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ORIGINAL ARTICLE

Understanding the Visual Behavior for the Improved Cone Beam Computed Tomography Diagnosis and Management of Traumatic Dental Injuries: An Eye-Tracking Study

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ABSTRACT
Objective: To investigate the relationship between eye-tracking visual parameters and the precision of diagnoses and management for traumatic dental injuries (TDIs) in anterior teeth, utilizing CBCT to understand how visual observation is linked to cognitive processing. **Material and Methods:** A total of nineteen calibrated endodontic postgraduate residents participated in this study. They were subjected to an eye-tracking technology to analyze their interaction and interpretation of CBCT images. CBCT scans of maxillary teeth affected by TDIs were collected from individuals seeking treatment at the endodontic division of KAUD. Seven TDI cases were viewed through the Experiment Centre software, integrated with a SensoMotoric Instruments (SMI) eye-tracking device (Sensomotoric Instruments, Teltow, Germany), capturing the participants' eye movements as they analyzed CBCT image views. Clinical details were provided for each case, and residents formulated their diagnoses and management. The association between the parameters of eye-tracking behavior and the accuracy of both diagnosis and management was examined using the Mann-Whitney test. **Results:** A longer duration spent scanning the entire CBCT scan and a prolonged time until pathology detection were associated with accurate diagnosis and treatment decisions. However, a significant association was not found between longer time spent on areas of interest or the number of revisits with the accurate diagnosis and management. **Conclusion:** This study demonstrates that detailed examination of CBCT scans enhances diagnostic precision and management for traumatic dental injuries, underscoring the potential of targeted training to improve diagnostic accuracy. Future research with larger and more diverse samples is recommended to confirm these findings.

Keywords: Cone-Beam Computed Tomography; Eye-Tracking Technology; Tooth Injuries.

Introduction

Cone-Beam Computed Tomography (CBCT) has gained significant attention in the field of endodontics and has become an essential tool in the diagnosis, management, and assessment of treatment outcomes [1]. Over recent years, numerous studies have confirmed the enhanced diagnostic accuracy of CBCT, highlighting its superiority over conventional radiographic techniques in detecting periapical pathosis, vertical root fractures, undiagnosed pathologies, missed canals, intra-treatment complications, surgical endodontics and traumatic dental injuries (TDIs) [2-4].

The diagnosis and management of TDIs is considered a challenging aspect in the endodontic field, necessitating a comprehensive understanding of both clinical and radiographic findings. One of the primary difficulties lies in the diverse presentation of TDIs, ranging from simple enamel fractures to intricate pulpal and periodontal complications. The transient nature of certain clinical symptoms, coupled with clinical factors like the unreliability of pulp sensibility testing [5], the poor recall of the traumatic event, or the absence of immediate post-trauma visible changes, further adds to the diagnostic complexity [6]. Addressing these challenges necessitates a multidimensional approach encompassing thorough clinical examination, patient history-taking, and the use of advanced imaging techniques to ensure precise and timely intervention. It is widely acknowledged that post-traumatic complications might be mitigated by early identification and management of TDIs, thereby enhancing the likelihood of preserving the tooth and its surrounding tissue [7].

The diagnostic values of and the higher sensitivity CBCT in TDIs have been wildly confirmed, and CBCT is considered a prerequisite prior to the initiation of management of TDIs [8-10]. Furthermore, CBCT provides a distinct advantage in its ability to visualize the intricate internal anatomy of teeth and surrounding structures, allowing the ability to detect subtle displacement or other signs of TDI [10]. Studies have shown that CBCT has changed the treatment plan of TDIs in around 30% of the cases of immature traumatized teeth [11,12]. Particularly, the employment of CBCT resulted in less follow-up and watchful waiting with more active treatment suggested, thus avoiding eventual complications of delayed therapy [12]. This is noted not only in TDI cases but also in endodontic case management and diagnosis with the utilization of CBCT [1,12-14].

Eye-tracking technology, initially developed in the late eighteenth century, identifies the human pupil, documenting ocular movement and fixation when viewing images [15]. It facilitates the recording of various metrics, including the participant's gaze, fixation, saccade, and the overall traceability of eye movements [16]. The utilization of eye-tracking technology in the medical and dental fields has been a subject of growing interest due to its potential to enhance diagnostic accuracy and treatment planning [17-21].

Numerous investigations have permeated eye-tracking in the medical field for educational objectives and to provide a means to quantify visual behaviors, which can be correlated with the accuracy of medical interpretations and decisions [20-22]. More contemporarily, eye-tracking has been incorporated into dentistry as a mechanism for disseminating knowledge and mitigating diagnostic errors [23]. In endodontics, a limited number of studies have employed eye-tracking technology to assess dental periapical radiographs (PA) and CBCTs [17,24]. One study aimed to identify the areas and patterns of visual fixation that attract dentists' attention. Their findings showed that dentists' first fixation is more likely to be in areas of high contrast, such as radiopaque or radiolucent areas than in normal areas. Moreover, dentists tend to revisit these areas [17]. The second investigation comprised a pilot study in which two CBCT volumes were analyzed by 12 examiners. The findings revealed that variations in the examination approach employed by the examiners significantly influenced the proportion of identifiable radiographic observations [24]. Neither of these two studies evaluated the visual behavior of CBCT interpretation and its impact on diagnosis and treatment planning of TDI cases [17,24].

While the benefits of CBCT are widely acknowledged, the role of eye movement and visual parameters in influencing diagnostic efficacy when examining CBCT scans is less explored. The present study aims to bridge this particular knowledge gap. This observational cross-sectional study aimed to investigate the association between eye-tracking visual parameters and the accuracy of diagnosis and treatment plans chosen for TDIs in anterior teeth, as visualized through CBCT scans. Thus, to evaluate how observers analyze or cognitively process the contents of an image.

Material and Methods

Ethical Approval

Ethical consent for conducting the research was obtained from the Institutional Research Board and the Research Ethics Committee at the Faculty of Dentistry, King Abdulaziz University, as documented by the ethical clearance number 4449727.

Participant Recruitment

Twenty-four postgraduate endodontics residents at King Abdulaziz University Dental Hospital (KAUDH), Jeddah, Saudi Arabia, were initially recruited for this study. Recruitment was conducted via e-mail, where a detailed description of the study goals and the specific role of the residents in assessing CBCT images was provided.

Participants were required to be healthy, not taking any medications that could influence eye movement, and have no reported cognitive, visual, hearing, or developmental issues. To maintain consistency, all experiments were conducted at 10 AM, a time chosen to ensure participants were well-rested and not fatigued. Participants were instructed to get a full night's sleep and to avoid strenuous activities the evening prior to the experiments. Moreover, all participants were required to be proficient in interpreting CBCT scans and TDIs. Thus, first-year residents were excluded due to their limited experience in interpreting CBCT scans. Participants who wore eyeglasses or contact lenses or had undergone eye surgeries were required to report this information prior to participating in the experiment. Those who failed to meet the eye-tracking calibration requirement, exhibiting an eye deviation greater than one prism-diopter in both eyes as detected by the eye-tracking device, were excluded.

Case Selection and CBCT Scans Acquisition

CBCT scans of maxillary teeth affected by TDIs were collected from individuals seeking treatment at the endodontic division of KAUDH. The compilation of cases extended from January 2018 through to December 2022, encompassing a diverse array of TDIs. To maintain patient confidentiality, all personal identifiers were anonymized, and unique serial numbers were allocated to each case. The CBCT images of the anterior maxillary region were captured using a KaVo 3D Pro machine (Instrumentarium Dental, PaloDEx Group Oy, Nahkekelantie, Finland). The acquisition parameters for the CBCT were set to 89 kVp, 6 mA, a 5 x 5 cm field of view, and a voxel size of 0.085 mm (Endo-resolution mode). Utilizing the OnDemand 3D Imaging Software (Cybermed, Seoul, South Korea), reconstructed images, including sagittal, coronal, and axial sections, were extracted from the CBCT scans. For each case, nine CBCT images (three axial, three coronal, and three sagittal images at different levels) were chosen and standardized for all cases. A thorough preliminary evaluation by a maxillofacial radiologist was executed prior to initiating the experiment, ensuring the orderly sequencing of slides, consistency in radiograph interpretation, and verifying image attributes such as resolution, focus, brightness, and contrast.

The Experimental Eye-Tracking Setup

Eye-tracking data collection was facilitated through an RED-m® SMI eye-tracking device (Sensomotoric Instruments, Teltow, Germany), which was securely attached to the laptop's lower edge via a magnetic strip. The radiographs were viewed on a 15.6-inch laptop with a resolution of 1600*900 pixels via the Experiment Center software (Sensomotoric Instruments, Teltow, Germany). A total of seven distinct cases of TDIs were observed. For each case, an introductory section detailing the clinical observations and the history of the TDI was provided. Subsequently, participants were presented with a PA radiograph along with nine different views of CBCT images for each case.

Participants were situated in a carefully controlled setting, in which the environment was intentionally dimmed and free from distractions to optimize focus, and the laptop screen was positioned at eye level. The distance between the device and the observer's eyes varied from 50 to 75 cm. Participants were aligned centrally within the camera's field of view, and meticulous camera-screen calibration was undertaken to ensure precise eye movement capture, with recalibration as necessary until the right eye's accuracy value was below one. Post-experiment, tracking ratios above 80% were mandated to confirm the validity of the collected data. Participants were provided with comprehensive instructions and a consent form prior to commencement.

Assessment of Diagnosis and Management of TDIs

For each individual tooth under examination, participants were next asked about diagnosis and management, and no constraints were imposed on the duration spent on the question slides. The first question required them to identify any of the listed characteristics or traumatic features apparent in the radiographs for the specified tooth, with options of normal findings/no trauma, non-complicated crown fracture, complicated crown fracture, horizontal/oblique root fracture, lateral luxation, intrusive luxation, extrusive luxation, cortical bone fracture, thickening of the periodontal ligament, ankylosis, periapical radiolucency, internal root resorption, and external root resorption. Subsequently, participants were asked to outline their preferred management strategy for the target tooth with the possibility of selecting multiple answers from a comprehensive list of options, including no active management, clinical and radiographic follow-up, splint, reposition and splint, start conventional endodontic treatment/retreatment, vital pulp therapy, apexifications, regenerative endodontics, and tooth extraction. The experiment's reference standard was determined by two experienced endodontists who collaboratively reviewed and deliberated upon the cases. They meticulously documented the most relevant diagnosis and management for each tooth, cross-referencing with the patient's records and outcomes. The reference standard was established through a consensus decision-making process, utilizing the exact same nine CBCT sections and the complete scan.

Data Collection and Analysis

The eye-tracking data were captured in real time using the Experiment Center software. Following the data collection, BeGaze software (Sensomotoric Instruments, Teltow, Germany) was employed to conduct a comprehensive analysis of the gathered data. The results obtained from the BeGaze analysis were subsequently transferred to Microsoft Excel (version 16.66.1, Microsoft Corporation, Redmond, WA, USA) to facilitate further formatting and organization of the data. A variety of eye-tracking parameters were meticulously extracted for in-depth analysis. The parameters included were the number of revisits to specific areas of interest (AOI), entry time (mean time from the start of the image examination to the first identification of the AOI), duration of attention or dwell time (the amount of time spent looking within an AOI), and the end time (the total time spent in one image) which were all recorded through the eye-tracking software. All data pertaining to the duration of time were conveniently converted to seconds to maintain consistency and for ease of interpretation.

The responses related to diagnosis and treatment options provided by the participants were categorically dichotomized into "accurate" and "inaccurate". The primary aim was to establish a clear association between the observed eye-tracking behavior parameters and the accuracy of both diagnosis and management suggested by the participants. To analyze these associations, the Mann-Whitney test was employed, a decision influenced by the non-parametric nature of the data distribution based on Kolmogorov-Smirnov and Shapiro-Wilk tests. All statistical analyses were performed using IBM SPSS Statistics software (version 28, IBM Corp., Armonk, NY, USA). To determine the statistical significance of the findings, a 5% level of significance was set as the threshold.

Results

A comprehensive scan and evaluation were conducted on 54 cases associated with TDIs. Post a stringent screening protocol, seven teeth showcasing varied forms of TDIs were selected for the subsequent analytical phase. These selected teeth collectively covered 44 distinct areas of interest (AOIs), with each case featuring 3 to 6 AOIs, each exhibiting a diverse array of trauma and pathological conditions as shown in Table 1. After exclusion, the study included 19 endodontic postgraduate residents. In terms of diagnosis, the collective performance of all residents across all cases yielded an accurate diagnosis rate of 63%, while correct management was observed in 58.1% of instances.

Table 1. Detailed clinical and radiographic findings of cases with TDIs included in this study.

	Tooth	Age	Gender	Brief Clinical History	AOI	PD	Mobility	Percussion Pain	Palpation Pain	Cold Test	EPT
1	11	10	M	Falling 10 months ago, tooth avulsion, replanted, extra-oral time was 2 hours	-External root resorption -Open apex -Lateral luxation	3,6,3,5	Grade I	N	N	_	_
2	12	13	M	Falling 10 days ago, tooth intruded.	-Intrusion -Buccal and palatal fracture line	2,3,2,3	Grade I	+	+	_	_
3	21	14	F	Bike accident, 5 hours ago, crown fractured	-Uncomplicated crown fracture -Extrusion	2,3,3,3	Garde II	+	+	+	_
4	12	16	F	Falling, 10 years ago, crown fractured	-Uncomplicated crown fracture -Periapical radiolucency	3,5,3,3	Grade I	+	+	_	_
5	11	28	M	Car accident, 10 years ago	Mid root horizontal root fracture	2,3,2,3	Grade III	+	+	_	_
6	11	47	M	Falling from stairs, 3 days ago	Horizontal root fracture	2,3,2,3	Grade II	+	+	_	_
7	21	13	M	Patient was hit on the face, one week ago	Horizontal root fracture	2,3,2,3	Grade II	+	+	_	_

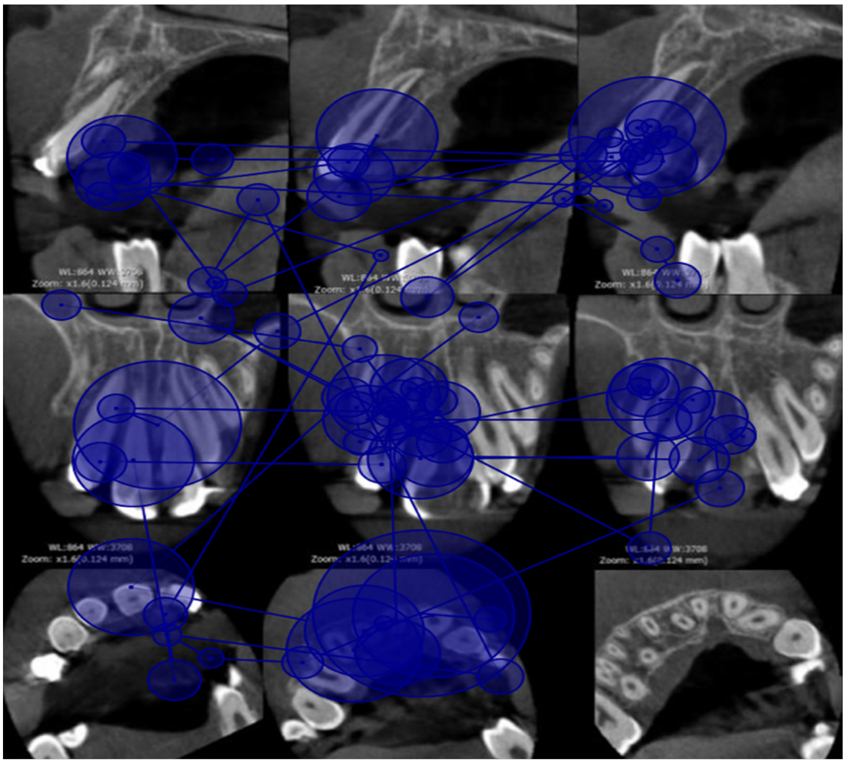
AOI: Area of Interest; PD: Probing Depths in mm (M, B, D, P); EPT: Electric Pulp Test; M: Male; N: Normal; F: Female; +: Positive Response or Pain; -: Negative Response or Absence of Pain; Mobility based on Miller's classification.

For cases that were correctly diagnosed, both the average entry and end times were higher when compared to cases incorrectly diagnosed (Table 2). This difference was statistically significant (p=0.033 for entry time, and p=0.001 for end time). On the other hand, the average attention span or dwell time between cases correctly and incorrectly diagnosed did not reach statistical significance (p=0.05). For the treatment decision-making, parallel observations were noted. A statistically significant difference in both end time and entry time was observed between cases managed accurately and those that were not (p=0.003 for end time and p=0.023 for entry time). Specifically, cases associated with accurate treatment decisions exhibited extended average entry and end times (Table 2). Conversely, the analysis did not reveal any significant difference in terms of dwell time and the number of revisits between the two groups. An example of inaccurate diagnosis and management is shown in Figure 1, while an example of accurate diagnosis and management is shown in Figure 2.

Table 2. The mean and standard deviation for entry time, end time, dwell time (in seconds) and revisits (counts) of both diagnostic and management groups.

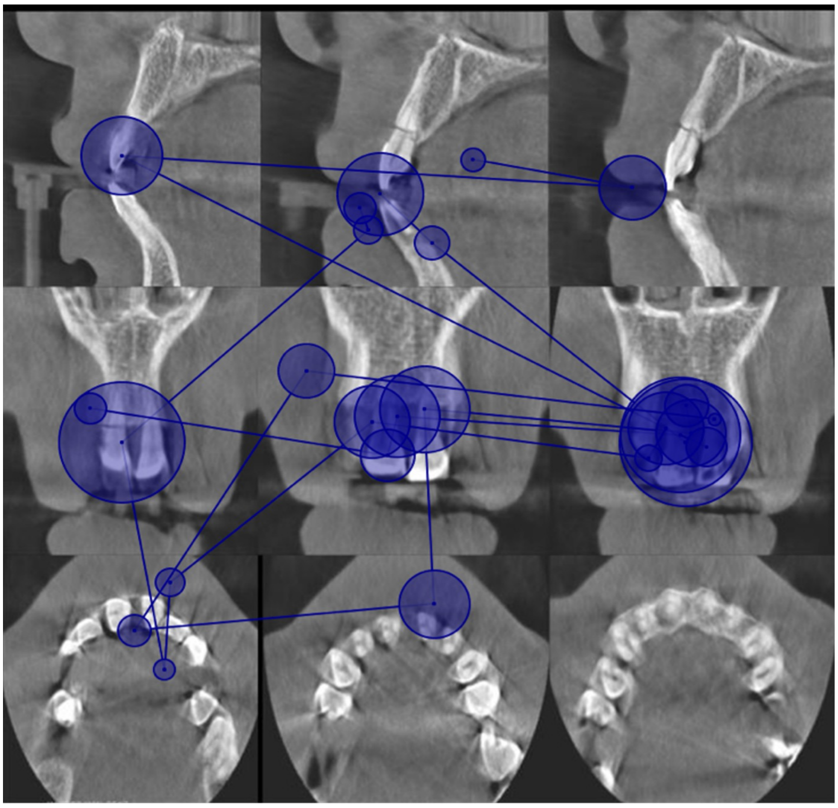
Variables	Entry Time	End Time	Dwell Time	Revisits
Diagnosis				
Correct	7.32 (± 0.60)	24.37 (± 1.09)	1.63 (± 0.13)	1.84 (± 0.18)
Incorrect	5.15 (± 0.91)	19.15 (± 1.97)	1.72 (± 0.20)	1.92 (± 0.25)
p-value#	0.033*	0.001*	0.050	0.204
Management				
Correct	7.17 (± 0.62)	24.89 (± 1.3)	1.67 (± 0.14)	1.9 (± 0.18)
Incorrect	6.02 (± 0.89)	19.5 (± 1.4)	1.64 (± 0.20)	1.76 (± 0.27)
p-value#	0.003*	0.023*	0.175	0.366

#Mann-Whitney U test; *Statistically Significant.



Tooth #12 (Case 2, Table 1) displayed signs of intrusion along with numerous fracture lines on both the buccal and palatal plates adjacent to #12. In this eye-tracking figure, larger blue circles represent extended periods of fixation on the Area of Interest (AOI). While this image shows prolonged fixation on the AOI, it is important to note that most participants did not accurately determine the diagnosis and management for this specific case.

Figure 1. Accurate diagnosis and management achieved.



Teeth #11 and #21 (Case 6, Table 1) displayed horizontal root fractures. Despite the brief fixation time on the Areas of Interest (AOIs), indicated by small blue circles, the participants successfully identified the correct diagnosis and management in this case. While the fixation time on the AOIs was limited, the participants spent a considerable amount of time scanning the entire image, and it took a longer time to locate the AOIs initially. These details, while not visually represented in the image, played a significant role in the accurate clinical decision-making observed in this scenario.

Figure 2. Accurate diagnosis and management not achieved.

Discussion

Eye-tracking technology has been employed to evaluate how dental professionals interpret visual data and enhance their skills in analyzing radiographic images [16]. There has yet to be any reported research on the application of eye-tracking to CBCT scans in the context of TDIs. This research aimed to explore the relationship between visual parameters and precise diagnostics and management for TDIs, thus providing a deeper insight into the intricate link between visual observation and cognitive processing, aiming to enhance the quality of diagnosis and treatment strategies. The study's results indicated a significant association between longer entry time and end time on a CBCT image with more accurate diagnoses and treatment decisions, as captured through eye-tracking technology.

When a correct diagnosis was achieved, endodontic residents dedicated a significantly extended time to analyze all the CBCT scans, which displayed a notable longer time until the AOIs were identified. This suggests a correlation where an increased amount of time spent on a CBCT scan enhances the thoroughness of the examination, subsequently reducing the probability of overlooking an accurate diagnosis. This observation aligns with previous research presenting a positive relationship between extended viewing time and a comprehensive evaluation of the scans [18]. On the contrary, one study highlighted that more experienced observers could identify abnormalities more quickly in panoramic radiographs than their less experienced counterparts. However, this study did not explicitly delineate the relationship between visual parameters and diagnostic accuracy [25].

The enhanced precision afforded by CBCT extends beyond diagnosis, impacting treatment planning significantly. Numerous studies have highlighted that CBCT substantially improves confidence and accuracy in both diagnosing and formulating treatment plans for TDIs, showing clear advantages over traditional radiography [11,12]. In the current study, a correlation was observed between prolonged time spent within an image and the selection of an accurate management and treatment decision. This phenomenon can be attributed to the fact that a precise diagnosis often precedes the formulation of accurate management. Previous research has supported this link, demonstrating a consistent association between accurate diagnostics and subsequent treatment planning in CBCT scans for various endodontic conditions [11,13,26]. A comprehensive systematic review investigated the relationship between visual search patterns and diagnostic performance and accuracy within medical radiology. The review concluded that visual attention, search patterns, eye movement characteristics of expert practitioners, and the implementation of visual search strategies significantly influence diagnostic outcomes [27]. This review underscores the critical role of visual parameters in both diagnostic and treatment planning processes.

Regarding fixation time (the duration spent focusing on a specific AOI), and the frequency of revisits to the AOI, this study did not identify a significant correlation between these parameters and either accurate diagnoses or management. While one eye-tracking study demonstrated that neurologists increased their fixation time on CT scans showing pathologies such as hemorrhages and cerebrovascular accidents [18], other research has suggested that fixation time is not a crucial factor for expertise [25]. Consistent with our results, various studies have reported that expert radiologists quickly focus on abnormalities in chest X-rays and skeletal images, leading to shorter durations spent on fracture sites, chest abnormalities, and mammograms. This implies that experienced observers tend to make swift decisions and have a higher confidence level in their conclusions [20-22]. Additionally, another study found no correlation between fixation time and correct diagnoses across a range of images with different paediatric dental pathologies, with the exception of anterior carious lesions [28]. Furthermore, another study showed that cases where participants fixated extensively on a particular AOI failed to arrive at the correct diagnosis [16]. These previous findings, aligning with the results of the current study, help to elucidate why fixation time may not be a pivotal parameter in the image analysis of pathologies, suggesting that other factors play more significant roles in the diagnostic and treatment planning processes.

In this study, to create a more realistic scenario for participants, details on the clinical presentation, comprehensive trauma history, and corresponding PA radiographs were provided. The influence of clinical history on observers' radiographic interpretations has been documented in various studies. Research has demonstrated that the inclusion of clinical history enhances accuracy in detecting lung nodules, identifying fractures, and other findings [29]. In dentistry, the availability of a detailed clinical history has been shown to significantly impact the detection of pathologies via CBCT, leading to improved accuracy in performance [30]. Eye-tracking studies have revealed that when specific target teeth are highlighted, observers devote more time and attention (fixations) to those teeth. Conversely, when no specific guidance is provided, observers tend to spend more time and have more fixations on all teeth present in the radiograph [31]. However, it is worth noting that some research suggests presenting clinical history prior to radiographic interpretation may bias observers, potentially directing their focus and perception toward specific regions [32]. One particular study reported that endodontists identified 25% fewer findings on CBCT scans when provided with a history and symptoms associated with the target tooth, potentially overlooking other pathologies [33]. Despite that, this study opted to include clinical history to ensure a more clinically realistic context for the participants.

The present study employed non-trackable multiple-choice question slides to minimize potential distractions. This approach stands in contrast to the think-aloud protocol, which can disrupt participants by requiring them to shift their gaze from the screen to document their findings [24]. Additionally, this study imposed no time restrictions on radiograph examination, allowing participants ample opportunity to thoroughly study and analyze the images at their own pace. This design choice aimed to mirror real-world clinical settings, where practitioners can take the necessary time to ensure accurate and comprehensive image analysis.

The current study has several limitations that warrant acknowledgment. First, there may be an introduction of bias due to the provision of fixed CBCT sections for each traumatic tooth, as opposed to allowing observers to navigate through 3D CBCT scan volumes. This approach might have inadvertently guided participants toward specific AOIs. To mitigate this, consistency was ensured by utilizing specific sections at precise measurements for all scans. Although navigating through 3D scans would present a more authentic and precise experience, the chosen protocol addresses the standardization challenge associated with eye-tracking during free scrolling through CBCT scans. Second, the study recorded specific parameters (entry time, end time, dwell time, and revisits) and analyzed their correlation with diagnostic and treatment outcomes. While these parameters can provide an insight into the cognitive processes of the participants, it is crucial to note that a direct relationship between these parameters should not be guaranteed. Third, the study included a certain number of postgraduate endodontic residents, a figure consistent with previous reports [10,24,26]. Nonetheless, a larger sample size could have helped to account for variations in expertise levels among the residents. Furthermore, while all residents had training in CBCT and advanced trauma cases, the sample might not perfectly represent endodontists. However, the inclusion of numerous residents enhances the study's external validity [2,13,14,26]. Finally, the questionnaire provided to participants included a list of criteria, that might have influenced their attention, leading to a more thorough evaluation of CBCT imaging. This aspect of the study design could have affected participants' perceptions and confidence levels, potentially impacting their diagnostic and treatment decision-making processes [11].

Conclusion

The research identifies clear links between specific eye-tracking parameters and the precision of diagnoses and management. In which more time spent reviewing comprehensive CBCT scans (analyzing preselected sequential images across different planes) and longer times to detect pathology correlate with more accurate diagnoses and treatment decisions. These findings suggest that focused training on these skills could significantly boost diagnostic and management accuracy among endodontic professionals. Future studies should involve larger participant groups and a variety of pathologies to validate these results further.

Authors' Contributions

SSZ	https://orcid.org/0000-0001-5016-3690	Conceptualization, Methodology, Formal Analysis, Investigation, Writing - Original Draft and Writing - Review and Editing.
All authors declare that they contributed to critical review of intellectual content and approval of the final version to be published.		

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None.

Conflict of Interest

The authors declare no conflicts of interest.

Data Availability

The data used to support the findings of this study can be made available upon request to the corresponding author.

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