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Understanding Children's Attention to Dental Caries through Eye-Tracking

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Early childhood caries · Eye-tracking technology · Children · Perception

Abstract
Visual attention is a significant gateway to a child's mind, and looking is one of the first behaviors young children develop. Untreated caries and the resulting poor dental aesthetics can have adverse emotional and social impacts on children's oral health-related quality of life due to its detrimental effects on self-esteem and self-concept. Therefore, we explored preschool children's eye movement patterns and visual attention to images with and without dental caries via eye movement analysis using hidden Markov models (EMHMM). We calibrated a convenience sample of 157 preschool children to the eye-tracker (Tobii Nano Pro) to ensure standardization. Consequently, each participant viewed the same standardized pictures with and without dental caries while an eye-tracking device tracked their eye movements. Subsequently, based on the sequence of viewed regions of interest (ROIs), a transition matrix was developed where the participants' previously viewed ROI informed their subsequently considered ROI. Hence, an individual's HMM was estimated from their eye movement data using a variational Bayesian approach to determine the optimal number of ROIs automatically. Consequently, this data-driven approach generated the visual task participants' most representative eye movement patterns. Preschool children exhibited two different eye movement patterns, distributed (78%) and selective (21%), which was statistically significant. Children switched between images with more similar probabilities in the distributed pattern while children remained looking at the same ROI than switching to the other ROI in the selective pattern. Nevertheless, all children exhibited an equal starting fixation on the right or left image and noticed teeth. The study findings reveal that most preschool children did not have an attentional bias to images with and without dental caries. Furthermore, only a few children selectively fixated on images with dental caries. Therefore, selective eye-movement patterns may strongly predict preschool children's sustained visual attention to dental caries. Nevertheless, future studies are essential to fully understand the developmental origins of differences in visual attention to common oral health presentations in children. Finally, EMHMM is appropriate for assessing inter-individual differences in children's visual attention.

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Introduction

Every child is at risk of dental caries, affecting approximately 48% of preschool children [Uribe et al., 2021]. Dental caries depicts a continuum of disease states, ranging from subclinical to cavitated lesions extending into enamel, dentine, or pulp. Untreated caries leads to pain, discomfort, infections, emergency visits, and hospitalization [King et al., 2007]. Moreover, its global distribution is among the most prevalent causes of hospitalization in children [Listl et al., 2015; Uribe et al., 2021]. These consequences can significantly impact children's overall health, growth, and development, ability to chew and eat properly, lost school hours, and affecting child's overall wellness and self-esteem [Jackson et al., 2011].

Aesthetically, caries may be perceived as being unpleasant. Untreated caries [Barasuol et al., 2017] and poor dental aesthetics [Seehra et al., 2011; Al-Bitar et al., 2013] can increase children's bullying risk. It can also have adverse emotional and social impacts on children's oral health-related quality of life due to its detrimental effects on self-esteem and self-concept [Phillips and Beal, 2009; Al-Omari et al., 2014; Gatto et al., 2019]. Furthermore, the consequences of bullying can range from physiological to psychological, and victims are considered anxious, insecure, sensitive, withdrawn, and with low self-esteem as adolescents [Barasuol et al., 2017]. Conversely, good oral health can facilitate healthy smiles and less bully victimization [Folayan et al., 2020]. Although this statement sounds logical, there is no scientific evidence to support this notion. Therefore, the assumption that good oral health in children would lead to less likelihood of bullying needs further investigation.

The presentation of dental caries in children can vary depending on the lesions' nature, size, and extent, with some being more obvious than others. Although the literature has a wealth of knowledge regarding the impact of caries on children's oral health-related quality of life, bullying and victimization, body weight, growth, and quality of life, little is known about children's attention to dental caries [Martins-Júnior et al., 2013]. Most published studies are based on surveys or questionnaires with parents/caregivers used as a proxy to reflect their children's choices. A few studies have used older children, 8 years and above, to ascertain some of the negative impacts of dental caries [Al-Bitar et al., 2013; Al-Omari et al., 2014; Barasuol et al., 2017].

Looking is one of the first behaviors young infants develop, and visual attention is a significant gateway into a child's mind. Eye movement analysis using hidden Markov models [EMHMM; Chuk et al., 2014; http://visal.cs.cityu.edu.hk/research/emhmm/] allows obtaining a quantitative measure of children's eye movement patterns while they observe various visual stimuli. Furthermore, these techniques facilitate meaningful interpretations of how children perceive the world with high spatial and temporal accuracy. We explored individual differences among preschool children's eye movement patterns and visual attention to images with and without dental caries via EMHMM. The assumption was that children would fixate on locations of high interest. Hence, the null hypothesis was that images with dental caries would hold or capture preschool children's visual attention more effectively than images without dental caries.

Materials and Methods

This child-centered visual task-based study with a cross-sectional design was approved by the University of Western Australia Human Research Ethics Committee (2019/RA/4/1/9331). We mapped the childcare center locations around the central business district in metropolitan Perth, Western Australia. Subsequently, we invited all 33 childcare centers within a 25-km radius, and 12 childcare centers agreed to participate in the study. Participants and their parents received information outlining the project details. Parents and/or legal guardians provided informed consent before study commencement.

As no previous studies investigated children's eye movement patterns and visual attention to dental caries, we recruited a convenience sample of 157 healthy children aged 2.5–5.5 years. Only children with normal or corrected-to-normal vision were included, while children with a history of developmental, hearing, or neurological disorders or syndromes were excluded.

Before viewing the pictures, all children undertook two activities (i) completing the pattern and (ii) joining the dots in a line (online suppl. Fig. 1; see www.karger.com/doi/10.1159/000524458 for all online suppl. material) to complete in their own time. These activities facilitated grouping children based on their ability to follow instructions and manual dexterity. Children who completed both activities were assigned to the "complete activity" group and the remaining to the "incomplete activity" group. Hence, we analyzed the data based on gender (male, female), age (2.6–3.5 years, 3.6–4.5 years, and 4.6–5.5 years) and the activity (complete or incomplete).

Setting and Equipment

We installed Tobii Studio software (Tobii, Danderyd, Sweden) onto a laptop computer (Hewlett Packard, Boeblingen, Germany) connected with a Tobii Pro Nano screen-based eye-tracking camera and recording at 60 frames per second. This laptop was set up in the childcare centers so the participants could independently view the images in a quiet room while seated on a stable chair approximately 30 cm–50 cm away from the laptop. All participants viewed the same pictures randomly displayed on a computer screen (Fig. 1).

A frontal photograph of a three-year-old exhibiting a complete smile with caries-free teeth was obtained using a digital camera (exposure time: 1/200 s, aperture: f/8.0, sensitivity: ISO 200, Canon EOS 200D; Canon Inc., Ota, Japan) with a macro lens (Canon EF 100 mm f/2.8 Macro USM; Canon Inc., Ota, Japan) and flashlight (Canon Speedlite 580EX II, Canon Inc, Ota, Japan) under standardized conditions. The initial resolution of the images was 4,752 pixels × 3,168 pixels. Furthermore, we cropped the eyes, neck, clothes, and other peripheral features. Finally, carious lesions were superimposed and photoshopped (Photopea [https://www.photopea.com/]) as shown in Figure 1. Thus, the first slide consisted of (i) carious free dentition and (ii) carious lesions on the primary maxillary incisors (Fig. 2a). Subsequently, the children viewed another slide consisting of two images with carious lesions (iii and iv) on different teeth (Fig. 3a).

All participants were positioned in the middle of the camera's field of view, and the screen and camera were adjusted to capture the participants' eye movements. The investigation started with a two-point eye-tracker calibration exercise, using an animation video of a duck that made an alerting sound to gain attention and moved across the screen, taking approximately 10 s. Hence, all participants were calibrated to the eye-tracker to ensure standardization. Consequently, each participant viewed the same images (Fig. 1) with a break in between, randomly sequenced, and did not perform other tasks until the screen went blank, indicating the end. Also, the instructions were very minimal to avoid differing interpretations of the task at hand. Subsequently, the fixation points for each participant were exported into an excel spreadsheet.

Data Analysis

The eye-fixation data was analyzed using EMHMMs [Chuk et al., 2014; Chuk et al., 2020; Hsiao et al., 2021], which incorporated individual differences in spatial (eye-fixation locations) and temporal dimensions (the order of eye-fixation sites). For assessing participants' eye movement patterns, predetermined equal-sized fixed regions of interest (ROI) were defined as ROI1 and ROI2 around the mouth region. We assumed each ROI would follow a 2D Gaussian distribution. A two-tailed t test was used to compare means for normally distributed and skewed data with the p values set at 0.05 for statistical significance. In addition, a T test was computed to compare eye movement patterns and consistency measures between gender and activity groups, while ANOVA was used for age groups. The transitions among the ROIs were summarized into a transition matrix showing the probability of eye gaze moving from a previously viewed ROI to the subsequent ROI. Subsequently, individual HMMs were clustered into groups according to the similarities of their ROIs and ROI sequences to discover representative eye movement patterns among the participants.

The most representative eye movement patterns are based on individual HMMs. The similarity of a participant's eye movement

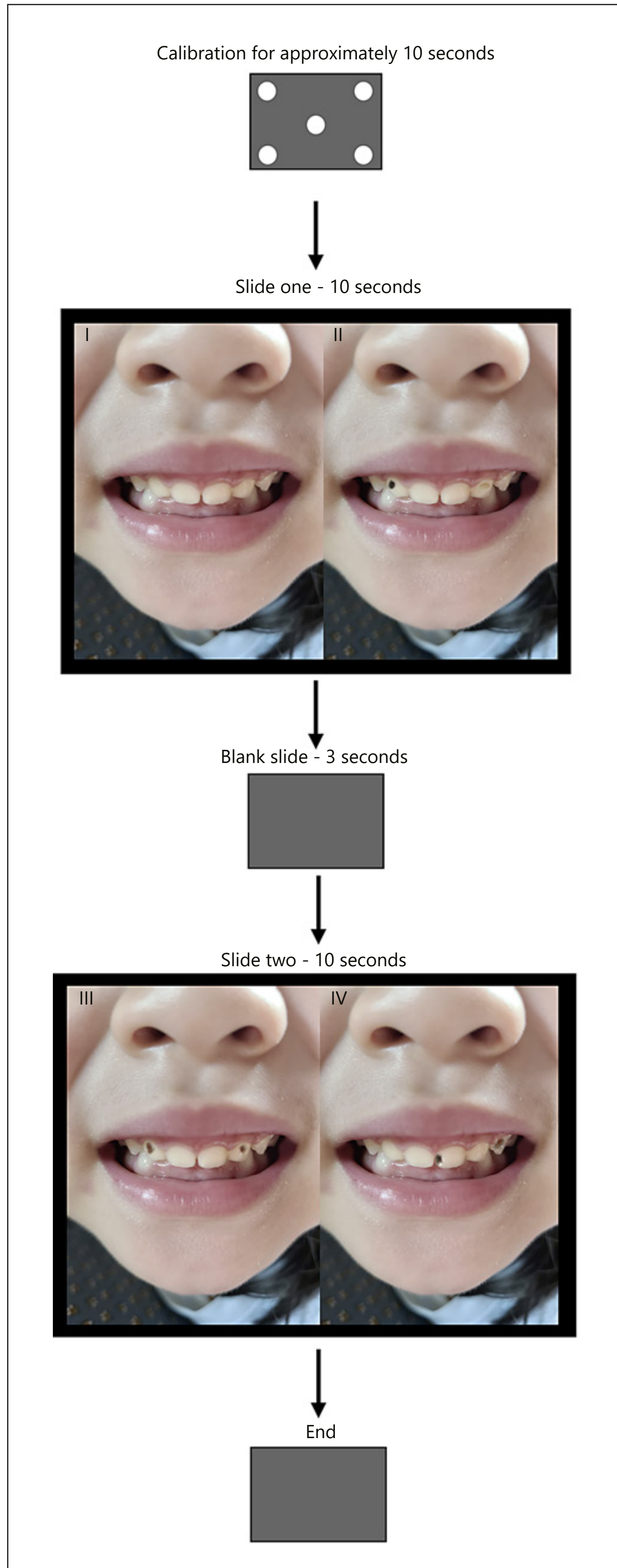

Fig. 1. Illustrates the eye-tracking sequence starting with calibration, followed by Slide one, presenting images (I) no dental caries and (II) dental caries on teeth 52 and 62. A break followed this, and children viewed Slide two, which consisted of images (III) dental caries (symmetric presentation) on teeth 52, 62 and (IV) asymmetric dental caries on teeth 61 and 63 (asymmetric presentation).

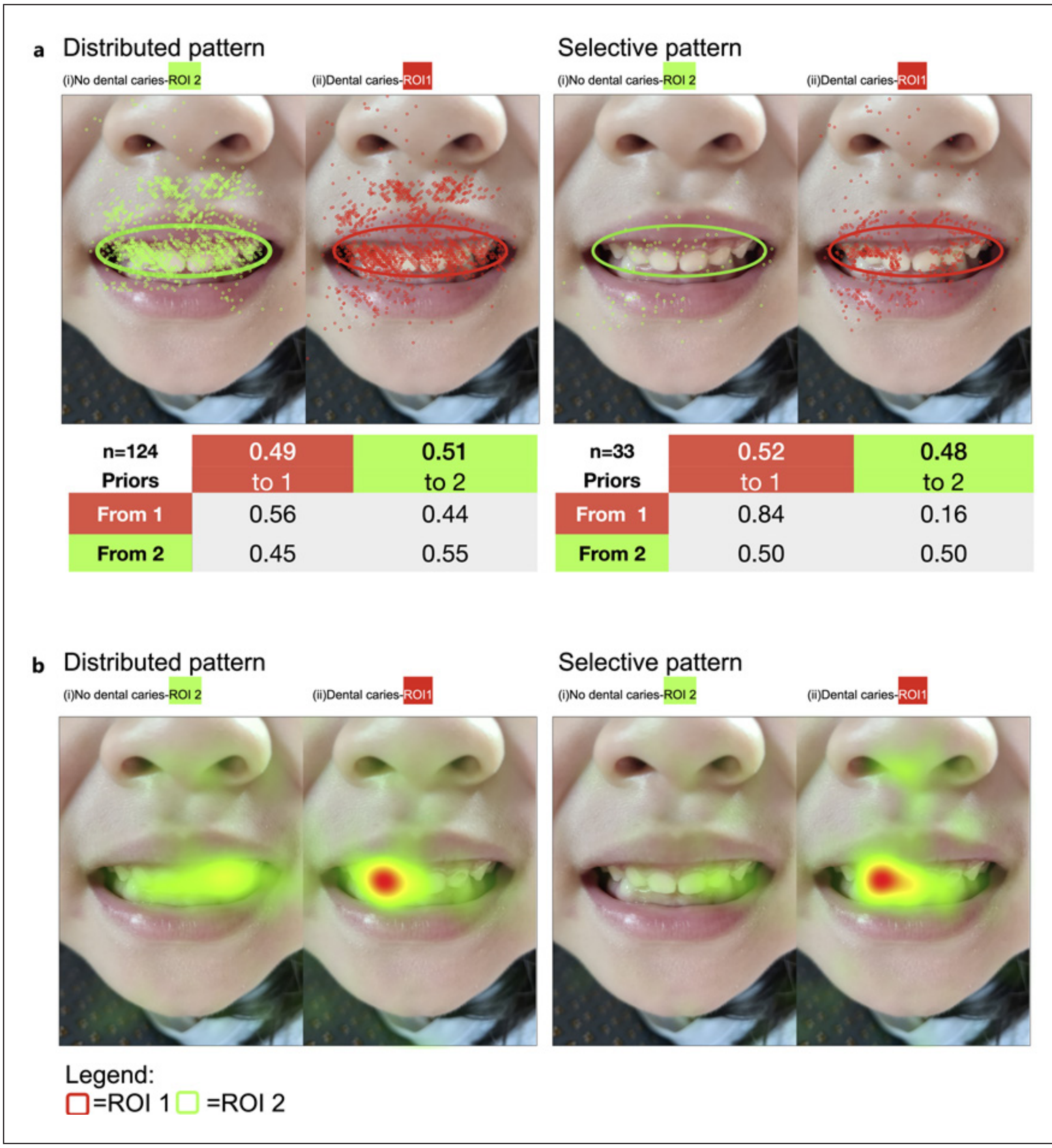

Fig. 2. a Illustrates the two eye movement patterns, namely distributed and selective, and the fixed ROI analysis for images with and without dental caries. The ROIs are defined as elliptical areas in the mouth region and represented as ROI1: dental caries and ROI2: no dental caries. Note: small circles show raw fixation locations, and the color of the small circles indicate ROI assignments. Priors indicate the probability that a fixation sequence starts from the corresponding ROI. The transition matrix suggests the likelihood of eye gaze transits between the ROIs. For example, in the distributed pattern group, children showed a 49% chance of their first fixation in ROI1 and 51% in ROI2. After that, they remained in the same ROI (ROI1 = 56%, ROI2 = 55%) or switched ROI (ROI1 to ROI2 = 44% and ROI2 to ROI1 = 45%). **b** Shows the representative heatmaps for each eye movement pattern. Note area in red indicates the maximum focus, which is predominantly on teeth with dental caries for both groups.

data to a suggestive pattern was quantified using the log-likelihood of the participant's eye movement data being generated by the representative model. Raw data were analyzed using EMHMM and GraphPad Instat (California, USA). See Chuk et al. [2017] for more details about the EMHMM method.

Results

The demographics for the participants are shown in Table 1. As young as two years old, all preschool children exhibited fixations on all images. Most children (78%) exhib-

Fig. 3. a Illustrates the two eye movement patterns, namely distributed and selective, and the fixed ROI for images with dental caries. The ROIs are defined as elliptical areas in the mouth region and represented as ROI1: dental caries on teeth 61 and 63, and ROI2: dental caries on teeth 52 and 62. Note: small circles show raw fixation locations, and the color of the small circles indicate ROI assignments. Priors indicate the probability that a fixation sequence starts from the corresponding ROI. The transition matrix suggests the likelihood of eye gaze transits between the ROIs. For example, in the distributed pattern group, children showed equal chance (50%) of their first fixation ROI1 or ROI2. They remained in the same ROI (ROI1 = 57%, ROI2 = 59%) or switching ROI (ROI1 to ROI2 = 43% and ROI2 to ROI1 = 41%). **b** Shows the representative heatmaps for each eye movement pattern. Note area in red indicates the maximum focus, which is predominantly on teeth with dental caries for both groups.

ited a distributed pattern, whereas 21% showed a selective eye movement pattern (Fig. 2, 3). In the distributed pattern, participants switched between images with more similar probabilities according to the transition matrix. Conversely, participants were more likely to stay looking at the same region than switch to the other ROI in the selective pattern. The two patterns were significantly different (according to KL divergence estimation, independent *t* test, $p < 0.05$).

Table 1. Demographic data for the 157 preschool children participants

Gender, *n*	Activity	Age (years)			Total
		2.6–3.5	3.6–4.5	4.6–5.5	
Male (83)	Incomplete	21	9	0	30
	Complete	9	21	23	53
Female (74)	Incomplete	16	5	0	21
	Complete	8	19	26	53
Total		54	54	49	157

Caries Free versus Carious Teeth (Fig. 2)

Most children exhibited a distributed pattern ($n = 124$) with no preference for images with or without caries. As illustrated in Figure 2 (image i), the prior indicates that children exhibited a 49% probability of starting in ROI1 while 51% started in ROI2. Furthermore, children who began their fixations in ROI1 had a 56% probability of staying in the same ROI, while 44% switched to ROI2 in the subsequent fixation. However, if they started in ROI2, 55% remained in the same ROI, and 45% switched to ROI1 in the subsequent fixation.

Children following the selective pattern ($n = 33$) exhibited an even distribution of the probability to start in either ROI1 or ROI2. However, if they began in ROI1 (carious teeth, 52%), they had an 84% probability of staying in the same ROI. If they began in ROI2 (caries-free teeth, 48%), they had a 50% chance of staying in the same ROI or switching to ROI1 in the subsequent fixation. There was significant interest in fixations for ROI1, as illustrated in Figure 2. Also, children exhibiting a selective pattern had a significantly ($p < 0.01$) higher preferential gaze for ROI1 (mean = 0.77) than the distributed group (mean = 0.53).

Symmetric versus Asymmetric Carious Lesions (Fig. 3)

Children exhibiting a distributed pattern had an equal chance (50%) of their first fixation starting in ROI1 or ROI2. They also demonstrated a higher probability of remaining in the same ROI they started (ROI1 = 57%, ROI2 = 59%) rather than switching to the opposite ROI (ROI 2 = 43%, ROI1 = 41%). Children following a selective eye movement pattern ($n = 36$) had an almost even distribution of their first fixation, starting in ROI1 or ROI2 (Fig. 2). If they began in ROI1 (44%), they had a 95% probability of remaining in ROI1; if they started in ROI2, they had a 96% probability of staying in the same ROI2 in the subsequent fixation. There was no difference ($p = 0.062$) in preference of ROI1 between children following a distributed (mean = 0.54) or selective (mean = 0.50) pattern. Also, there were no differences in choice for ROIs between gender, age, and activity groups for all images viewed.

Discussion

The present study demonstrates that the EMHMM analysis method is a reliable approach to ascertaining children's eye movement patterns. In addition, the fixed ROI analysis facilitates meaningful insights into young children's attention, perception or understanding, and cognitive process while viewing a range of visual stimuli, like dental caries. Most preschool children followed a distributed pattern when considering the two images and did not strongly prefer their eye fixation on dental caries. However, a small group of children who exhibited selective eye-movement patterns showed a solid attentional bias toward dental caries. Therefore, for most children, images with dental caries did not hold or capture their visual attention more effectively than images without dental caries. Therefore, we rejected the null hypothesis.

Although fixation may not be a true reflection of choice or concern, the gaze bias theory states that gaze is actively involved in preference formation and attractiveness [Shimojo et al., 2003; Chuk et al., 2020]. Previous studies have investigated children's eye movements, fixations, and qualitative analysis using heatmaps related to choose tasks, namely dentists' attire and dental operatory [Celine et al., 2018; Celine et al., 2021]. Recently, Tschammler et al. [2018] et al. reported that dentists and laypeople rated children with healthy teeth as more attractive, pleasant, and calm than children with untreated or treated dental caries. However, the authors only analyzed the first fixation, total fixation time, and the number of fixations in the areas of interest, namely, eyes, nose, and mouth. This conventional approach of only metric analyses does not adequately reflect individual differences in either spatial (ROI choices) or temporal dimensions (such as gaze transition among the ROIs) of eye movements. Furthermore, it does not provide insights into specific patterns or predictions of eye movement data.

EMHMM utilizes the sequence of viewed ROIs to develop a Markov process where the participants' previously viewed ROI informs their subsequently considered ROI [An et al., 2021]. Therefore, an individual's HMM is estimated from their eye movement data using a variational Bayesian approach to determine the optimal number of ROIs automatically [Lee et al., 2021]. Consequently, this data-driven approach generates the visual task participants' most representative eye movement patterns. This difference in the gaze transition behavior between the two images is only noticeable via EMHMM and is not evident when looking at heatmaps of eye fixations (Fig. 2b, 3b). Possible explanations to the two eye-movement patterns, namely distributed and selective, identified in the present study may be due to processes such as avoidance, visual cues, and/or memory activation, which explain the selective attention exhibited by preschool children [Benitez et al., 2017]. However, children did not show a preferential bias to the two images irrespective of the eye movement pattern. Therefore, we opine that sustained fixation on the preferred ROI may simultaneously develop and/or depend on solid avoidance of the non-preferred ROI [Buss and Spencer, 2014], as exhibited in the selective pattern group.

To our knowledge, this is the first study reporting on children's visual attention to dental caries using eye-tracking devices. Unfortunately, therefore, it was impossible to estimate the sample size. Recently, Tschammler et al. [Tschammler et al., 2018] investigated the perception of dental caries among 20 dentists and 18 laypeople using standard eye-tracking metric analysis, which we considered inappropriate for possible sample size estimation. The main reasons were the different assessment techniques used, such as EMHMM and fixed ROI and, importantly, attentional differences between children and adults. Nevertheless, a hypothetical assessment based on Tschammler et al. [2018], would require 142 participants to obtain a power of 0.85, which the present study qualifies with 157 participants. Furthermore, a sensitivity analysis indicated to recruit approximately 94 children for an expected sensitivity of 0.9, a prevalence 0.2, and a confidence level of 85%.

The adequate sample size, with different age groups and learning capabilities, various day-care centers, and the EMHMM approach, strengthen the present study findings. Also, to avoid potential effects of facial characteristics and ethnic origin and ensure consistency, we used the same, edited images, matched for resolution, and displayed similar sizes, contrast, and contour density. Infants and young children aged 30 months and above can interpret the pictures as representations of current reality [DeLoache and Burns, 1994], a reason for including children above 2.5 years of age. However, there were no significant differences in the eye movement patterns irrespective of age, gender, and learning capacities, which we assessed based on activity completion before the eye-tracking task. Two children of the same age can act drastically different in behaviors, which was not accounted for in the present study. Therefore, future studies should investigate the potential associations between children's behavior and their eye-movement pattern to better understand bullying and victimization in light of relevant social determinants.

Screen-based eye-tracking visual tasks predominantly measure children's visual attention while viewing static images and fail to capture the dynamic nature of children's natural visual attention, which one can resolve by using mobile eye-tracking devices. In addition, due to young children's limited attention span, we only used two images with and without dental caries that does not cover the entire range and severity of various presentations in the primary dentition. Using EMHMM, we illustrated that all children exhibit an equal starting fixation on the right or left image, overcoming the likely lateral viewing behavior. Also, concurrently presenting the two images replicates attentional orientation closely toward particular real-world presentations. Likewise, we did not ask the children for their preferences to avoid potential confirmation bias. Furthermore, children's responses may not reflect their choices in this young age group. Additional physiological assessments, such as heart rate galvanic response, could have provided further support in determining children's reactions to the visual task, which future studies should explore.

The current study finding indicates that the selective eye-movement pattern may strongly predict preschool children's sustained visual attention to dental caries. Using EMHMM, we clearly illustrate the different eye movement patterns among preschool children, which of the two images attracts their attention, in what order, and how often. The lack of attentional bias between the two images may be due to the children's young age or understanding of dental caries. However, they noticed teeth in both the photos because children generally use the mouth region as an essential source of social information through development, especially during language acquisition [Lewkowicz and Hansen-Tift 2012; Oakes and Ellis 2013; Tenenbaum et al., 2013].

The study findings reveal that most preschool children did not have an attentional bias to images with and without dental caries. Furthermore, only a few children selectively fixated on images with dental caries. Therefore, selective eye-movement patterns may strongly predict preschool children's sustained visual attention to dental caries. Nevertheless, future studies are essential to fully understand the developmental origins of differences in visual attention to common oral health presentations in children. Finally, EMHMM is appropriate for assessing inter-individual differences in children's visual attention.

Acknowledgment

We would like to thank the day-care centers, children, parents, caregivers, and educators for participating in the study.

Statement of Ethics

This study was approved by the University of Western Australia Human Research Ethics Committee, approval number (2019/RA/4/1/9331). All participants legal guardian gave written informed consent to participate in the study and we received permission to publish the accompanying images.

Conflict of Interest Statement

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Author Contributions

Vanessa Y. Cho: contributed to conception, design, data acquisition, and interpretation, performed the statistical analysis, and drafted the manuscript. Nigel M. King: contributed to conception and design and critically revised the manuscript. Hien Ngo: contributed to concept and design and critically revised the manuscript. Janet H. Hsiao: contributed data acquisition and interpretation, performed the statistical analysis, and critically revised the manuscript. Antoni B. Chan: contributed data acquisition and interpretation, performed the statistical analysis, and critically revised the manuscript. Robert Anthonappa: contributed to conception, design, data acquisition, and interpretation and critically revised the manuscript. All the authors gave their final approval and agree to be accountable for all aspects of the work.

Data Availability Statement

All data generated or analyzed during this study are included in this article [and/or] its supplementary material files. Further inquiries can be directed to the corresponding author.

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