Exploring the Impact of Expertise, Clinical History, and Visual Search on Electrocardiogram Interpretation

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Background: *The primary aim of this study is to understand more about the perceptual-cognitive mechanisms underpinning the expert advantage in electrocardiogram (ECG) interpretation. While research has examined visual search processes in other aspects of medical decision making (e.g., radiology), this is the first study to apply the paradigm to ECG interpretation. The secondary aim is to explore the role that clinical history plays in influencing visual search behavior and diagnostic decision making. While clinical history may aid diagnostic decision making, it may also bias the visual search process.* ***Methods:*** *Ten final-year medical students and 10 consultant emergency medics were presented with 16 ECG traces (8 with clinical history that was not manipulated independently of case) while wearing eye tracking equipment. The ECGs represented common abnormalities encountered in emergency departments and were among those taught to final-year medical students. Participants were asked to make a diagnosis on each presented trace and report their level of diagnostic confidence.* ***Results:*** *Experts made significantly faster, more accurate, and more confident diagnoses, and this advantage was underpinned by differences in visual search behavior. Specifically, experts were significantly quicker at locating the leads of critical importance. Contrary to our hypothesis, clinical history had no significant effect on the readers' ability to detect the abnormality or make an accurate diagnosis.* ***Conclusions:*** *Accurate ECG interpretation appears dependent on the perceptual skill of pattern recognition and specifically the time to fixate the critical lead(s). Therefore, there is potential clinical utility in developing perceptual training programs to train novices to detect abnormalities more effectively.* ***Key words:*** *gaze behavior; eye movements; holistic processing; diagnostic accuracy.* ***(Med Decis Making 2014;34:75–83)***

Electrocardiogram (ECG) interpretation is a key clinical skill, particularly in acute and emergency medical settings. However, recent reviews of studies assessing the severity of interpretation errors have reported that 4% to 33% of interpretations contained errors of major importance.[1,2] Furthermore, there is little published evidence supporting quantitative standards for attaining and maintaining competency in interpreting ECGs.[2] The current study therefore seeks to add to this evidence base by furthering our understanding of the perceptual-cognitive processes underpinning ECG interpretation expertise. Specifically, the research is the first to investigate how clinicians scan ECG traces in order to extract the pertinent information that supports their diagnostic judgments and the first to explore how clinical history can influence this decision-making process.

Common understanding would lead us to expect that experts in medical interpretation would make quicker and more accurate diagnoses than their novice counterparts.[2] The mechanisms behind this performance advantage are less obvious. However, it has been reported that accurate medical image interpretation is the culmination of a 2-stage process that depends on both the perceptual skills (they must be able to search the image and detect the abnormality)

Received 26 November 2012 from College of Life and Environmental Sciences, University of Exeter, Exeter, UK (GW, JB, MRW); and Emergency Department, Royal Devon and Exeter NHS Foundation Trust, UK (AA, AH). Revision accepted for publication 6 May 2013.

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DOI: 10.1177/0272989X13492016

and the decision skills of the reader (once the abnormality is focused upon, readers must interpret it). Errors in diagnosis can happen at both of these stages.[3–6]

While perceptual skill has not been examined in ECG interpretation, there is a body of literature in radiology that has explored how experts extract information from radiographs to detect abnormalities.[3–7] For experts, abnormal features of the image that do not conform to their a priori expectations of what constitutes normality are detected almost immediately and are then scrutinized using foveal vision (the area of the eye allowing for maximum visual acuity) to aid interpretation.[7] However, as novices have not built up this knowledge base to form such a priori expectations, these perceptual skills cannot be used. Instead, these readers are left to exhaustively search the image with foveal vision in a step-by-step nature to discover possible abnormalities. Such a visual strategy is inefficient, time-consuming, and prone to errors.[4]

Once an abnormality in the image has been detected, the reader must interpret it and make an appropriate diagnosis. A potentially important source of additional information used to guide the diagnostic process is the clinical history provided. Research has suggested that clinical history can improve diagnostic accuracy in ECG interpretation by as much as 4% to 12% compared with no history,[8] although this has been disputed.[9] However, clinicians with less training do seem to be influenced by the history to a greater extent than are more experienced readers.[8,9] This information suggests that less experienced readers may make more accurate interpretations when they know the clinical context of the ECG.[3] To date, no studies have explored whether and how clinical history influences visual perception and diagnostic performance in ECG interpretation. Does this information guide and enhance the perceptual skill of the reader? Or is it used in the second, decision-making stage of diagnosis? Similar research has been carried out in various disciplines of radiology where the availability of clinical history has been associated with enhancing the perceptual skill of the reader, making for faster detection of areas of abnormality and better performance.[10]

The primary objective of the current work is therefore to understand more about the expert advantage in ECG interpretation. The secondary objective is to assess the influence of case history on perception and diagnostic performance. In line with similar studies from radiology, we expected that experts would be quicker, more accurate, and more confident in their diagnoses compared with novices and that this superior performance would be underpinned by fundamental differences in the perceptual skill of each group. Specifically, experts were expected to detect the critical leads (the area of abnormality) more quickly than their novice counterparts.[11] Finally, we expected that availability of clinical history for cases would improve diagnostic performance, particularly for novices, by guiding the readers to critical leads faster.[10]

MATERIALS AND METHODS

Participants and ECG Traces

Twenty participants (10 fifth-year UK medical students and 10 consultant emergency department physicians from the UK) volunteered to partake in the study, which ran from November 2011 to July 2012. All participants gave written consent prior to testing, and all procedures were approved by the university and NHS ethics committees prior to commencement. Each participant was presented with 16 clinical cases of normal (n = 3) and abnormal ECG traces (n = 13); half were preceded by a brief clinical history that was concordant with but not diagnostic of the abnormality (consisting of age, sex, and presenting complaint), and half presented with no history (see Table 1). History was not randomized, and the same history was always shown with the same case across both groups. Each ECG was selected from a large database of images used for training medical students by a consultant emergency physician who was not on the research team. Traces were chosen on the premise that they were accurate representations of common abnormalities presenting to emergency departments, such as myocardial infarction. They were also abnormalities that all graduating junior doctors should be expected to recognize based on their teaching curriculum. All images were standardized in size to fit Microsoft PowerPoint presentation slides; all patient information was removed prior to testing; and each participant was presented with the traces in the same randomized order (Table 1).

Experimental Setup and Procedures

Participants attended individually, and the experiment took place in a quiet room. Participants were fitted with an Applied Science Laboratories (ASL; Bedford, MA) Mobile Eye gaze registration system that measures eye line of gaze at 25 Hz with respect

Table 1 Characteristics of Stimulus Cases and Their ECGs

ECG	Clinical History	Critical Lead(s)	Diagnosis	Also Accepted
1	No history	II, III, AVF	Inferior MI[a]	Inferior ST elevation with inferior Q waves and ST elevation V3. Recent or previous inferior MI.
2	75-year-old male following a collapse	Rhythm strip	First-degree AV block	AV block
3	No history		Normal	
4	85-year-old with palpitations	Rhythm strip	Atrial fibrillation	
5	No history	Rhythm strip	Atrial fibrillation	Atrial fibrillation with lateral T-wave inversion and ventricular ectopic
6	16-year-old following a collapse	Rhythm strip	Long-QT	Prolonged QT
7	20-year-old male with chest pain		Normal	Normal with BER, LVH
8	55-year-old male with chest pain	II, III, AVF	Inferior MI	Acute inferior STEMI with reciprocal change or lateral ischemia
9	No history	II, III, AVF	Inferior/inferolateral MI	Acute inferolateral STEMI
10	50-year-old female with chest pain	II, III, AVF	Inferior MI	Acute inferior STEMI with posterior involvement or reciprocal change in V2
11	No history	V1, V2, V3, V4, V5, V6	Anterior/anteroseptal MI	Old or recent anteroseptal MI with LAD or LAHB. LBBB.
12	Asymptomatic 19-year-old Royal Marine		Normal	LVH, peaked or large T waves. High takeoff or BER.
13	No history	Rhythm strip	First-degree AV block	AV block
14	60-year-old diabetic with chest pain	V1, V2, V3, V4, V5, V6	Anterior MI	Old or recent anterior MI, LV aneurism
15	No history		Normal	High takeoff in V3. Minor nonspecific intraventricular delay, sinus arrhythmia.
16	No history	Rhythm strip	Long QT	Prolonged QT

Note: AV = atrioventricular; BER = benign early repolarization; LAD = left axis deviation; LAHB = left anterior hemiblock; LBBB = left bundle branch block; LV = left ventricular; LVH = left ventricular hypertrophy; MI = myocardial infarction; STEMI = ST-segment elevation myocardial infarction.

a. We included 6 cases of MI, because cardiac ischemia (notably STEMI) is one of the most important immediate ECG diagnoses made in the emergency department and we therefore felt that this should be well represented. However, each varied considerably in the areas of extension present.

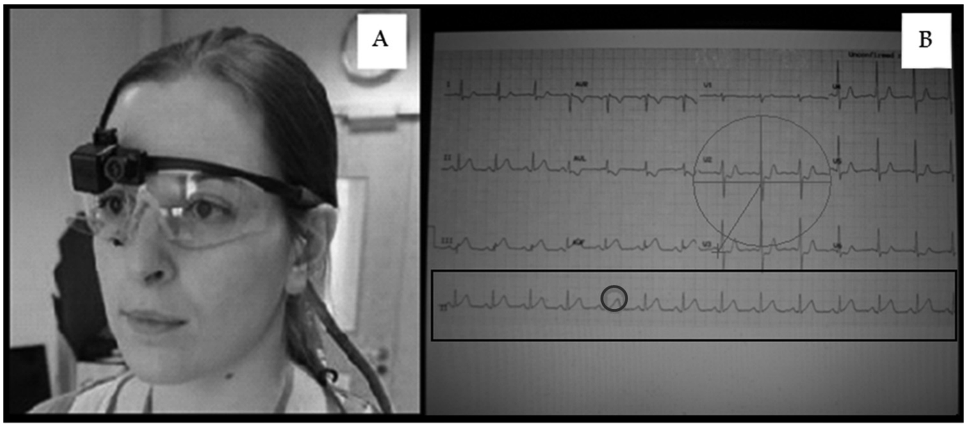

Figure 1 *The ASL Mobile Eye gaze registration system (A) and a screen grab of the video developed for subsequent analyses (B), showing the gaze cursor (the small circular cursor on the rhythm strip of the ECG trace) and the rectangular Lookzone created around the rhythm strip.*

to eye and scene cameras mounted on a pair of glasses enabling normal head movement (see Figure 1A). The system has been used to explore visual expertise in other areas of medicine (e.g., radiology[7] and surgery[12]) and consists of a recording device (a modified digital video recorder) and a laptop (Dell Inspiron6400) with Eyevision (ASL) software installed. A circular cursor, representing 1° of visual angle with a 4.5-mm lens, indicating the location of gaze in a video image of the scene (spatial accuracy of $\pm$ 0.5° visual angle; 0.1° precision) was recorded for analysis (see Figure 1B). Participants sat 50 $\pm$ 10 cm away from a second laptop (High-Grade with 15-inch screen) that displayed the ECG traces. The eye tracker was calibrated by asking participants to focus on a 9-point numbered grid displayed on the screen.

Once the system was calibrated, participants were given written instructions on the screen about the test before being presented with the ECG traces. After each trace and when they were ready to make a diagnosis, they were asked to click the mouse (removing the ECG from view to signal the end of the trial) and state their diagnosis and the level of confidence in that diagnosis from 0 (not at all confident) to 10 (extremely confident). Between each trace, participants performed a brief calibration check. The experiment was completed when participants had completed all 16 traces.

Analysis and Statistical Procedures

Participants' diagnoses were recorded by author 2, tabulated, and then blindly and independently marked by authors 3 and 4 according to a previously agreed marking scheme for correct and acceptable ECG diagnoses (see Table 1). The reports were marked using a binary scale, with 1 for a correct diagnosis and 0 for an incorrect diagnosis. A total diagnostic accuracy score (out of 8) was calculated for each participant for trials with and without clinical history, and agreement between 2 markers was almost perfect: kappa = 0.98, $P < 0.001$.[13] In this manner, case order was confounded with clinical history, and we acknowledge this as a potential weakness in the research design.

Gazetracker analysis software (Eye Response Technologies, Charlottesville, VA) was used to perform post hoc analyses on the eye movement data. Onset of each trial began when each trace first appeared and ended when each ECG disappeared. During this period, Gazetracker automatically generated search rate data (number of fixations per second). Lookzones (areas of interest) were created around the most important and informative lead(s) on each trace. These ''critical leads'' were identified and agreed upon by 2 experienced clinicians as the most pertinent area of the trace to diagnose the abnormality. Gaze data videos were played at $\geq$40 Hz so that Lookzones could be manually manipulated, ensuring they remained on the relevant lead(s) despite participants' head movements. Gazetracker measured the time from trial onset to the first dwell fixation (when participants focused on the critical leads for $\geq$1000 ms). This temporal threshold was applied, as previous research has suggested that it can distinguish between recognition and decision errors in medical image interpretation,[14] and this has been used in studies that have explored expertise in detecting

Table 2 Mean Group Differences in Performance and Gaze Measures

	Performance			Gaze		
	Diagnostic Accuracy	Diagnosis Speed	Diagnosis Confidence	Time to Dwell on Abnormality	Time from Dwell to Diagnosis	Search Rate
Novices	2.90 (1.68)	46.22 (14.69)	5.41 (1.36)	6.62 (4.14)	37.29 (17.94)	2.40 (0.14)
Experts	6.05[a] (1.17)	23.20[a] (8.63)	8.27[a] (0.89)	3.43[b] (2.01)	19.52[b] (8.48)	2.40 (0.14)

a. $P < 0.001$. b. $P < 0.01$.

abnormalities in pulmonary nodules,[15] skeletal fractures,[16] and diverse chest abnormalities.[17] Finally, the time from the first dwell on the critical lead(s) to subsequent diagnosis was measured to index the speed of the decision-making process after the abnormality had been detected.

Data were analyzed using 2 × 2 multivariate analysis of variance (MANOVA) (group × clinical information) for accuracy scores, confidence, diagnosis time, search rate, the time to dwell on the critical leads, and the time from this dwell fixation to eventual diagnosis. Significant effects were followed up with 1-way ANOVAs. Effect sizes were calculated using partial eta-squared (η_p^2).

RESULTS

MANOVA revealed significant group differences, Wilks' $\lambda = 0.15$, $F(6,31) = 29.06$, $P < 0.001$, $\eta_p^2 = 0.85$, and these data are presented in Table 2. Specifically, experts were significantly more accurate, $F(1,36) = 47.06$, $P < 0.001$, $\eta_p^2 = 0.57$; were significantly quicker, $F(1,36) = 36.19$, $P < 0.001$, $\eta_p^2 = 0.50$; and were significantly more confident, $F(1,36) = 61.60$, $P < 0.001$, $\eta_p^2 = 0.63$, in their diagnoses compared with novices.

Furthermore, these performance differences were also reflected in significant differences in the eye movement data. Experts were significantly faster, $F(1,36) = 9.66$, $P < 0.01$, $\eta_p^2 = 0.21$, to dwell on the critical leads compared with novices and also faster, $F(1,36) = 17.12$, $P < 0.001$, $\eta_p^2 = 0.32$, at making a diagnosis once the abnormality had been detected compared with novices. No significant differences were evident for search rate, $F(1,36) = 0.00$, $P = 0.99$ (see Table 2).

MANOVA revealed no significant main effect for history, Wilks' $\lambda = 0.91$, $F(6,31) = 0.50$, $P = 0.80$, and the interaction between group and history was also nonsignificant, Wilks'$\lambda = 0.92$, $F(6,31) = 0.43$, $P = 0.85$, for both performance (Figure 2) and eye movement variables (Figure 3).

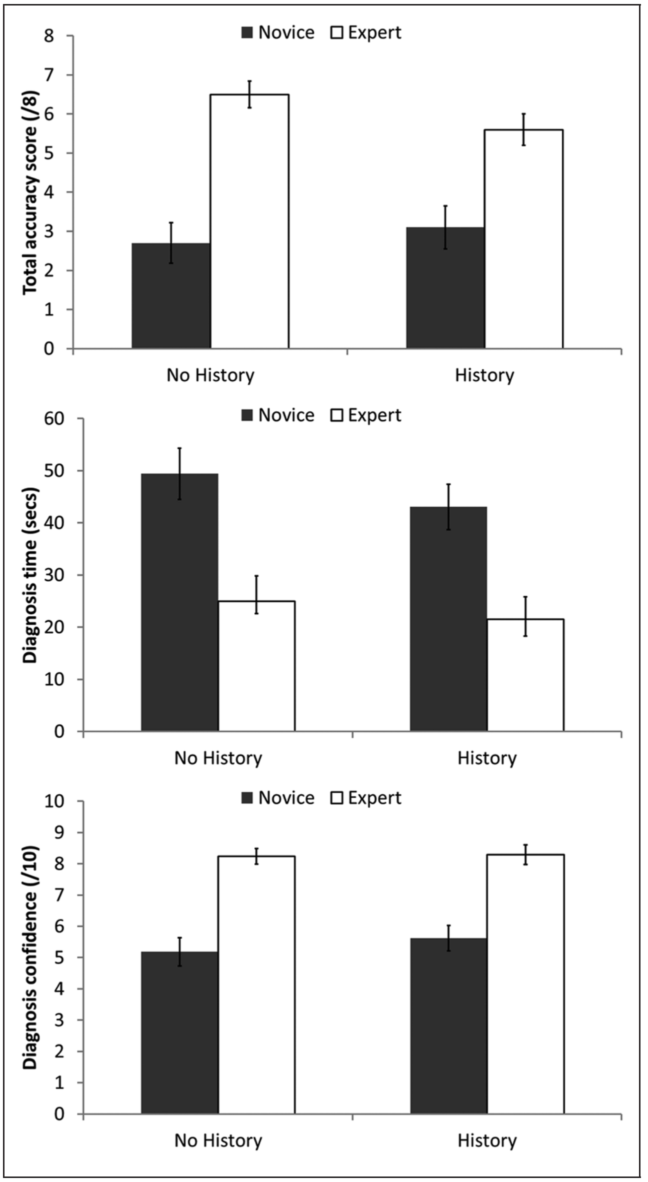

Figure 2 Performance data showing the mean (± standard error of measurement) accuracy scores (top); diagnosis time (middle); and confidence scores (bottom) for novices and experts with and without clinical history.

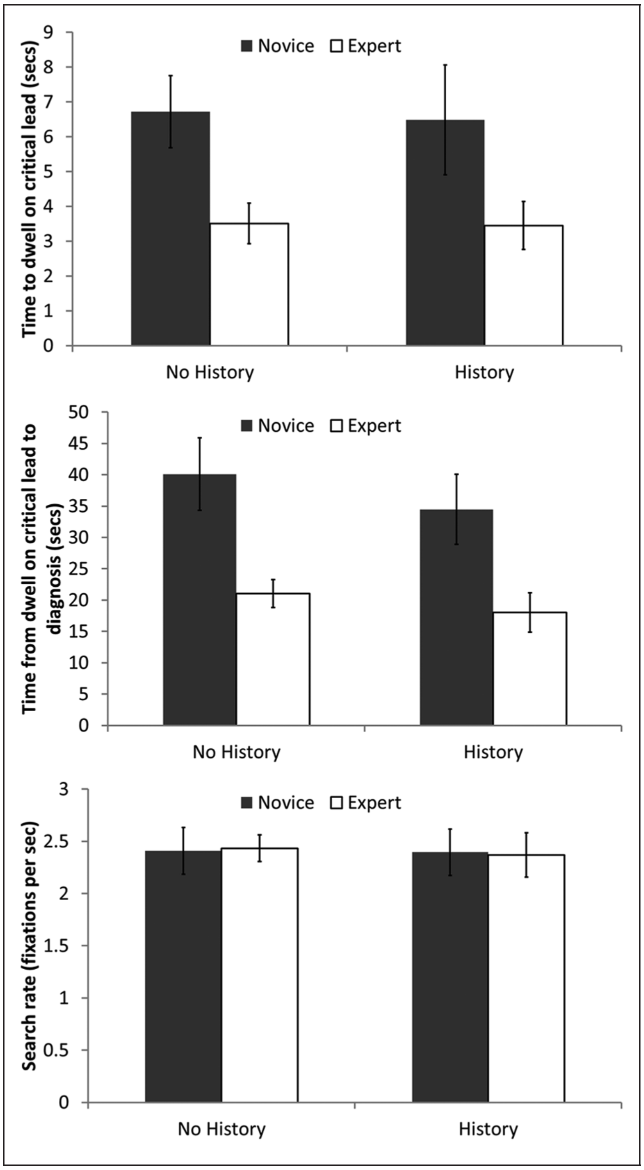

Figure 3 Eye movement data showing the mean (± standard error of measurement) time to dwell on the critical lead(s) (top); the time from this dwell fixation to eventual diagnosis (middle); and search rate (bottom) for novices and experts with and without clinical history.

DISCUSSION

This study is the first to have explored the perceptual and decision-making skills of expert and novice readers of ECGs in order to better understand the mechanisms underpinning expertise. It is also the first to explore the role that clinical history plays in guiding visual search behavior and influencing diagnostic performance in this critical medical decision-making process. While it may be pertinent to assume that experts, by definition, possess superior skill compared with their novice counterparts, there is a paucity of evidence that addresses the precise mechanisms behind this performance advantage. Therefore, research comparing perceptual and decision-making skills of expert and novice readers is vital so that the processes underpinning expertise can be outlined and eventually used to guide the development of training for novices.

Performance

As predicted, experts revealed a significant performance advantage in ECG interpretation over their novice counterparts. Experts were twice as accurate, twice as quick, and one and half times more confident in their diagnoses than novices (see Table 2). However, the availability of clinical history did not significantly improve any performance variables in the manner that we predicted (Figure 2 and 3). An explanation for this finding could be that the brief history provided in this study (patient's age and chief complaint) is less comprehensive than the clinical history provided in some real-world scenarios, possibly diluting its influence on diagnostic performance. In fact, a common difficulty with studies that have explored clinical history's influence on diagnostic accuracy is the lack of an agreed definition of what constitutes a history. However, emergency department physicians are frequently asked to review ECGs with only a brief history or description of the presenting complaint in order to consider whether any immediate action is needed as part of the triage process. We therefore feel that the clinical history given in the current study is representative of at least some in vivo situations.

Expertise in Perception and Decision Making

These group differences in diagnostic performance were underpinned by significant differences in the perceptual ability of each group. Specifically, experts were twice as quick as novices to fixate and dwell attention on the critical lead(s) (Table 2). However, there was no difference in the general way that the traces were scanned (search rate; Table 2). Taken together, these gaze results suggest that the experts' ability to more quickly locate the critical leads is not due to a faster search of all the information present but, rather, to a more discriminatory strategy that enables them to quickly identify the critical

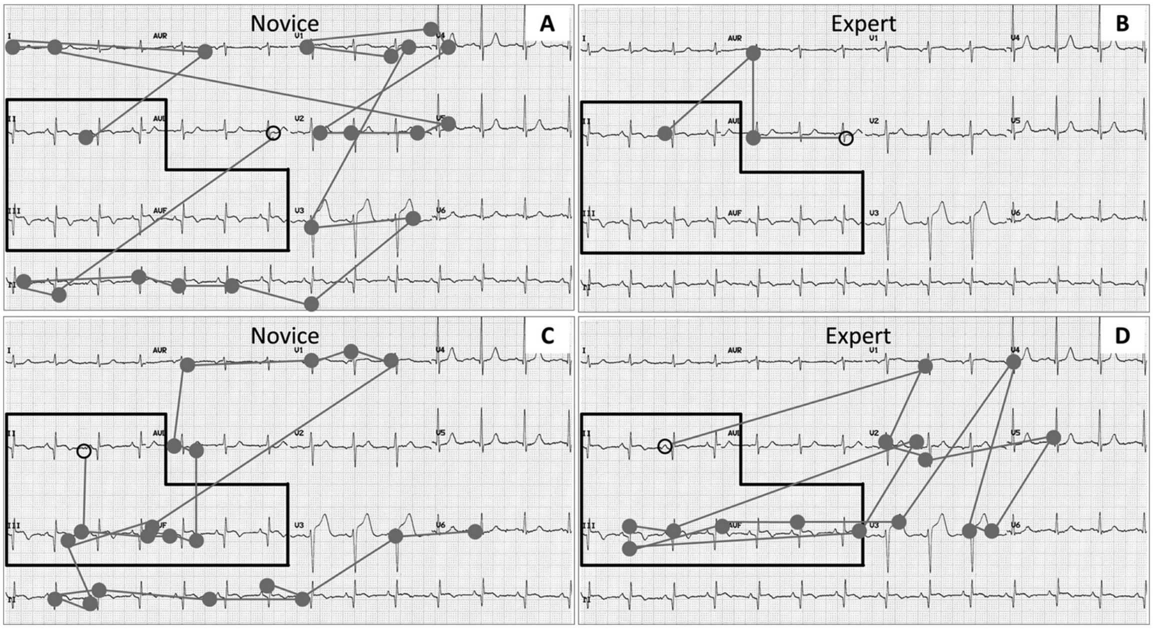

Figure 4 *A schematic representation of the scan path of dwell fixations of the worst (novice) and best (expert) performer, in the interpretation of case 1 (inferior MI; see Table 1). Traces A and B represent the scan path in the initial* perceptual phase*—from trial initiation until the first dwell on the critical leads—for the novice and expert, respectively. Traces C and D represent the* decision-making phase*—the scan path from this first dwell on the critical leads until the diagnosis is made—for the novice and expert, respectively. The black circle signifies the first dwell fixation in each trace, and each gray circle represents subsequent dwell fixations. The black box outlines the 3 critical leads that provide the discriminatory information about the abnormality (i.e., the relevant Lookzone). The novice (A) took 30.27 seconds to first dwell on the critical leads, whereas the expert's (B) superior pattern recognition allowed him to make his first dwell after only 4.74 seconds. Once this abnormality was focused upon, the novice (C) took a further 54.62 seconds to make the correct diagnosis, whereas the expert (D) took only 20.17 seconds. Note that the way in which the trace was searched in general (fixations per second) was similar for both the novice (2.46) and the expert (2.38).*

information while ignoring less relevant information on the trace. In effect, experts appear to make an initial global or holistic impression upon image onset, without the need for an exhaustive visual search strategy[4] (see Figure 4). The results therefore provide further support for the contention that expertise in medical image interpretation is related to improved pattern recognition.[11] In the first few seconds of the initial perception phase, the expert appears to notice possible perturbations, or suspicious (abnormal) features that do not conform to their a priori expectations of what a normal trace looks like.[18]

Experts were also significantly faster to make a diagnosis after dwelling on the critical lead(s). This quicker decision-making process is thought to be reflective of experts' superior knowledge and experience of both normal and abnormal traces, which allows them to act with accuracy, speed, and confidence once their advanced perceptual skills have successfully located the abnormality. Such superior speed and confidence in diagnosis are likely to allow greater time for reflection and innovation in problem solving, which in turn allows the expert to focus on the relevant information while dismissing irrelevant information.[19] By way of illustrating this point, Figure 4 presents schematic representations of the visual processes of an expert and a novice interpreting one of the presented traces (an inferior myocardial infarction). As well as the differences in overall speed of diagnosis, it is noticeable how much more exhaustive the novice's search of the trace is, particularly in the initial perception phase.

Furthermore, the expert seemed to be cross-referencing the ST segments of the inferior leads with those of the chest leads (Figure 4D), presumably to confirm that there were ST elevations (in II, III, AVF) compared with other leads and to look for reciprocal changes in the chest leads. In comparison, the novice (Figure 4C) seems to have randomly scanned the whole ECG trace. While these scan path differences are not representative of the whole sample (there were a number of idiosyncratic differences even among experts, which made a quantitative analysis impossible), they do suggest that a 2-stage model of medical image interpretation may be overly simplistic. Other theoretical models, which draw less of a distinction between the 2 phases, may better explain the potentially reciprocal and interdependent relationship between detecting (perception) and diagnosing (decision making) abnormalities in ECGs,[20] particularly when information (such as clinical history) can distort such judgments.[21]

Despite such concerns, it is clear that the experts do exhibit a perceptual advantage over their novice counterparts that at least partially explains how fast they detect an abnormality. While it may be simplistic, such knowledge may help educators to eventually develop more effective training in ECG interpretation to expedite the learning process in novices. Specifically we would encourage any intervention that helps novice performers to develop such perceptual skills. In fact, research from radiology has suggested that novices should be exposed to a greater number of clinical cases that lie within the parameters of normality in order to develop the pattern recognition skills needed to efficiently detect abnormalities.[6] The rationale for such training is that readers of medical images can only detect *abnormality* if they have knowledge or a mental representation of what constitutes *normality*.[18] Thus, as clinicians acquire more knowledge about the normal appearance of images, or the relative parameters of normality, they should begin to detect abnormalities in a more efficient and effective manner. Research in mainstream psychology supports this contention that an enhanced ability to discriminate between stimuli is a consequence of the right kind of experience with the right kind of stimuli (i.e., perceptual learning).[22]

Alternatively, recent evidence has suggested that the detection rates of novice radiologists can benefit from viewing the eye movements of more experienced performers in pulmonary nodules detection,[23] and we have also shown that such training can have a positive impact on laparoscopic surgical performance.[24,25] It is therefore possible that novice readers of ECGs may experience similar performance benefits after being exposed to the visual behaviors of more experienced readers. While both interventions require a significant amount of further empirical investigation, we feel that studies that highlight the possible mechanisms behind expertise in this task, such as the current one, provide a critical insight into the direction and focus of such work.

Effects of Clinical History

Contrary to our initial hypotheses, the availability of clinical information had no significant effect on how quickly participants focused on the critical lead(s) or how fast they were to make a diagnosis once they had focused on the abnormality. The nature of clinical history in ECG interpretation compared with other medical disciplines might explain this unexpected finding. For example, in skeletal radiology, case history regarding the nature of an injury and the patient's self-reported area of discomfort are expected to have a greater influence on how a clinician scans the image for potential fractures or abnormalities. In ECG interpretation, it is difficult for patients or the history they provide to localize areas of abnormality in the same manner, leaving practitioners to perform a retrospective ''matching'' of their ECG interpretation with their knowledge of presented symptoms and other predisposing factors such as age.[26] Taken together, these findings support those of other researchers who have also suggested that clinical history does not affect the diagnostic accuracy of clinicians in ECG interpretation.[9] However, as case order and clinical history were not systematically randomized (see Limitations below), these conclusions should be viewed with a degree of caution.

Limitations

While the results of the current study are interesting and represent the first exploratory examination of the perceptual processes behind ECG interpretation, limitations concerning the lack of randomization of case order and history were present in the research design. All participants were shown the clinical cases in the exact same order, so there is potential for fatigue or learning effects to be present in latter cases. Furthermore, as case history was not randomized (each case was not presented with and without case history), it is very difficult to truly measure the additional contributing effect of the availability of this clinical information. Therefore, we advise that these results to be interpreted with caution. However, the primary focus of this study was to explore differences between expert and novice interpreters. We therefore felt that presenting both groups with exactly the same clinical information was the most efficient way to explore between-group differences. It is clear that future work should address these issues in order to test the contribution of clinical history more comprehensively and should also explore the impact of discordant history on visual search behavior and diagnostic performance in ECG interpretation.

CONCLUSIONS

This study has highlighted several important factors that elucidate the mechanisms by which experts exert their superiority in diagnostic accuracy and shed light on how all participants, regardless of expertise, use clinical history in ECG interpretation. Put simply, the conclusions from this study are twofold. First, experts have superior pattern recognition skills that provide them with a diagnostic advantage when detecting abnormalities in ECG traces. Second, a brief clinical history does not appear to influence the way in which the reader scans the image or the speed or accuracy of resultant diagnoses. It is accepted in the medical image interpretation literature that exploring and recognizing the differences between experts and novices are fundamental in helping to guide the development of evidence-based training.[19] It is therefore hoped that this study might act as a springboard for the formulation of such targeted interventions. In fact, similar research has been an important forerunner to the development of successful evidence-based training techniques in other areas of medical training, such as laparoscopic surgery.[24,25]

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