtual Baby provides a learning tool for visualizing the anatomy and physiology of sucking and swallowing in full-term newborns. The tool addresses the significant morphofunctional aspects of the breastfeeding process, supported by scientific literature, and can be used for student or professional training and in primary health care.

Keywords: *breastfeeding, computerized model, swallowing, anatomy, physiology, infant*

INTRODUCTION

Breastfeeding is a complex process that requires effective coordination between sucking, swallowing, and breathing (Geddes & Sakalidis, 2016). Such complexity has led several researchers to conduct studies to understand its dynamics. Furthermore, technological advances supporting current research allow for a better understanding of the breastfeeding process better and provide an opportunity to shift paradigms regarding the subject (Elad et al., 2014; Geddes & Sakalidis, 2016; Geddes et al., 2012; Mills et al., 2020; Sakalidis et al., 2013).

Previous understanding of breastfeeding was that milk was extracted through peristaltic tongue movements that would press the nipple against the palate (Adran; Kemp; Lind, 1958; Hayashi; Hoashi; Nara, 1997; Herbst, 1983; Palmer, 1998; Neiva, 2000). However, more recent studies using ultrasonography to analyze the biomechanics of breastfeeding reported that milk secretion happens due to the intraoral vacuum from sucking. This generates negative pressure and is aided by tongue movements, enabling milk to flow out of milk ducts. Then, the tongue's anterior and middle portions move like a rigid body, and the ensuing vacuum increases as the tongue moves down, expanding the nipple and allowing the milk to flow out. Pressure then normalizes when the tongue returns to the superior position and closer to the palate (Elad et al., 2014; Geddes & Sakalidis, 2016; Geddes et al., 2012; Sakalidis et al., 2013).

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For sucking efficiency, the oral cavity is sealed, and the tongue fills most of that space with its sides touching the palate and its center surrounding the nipple (Elad et al., 2014; Geddes et al., 2012; Mills et al., 2020; Sakalidis et al., 2013).

Health organizations recommend that infants be exclusively breastfed until they are approximately six months old; breastfeeding with complementary feeding may continue for up to 2 years or longer (Brazil, 2015; World Health Organization, 2017). There are several benefits for both baby's and mother's health, including reduced risk of infant death, protection against infections, allergies, respiratory diseases, diarrhea, necessary nutritional support, and mother and baby bonding. In addition, it is considered an essential factor for the stomatognathic system and orofacial function development (Brazil, 2015; Geddes et al., 2019; Victoria et al., 2016).

Despite the many advantages, studies point to the occurrence of early weaning, which is justified by multiple factors, such as the low level of breastfeeding self-efficacy, the mother's insecurity, her lack of intention to breastfeed, breastfeeding problems, sociodemographic factors, and the lack of support from health care professionals (Kronborg & Foverskov, 2020; Mangrio et al., 2018; Vargas et al., 2016).

Health professionals' guidance and counseling on breastfeeding are essential for successful breastfeeding and its increased duration. Performing these effectively favors the mother's sense of security and increases her effort to overcome difficulties and breastfeed successfully (Alves et al., 2018; Kronborg & Foverskov, 2020).

Academically trained professionals and community health care agents have developed different studies to educate people, especially pregnant and postpartum women, on the benefits of natural breastfeeding for babies' health and development (Coutinho et al., 2014; Shafaei et al., 2020). In addition, other studies have been performed to train those professionals regarding counseling and health promotion-related actions toward breastfeeding (Buskens e Jaffe, 2008; O'Sullivan et al., 2019; Wallace et al., 2018).

Technological advances enabled many audiovisual resources and educational technologies to support health care guidelines, promotion, and therapies. These serve as strategies to improve patients' and health care providers' knowledge and make them agents to empower adherence to recommendations (Adhisivam et al., 2017; Oriá et al., 2018; Silva et al., 2019). Consequently, three-dimensional (3D) computer graphics is one of the fastest-growing technologies in the health sciences, especially when teaching anatomy and physiology (Cemenasco et al., 2004; Petersson et al., 2009; Temkin et al., 2006). Different studies have used models and simulators with that type of resource. (Lara et al., 2020; Vieira et al. 2009). However, none contemplates dynamic 3D computer graphics iconography for breastfeeding-related anatomy and physiology of the baby's sucking and swallowing.

Recent literature also addresses technological resources to offer health promotion and counseling for families with newborns regarding breastfeeding and newborns' first care. The resources include video and web conferences, e-learning programs, and email or text message exchanges between families and health care professionals (Chaves et al., 2019; Friesen et al., 2015; Lau et al., 2021; Oriá et al., 2018). However, no study used 3D computer graphics iconography regarding the theme of breastfeeding.

Considering how important it is to understand the breastfeeding process using audiovisual resources to improve the training of health care professionals, students, mothers, and caregivers, this study aimed to develop and update a dynamic 3D graphic video learning object showing newborns' anatomy and physiology of sucking and swallowing during breastfeeding. It also aims to analyze 3D graphic material content and appearance in the current scientific literature.

METHODS

We developed this research as a multi-disciplinary project to build a learning object called “Virtual Baby." It was a partnership between the University of São Paulo's Bauru School of Dentistry's Department of Speech Therapy (FOB USP) and the University of São Paulo's Medical School's Telemedicine class (FMUSP). The first version of the learning object was developed in 2010 and received an update in 2021 to improve content and image. The methodology follows the Virtual Man Project's precepts, which are three-dimensional modeling of the structures of the human body based on scientific details using 3D computer graphics resources and its conversion into directed and objective knowledge units https://homemvirtual.org.br/projeto/.

We organized a transdisciplinary team with anatomy, speech therapy, medicine, communication, and digital design professionals to develop this project. The team defined a theme to build the educational material in a 3D computer graphics realistic simulator format: the anatomy and physiology of the orofacial myofunctional system of the full-term newborn during breastfeeding. This choice considered the theme's relevance to primary health care, health education, and public health care.

To guide the digital designer's structural (static) and functional (dynamic) graphic modeling, we defined the objectives of the learning object, and created a script based on academic bibliographic references. The script focused on describing the anatomy of the newborn's face, skull, oral cavity, pharynx and esophagus, the mechanisms related to sucking, and the oral and pharyngeal phases of swallowing.

To support the scientific development roadmap of the first Virtual Baby version, we performed a literature review in the Lilacs and MedLine databases and selected scientific works with information on the anatomical and physiological of the sucking and swallowing processes. The keywords were suction, swallowing, breastfeeding, infant, and anatomy.

Additionally, we studied anatomy, physiology, speech therapy, and pediatric dentistry books, anatomy atlases, photos, skeletons of newborns and fetuses in different gestational periods preserved in vitro, as well as videofluoroscopy videos (swallowing dynamics assessment via radiological imaging), and dynamic ultrasound images of the oral cavity during suction and swallowing. Finally, we examined computed tomography scans for morphofunctional details of the orofacial myofunctional system.

To prepare for the updated version of the Virtual Baby, we conducted a second bibliographical review to update and improve its content and image, covering the MedLine, Lilacs, and PubMed databases. In addition, we paired the following Portuguese and English descriptors/ keywords to check for representativeness of all items: anatomy, physiology, sucking behavior, swallowing, newborn, and breastfeeding.

Studies selected for informational content included full-term and healthy babies with no neurological changes or craniofacial anomalies. Excluded studies involved preterm babies with ankyloglossia, patients with neurological diseases, chromosomal syndromes, craniofacial anomalies, or any anatomical changes that could interfere with breastfeeding.

Article analysis considered casuistry, evaluation procedures, methodology, and results related to the anatomical and physiological aspects of sucking and swallowing during breastfeeding in full-term newborns. The selected studies were classified according to their level of scientific evidence, as follows: evidence resulting from the meta-analysis of multiple randomized controlled clinical trials (Level 1); evidence from individual studies with experimental design (Level 2); evidence from quasi-experimental studies (Level 3); evidence of descriptive (non-experimental) studies or with a qualitative approach (Level 4); evidence from case reports or experience (Level 5); evidence based on specialist's opinions (Level 6) (Souza et al., 2010).

Script development allowed the designer to build scientific evidence-based iconographies in 3D computer graphics, whose production was divided into modeling, animation, texturing, lighting, rendering, composition, and post-production. The programs used were 3DS Max 2010, ZBrush 3.5, Photoshop CS4, and After Effects CS4. Regarding the technological infrastructure, the following resources were available: Core 2 Quad Q8200 Processor (Speed: 2.33 GHz / FSB: 1333 Mhz / L2 Cache: 4 Mb / Technology: 45 NM); 4 GB DDR2 800 Kingston Memory (two 2 GB DDR800 Kingston PC 6400 Dual Channel models); Geforce 9500 GT 1GB Video Card (1024Mb/128Bit GDDR2 PCI-Ex 16X/DVI TV OUT/DX10 - Shader 4.0); 500GB 7200 RPM SATA 2 hard drive; two LCD widescreen 18.5-inch 933sn Samsung monitors; Wacom Bamboo Pen Ctl-460 tablet.

RESULTS

The script that guided the preparation of the 3D iconographies was created based on the literature review, which included a survey that included 14 publications with six scientific articles and eight book chapters (Table 1). These materials helped guide our representation of the breastfeeding process into two sections: the first contains descriptions and information about the anatomy of the newborns' face, skull, oral cavity, pharynx and esophagus; and the second addresses the description of the physiological mechanisms related to sucking and swallowing during breastfeeding.

Upon completing the academic bibliographic reference-based script, the designer created the 3D iconographies for the Virtual Baby's anatomy and physiology of sucking and swallowing. This stage included interactions between health care professionals and digital designers so they could discuss the script information, analyze and revise image details, and confirm the accuracy of the final product regarding newborns anatomy.

Table 1: Literature review regarding the anatomophysiological aspects of sucking and swallowing in full-term newborns

Publication Type	Year	Author(s)	Contents	
			Anatomy	Physiology
Article	1998	Derkay & Schechter	Anatomy of swallowing disorders	Swallowing disorder physiology in infants
Book	1998	Morris	Impact of anatomical knowledge on assessing and treating childhood dysphagia	Impact of physiological knowledge on assessing and treating childhood dysphagia
Book	1998	Villena & Corrêa	Stomatognathic system anatomical characteristics	
Book	1999	Marchesan		Swallowing physiology
Book	1999	Moreira	Oral anatomy and development	Mouth physiology and development
Book	2001	Behlau et al.	Oral cavity, pharynx, and larynx anatomy	
Article	2002	Pérez Navarro & López	Lingual frenulum and oral cavity anatomy	Ankyloglossia-related physiology
Book	2003	Moreira	Clinical aspects of the oral cavity anatomy	Clinical aspects of the oral cavity physiology
Article	2003	Neiva et al.	Implications of early weaning on orofacial myofunctional development	
Article	2006	Costas et al.		Sucking and swallowing pattern of full-term and preterm babies
Article	2004	Sanches	Facial anatomy in babies	Breastfeeding-related orofacial functions
Book	2006	Douglas		Sucking and swallowing physiology
Book	2008	Madeira	Facial anatomy	Orofacial functions physiology
Article	2008	Tavano	Baby and child anatomy	

The Virtual Baby was updated in 2021 to ensure improved content and more detailed images and content. The update included a new bibliographic review with 11 updated articles that relied on the use of technologies to educate on the breastfeeding process (Tables 2 and 3). As indicated in Table 2, the studies' levels of evidence ranged from 2 to 4; level 3 was the most frequent. Updating the computer graphics involved meetings between health professionals and digital designers to ensure material quality and reliability.

Considering the selected theoretical framework, sucking and swallowing adjustment for the Virtual Baby was performed in five steps described in Table 4. This progression allowed the educational 3D model to come closer to the reality indicated by the current literature.

Figures 1 and 2 correspond to the images of the first version of Virtual Baby. Figures 3, 4, and 5 show the current model during breastfeeding. In addition, a video clip of the Virtual Baby model as an embedded and downloadable link is available on this article's homepage (https://ijom.iaom.com/journal/vol48/iss1/4/).

DISCUSSION

This project developed both the content and appearance of a learning object that shows the mechanisms involved in breastfeeding. An interdisciplinary team created and modeled the Virtual Baby's breastfeeding 3D computer graphics based on reviewing and analyzing studies published in scientific journals and anatomy and physiology books. The analysis of this theoretical framework showed that the first studies on sucking during breastfeeding were performed using cineradiography (Adran et al., 1958). In addition, the authors reported that the tongue performs peristaltic movements during sucking (Adran et al., 1958), and these findings

Table 2: Bibliographic references on the anatomical and physiological aspects of sucking and swallowing in full-term newborns

Author (Year)	Theme	Level of Evidence*
da Costa et al. (2010)	Suction patterns and age-specific variations	3
McClellan et al. (2010)	Tongue movement during breastfeeding and nipple diameter through ultrasound	4
Lang et al. (2011)	Sucking parameters in breastfeeding	3
Geddes et al. (2012)	Milk secretion mechanism during breastfeeding	4
McClellan et al. (2012)	Relationship between nipple pain, increased vacuum due to baby's sucking, and decreased milk	3
Burton et al. (2013)	Children's tongue movements to check for peristaltic movements in breastfeeding using 3D ultrasound	3
Sakalidis et al. (2013a)	Describes tongue movements during nutritive and non-nutritive sucking	3
Sakalidis et al. (2013b)	Comparison of sucking and breastfeeding between C-section and natural birth babies	3
Elad et al. (2014)	Development of a breastfeeding biophysical model and sucking biomechanics analysis	2
Cannon et al. (2016)	Analysis of the intraoral vacuum created during breastfeeding and the amount of milk secretion	3
Geddes & Sakalidis (2016)	Literature review on sucking using ultrasound	3
Mills et al. (2020)	Analysis of sucking and swallowing in babies during breastfeeding	3

***Level 2:** Evidence from individual study with experimental design; **Level 3**: Evidence from quasi-experimental studies; **Level: 4**: Evidence of descriptive (non-experimental) studies or those with a qualitative approach

Table 3: Selected articles that used technological tests for the baby's virtual suitability

Author (Year)	Case Series	Technology Used	Relevant Findings
da Costa et al. (2010)	30 full-term babies with typical development, no breastfeeding difficulties, gestational age >37 and <42 weeks	Video recording + NOMAS protocol application	According to the Neonatal Oral-Motor Assessment Scale (NOMAS), which assesses breastfeeding aspects, 90% of babies have a normal sucking pattern 2-3 days after they are born; that is, 10 to 30 sucking movements without rest, one suck, one swallow, and one breath and jaw movement at approximately every one second.
McClellan et al. (2010)	30 full-term babies, <6 months old, no breast-feeding problems	ultrasound	Vacuum is the primary mechanism for milk secretion during breastfeeding. It was not possible to confirm the existence of peristaltic tongue movements. Nipple displacement and diameter increase are related to the up and down tongue movements.
Lang et al. (2011)	91 full-term babies between 38 and 47 weeks	Orometer + sucking editor	The baby's sucking pattern changes during breastfeeding, which may be related to satiety or fatigue.
Geddes et al. (2012)	18 full-term, healthy, breastfed babies	Experimental nipple + ultrasound + intraoral pressure gauge	Lowering the middle section of the tongue increases the intraoral vacuum, makes nipple ducts visible, and allowing milk to flow into the baby's oral cavity. The tongue starts to rise from its apex to its back, directing the milk to be swallowed. The distance from the nipple to the junction between hard and soft palate was significantly shorter in the lowered tongue than when the tongue was raised. Nipple diameter increased significantly when the tongue descended.

Burton et al. (2013)	15 babies, gestational age >37 weeks, weight >2.5kg	Ultrasound	Peristaltic tongue movements were inconsistent, and it was not possible to conclude whether or not they were present.
Sakalidis et al. (2013a)	15 babies	Ultrasound	Lowering the middle section of the tongue enables milk to flow, increases its diameter and allows the nipple to shift towards the junction of the hard palate with the soft palate without touching that junction.
Sakalidis et al. (2013b)	34 babies, 19 C-sections and 15 vaginal deliveries	Ultrasound	The anterior third of the tongue rests at the base of the nipple, and the rest of the tongue presses the nipple against the hard palate. Sucking occurs when the middle section of the tongue begins to descend, the nipple diameter increases, and the ducts open in preparation for milk secretion. Next, the front section of the tongue starts to rise again, compressing the base of the nipple, and the milk flows into the baby's oral cavity. Then, the middle and posterior sections of the tongue rise, coming into contact with the palate. The nipple moves towards the junction of the palates but does not reach it.
Elad et al. (2014)		Ultrasound + biophysiological model	Breastfeeding requires synchronized jaw, lip, and tongue movements. Milk secretion occurs due to the vacuum created by tongue movements. The tongue performs undulatory movements in a pattern similar to a propagating peristaltic wave. The front of the tongue moves with the cyclic jaw movements and the back of the tongue in a wavy fashion.
Cannon et al. (2016)	19 babies	pressure transducer + ultrasound	The intraoral vacuum plays a vital role in secreting milk from the nipple ducts. The greater the intraoral vacuum peak, the greater the milk secreted.
Geddes & Sakalidis (2016)		Ultrasound	Sucking during breastfeeding occurs by crea-ting the existing intraoral vacuum. The tongue then performs descending movements, ex-panding the nipple and allowing milk secretion.
Mills et al. (2020)	12 babies	Magnetic resonance imaging	Intraoral vacuum plays a vital role in milk secretion as there is no air in the oral cavity during sucking. The tongue wraps around the nipple, lifts it to the hard palate, and its tip is positioned regarding the lower gums. There is velopharyngeal closure and laryngeal elevation during swallowing, followed by peristaltic pharyngeal contraction.

Table 4. Adjustments in sucking and swallowing for the Virtual Baby

Stage	Description
Step 1	Adjusted sucking/swallowing/breathing synchronization; improved sliding jaw movement during sucking; increased video speed for a more realistic quality; tongue movement synchronization with peak vacuum, nipple expansion, milk flow, and swallowing
Step 2	Adjusted tongue movement; increased laryngeal elevation when swallowing
Step 3	Adjusted nipple attachment and laryngeal elevation when swallowing
Step 4	Adjusted laryngeal elevation and soft palate function when swallowing
Step 5	Completion of 3D iconographies with placing and rendering of the mucosa

Figure 1. Image of nipple attachment in the first version of Virtual Baby

Figure 2. Image of sucking movement in the first version of Virtual Baby

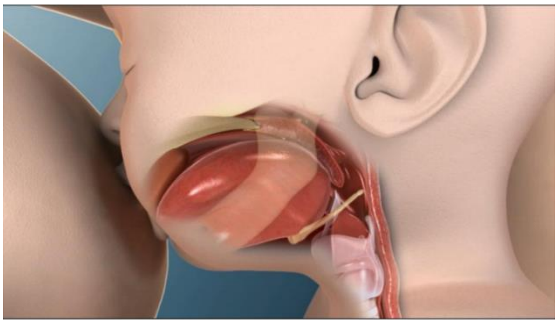

Figure 3. Image of nipple attachment and early sucking movement in the Virtual Baby

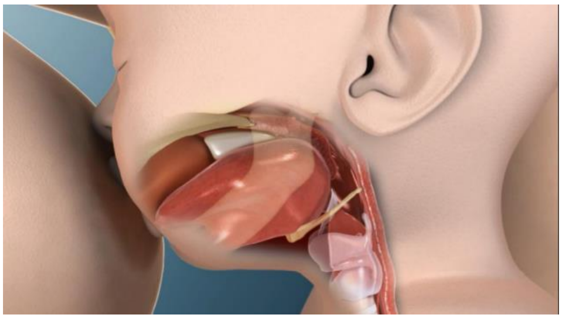

Figure 4. Tongue lowers and nipple diameter increases while sucking in the Virtual Baby

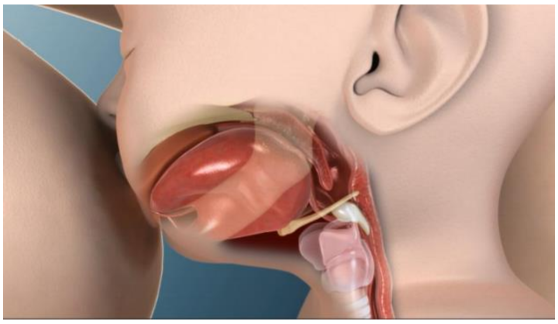

Figure 5. Swallowing pharyngeal phase in the Virtual Baby

were later reproduced in other studies (Hayashi et al., 1997; Herbst, 1983; Neiva, 2000; Palmer, 1998) over many years.

Technological evolution enabled current studies to show that the tongue, composed of striated skeletal musculature, does not perform peristaltic movements (Elad et al., 2014; Geddes et al., 2012) since such movement can only be performed by smooth musculature and undulatory movements similar to peristaltic waves.

Milk is not secreted when the tongue is pressing the nipple but rather by the vacuum created in the oral cavity as a result of tongue movements (Elad et al., 2014; Geddes & Sakalidis, 2016; Geddes et al., 2012; Mills et al., 2020; Sakalidis et al., 2013a). The baby's grip needed for anterior sealing helps create a vacuum and prevents milk from escaping through the mouth (Tamilla et al., 2014). A vacuum begins to form when the middle portion of the tongue rises and comes into contact with the hard palate. When the tongue descends, the vacuum and nipple diameter increase, and milk flows into the oral cavity (Geddes & Sakalidis, 2016; Geddes et al., 2012; Sakalidis et al., 2013). During sucking, the nipple moves towards the junction of the hard and soft palates but does not extend to this junction, remaining a few millimeters away (Elad et al., 2014; Geddes & Sakalidis, 2016; Geddes et al., 2012; Sakalidis et al., 2013a).

Once milk is expressed from the nipple, it is directed from the oral cavity to the pharynx, initiating the pharyngeal phase of swallowing. At this point, the velopharynx closes to ensure that the milk does not enter the nasopharynx; finally, the larynx elevates. The fluid is then transferred to the esophagus with the aid of constricting movements of the pharyngeal muscles. The esophageal phase begins when food passes through the upper esophageal sphincter on its way to the stomach (Lau, 2015; Mills et al., 2020).

Current studies performed based on instrumental methods served to create the Virtual Baby's 3D computer graphics. In addition, they allowed us to develop a learning object based on up-to-date scientific evidence.

Initially, the Virtual Baby's first version had a sequence of dynamic 3D iconographies picturing the baby latching on. Then the forward tongue movement was associated with the forward mandibular movement for milk extraction. Lastly, the swallowing movement occurred along with laryngeal elevation and velopharyngeal closure.

We changed the sequence in the second version after updating the studies on the newborns' anatomy and physiology of sucking and swallowing. As a result, there were adjustments in the synchronization between sucking, swallowing, and breathing, improved sliding of mandibular movement during suction, increased video speed for more realistic results, synchronized tongue movements with peak vacuum and increased nipple expansion and larynx elevation during swallowing. The update also included a video demonstrating improved nipple latching.

Future work is needed to validate the developed material. In addition, we recommend developing additional tools for babies with or at risk for developing orofacial myofunctional disorders, such as those with a cleft lip or cleft palate, those born prematurely, babies with Down syndrome, and those with ankyloglossia.

The Virtual Baby learning object can be applied in education and health promotion strategies, both for formal education and interactive tele-education. It has the potential to contribute to the training of students and health professionals and to benefit patients' health.

CONCLUSION

This original and innovative project produced both the content and appearance of a dynamic 3-dimensional graphical learning object created to demonstrate the anatomy and physiology of sucking and swallowing in full-term newborns. In addition, the tool addresses the significant morphofunctional aspects of the breastfeeding process, which are consistent with current scientific literature and can be used for professional training or in primary health care.

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