New Interface Metaphors for Complex Information Space Visualization: an ECG Monitor Object Prototype

Stan Kaufman[1,2], Ivan Poupyrev[2], Edward Miller[2], Mark Billinghurst[2], Peter Oppenheimer[2], Suzanne Weghorst[2]

[1]Division of Cardiology, VA Medical Center and U. of Washington
[2]Human Interface Technology Laboratory, U. of Washington
Box 352-142, Seattle, WA 98195
tinman@u.washington.edu
{poup, ecmill, grof, peter, weghorst}@hitl.washington.edu

Abstract

Wearable augmented reality medical (WARM) interfaces could provide ubiquitous point-of-care decision support and enhance the quality and efficiency of clinicians' efforts. Creation of such systems involves the design and evaluation of new information displays that leverage the representational and presentational capabilities of three-dimensional AR environments. We describe our first efforts in this process: the implementation of interface objects for display of real-time electrocardiographic monitoring information and an evaluation methodology using a simulated clinical environment. Our pilot data confirm the utility of presentation modes that place simultaneous information tasks in close proximity, and highlight issues encountered in designing new representations of medical information.

1. Introduction

In caring for patients, clinicians must rapidly and accurately integrate large, complex and variable sets of information—including patient-specific data, general medical knowledge and literature references, and management guidelines. Current changes in the health care system push responsibility for this decision making onto less expert providers who must function ever more efficiently. We believe that augmented reality (AR) interfaces will allow the creation of new integrated information system applications that empower clinicians at all levels to better navigate through, analyze, and manage this welter of information.

In contrast to occlusive virtual reality (VR) environments, augmented reality interfaces consist of registered computer-generated imagery superimposed on the user's real environment [1, 2]. Like VR, AR offers many compelling benefits of advanced three-dimensional interfaces such as new forms of data visualization across environment "landscapes", user "presence", and multi-modal interactivity. Mobile AR interfaces are becoming possible through emerging technologies such as the Virtual Retinal Display (VRD) [3], distributed network software architectures, multi-modal input systems and wireless communication methods. Users will be able to move through both her physical workspace as well as a context-appropriate informational workspace. For ambulatory disciplines such as medicine—for which "furniture" ("desktop", "windows") paradigms have imposed severe limits—these capabilities promise to revolutionize application development [4].

However, in order for these “wearable augmented reality medical” (WARM) applications to be more than renderings of conventional 2D screen displays hung in 3D environments, new representations of medical information and their “control surfaces” for interaction will have to be designed. Careful validation and verification developmental methodologies will have to be established for these systems to the extent they manage critical patient data and are regulated by the FDA.

We report here our first empirical work in WARM system development at the U. of Washington’s Human Interface Technology Lab. For this study, electrocardiographic (ECG) data were chosen for several reasons. ECGs are ubiquitous in all but the most sedate clinical environments. Many different types of clinicians bear the responsibility of being able to interpret the information, but for the less experienced, this responsibility is at best a source of discomfort and at worst a source of significant error. ECG rhythms require varying levels of attention, from background surveillance when abnormalities are absent, to close examination when problems arise. Displays must make such attention shifts easy, since the speed and accuracy with which a clinician makes a decision about management can have grave clinical consequences. Finally, ECGs are real-time data and provide important design challenges beyond those posed by static data such as laboratory results.

It is our presumption that WARM interface technologies can provide better decision support for clinicians. More specifically, we hypothesize that new 3D displays of ECG information and new presentation modes of ECG display organization can produce faster and more accurate clinical decisions. To test these hypotheses, we have created a pair of ECG interface objects, a set of presentation mechanisms by which the interface objects can be placed in the 3D environment, and a test methodology that uses task loading through a simulated confounder clinical task to evaluate the speed and accuracy with which clinicians can make decisions under the different study conditions.

2. Related Work

Most of the medical AR applications reported to date involve structural information to assist surgical procedures. Robb et al. report a system for use in surgery planning, rehearsal and performance [5]. Grimson et al. have created a system to guide neurosurgical procedures that mixes video from a patient with MRI imagery [6]. Pieper et al. have created a real-time system to assist arthroscopy [7]. Non-surgical structural visualization projects include the work of Slate et al. who have prototyped a system that superimposes real-time fetal ultrasound images on the mother’s abdomen [8, 9], and Chihara et al. whose system projects live echocardiographic images on a patient’s chest [10].

Non-structural medical information has been much less explored so far. Block et al. describe a monocular heads-up system that displays anesthesia machine information that is conventionally seen in on a computer monitor [11]. Horvitz et al. have shown an early prototype of a hands-free medical computing environment for use by emergency personnel; this system presents users information via see-through heads-up displays, but the information itself is conventional windows-based data [12]. The use of AR for non-structural information is much further advanced in non-medical domains. Feiner et al. have developed a variety of interfaces for maintenance and repair tasks [13, 14]. Other applications include aviation design and manufacturing [15, 16].

Our work reported here differs from the above efforts in that we are modeling waveform data, not structural data. We are rendering information which is not registered with any “real” object in the environment—a considerably easier challenge that “true” AR. Finally, our current focus is on individual interface components, not the larger system issues.

The other stream of related work is the long-standing effort to design new representations for medical information. Several groups have developed new graphical techniques to portray laboratory information [17-19]. Many groups are working on 3D reconstruction techniques for MRI images [20] and echocardiography [20, 21], and Jensch et al. report a novel technique that combines angiographic, nuclear scans and PET imaging into a single 3D display [22]. A number of groups have reported with 3D visualization techniques for intraoperative cardiac electric fields obtained through application of large numbers of epicardial and endocardial electrodes [23-27]. Hulin et al. describe a novel animated "billowing sheet" representation of ECG data in which voltages are mapped distinctively to elevations above a reference plane [28, 29]. New information representations have generally received cool receptions in the medical domain, partly because of practitioners' psychological inertia, and partly because effective designs are extremely difficult to create and validate [30-33]. Our work is similar to these other efforts in that we are trying to apply new technologies to old information tasks, but we are working in an AR/VR medium.

3. Methods

3.1 System Development

This work was performed within the "Virtual Emergency Room" (VER) of the "Laboratory for Integrated Medical Interface Technology" (LIMIT) environment at the HITL [34]. The VER consists of a cylindrical space whose walls are texture maps created from video of the local county trauma center. The VER is implemented with Sense8's WorldToolKit, and runs on an SGI Onyx Reality Engine-II computer. The user display is created by Virtual Research VR4 head-mounted displays, and user head tracking is accomplished by a Polhemus Fastrak. The VER is thus a VR "simulation" of an AR medical environment which allows testing of AR constructs within the nonmedical setting of the HITL.

For this study, two ECG monitor object variants and one blood pressure (BP) monitor object were created and added to the VER. These objects were implemented with the WorldToolKit plus a custom 3D graphics library written by Poupyrev and Miller, and are shown in Figure 1.

Fig. 1

One ECG monitor variant is a conventional waveform (WF) representation of the ECG rhythm. The other is a novel 3D representation consisting of an iconized version of the cardiac conduction system and chambers. Both models are driven by a common data schema for cardiac rhythms inspired by the work of Widman and Tong [35]. This schema enables the creation of arbitrarily long sequences of different rhythms combined in a seamless fashion. Ten rhythms were implemented: 1) Normal Sinus Rhythm (NSR); 2) Ventricular fibrillation (VF); 3) Unifocal PVCs (PVCs); 4) Complex, repetitive PVCs (CmplxPVCs); 5) Ventricular tachycardia (VT); 6) Atrial flutter (AFlut); 7) Atrial fibrillation (AFib); 8) Supraventricular tachycardia (SVT); 9) Complete heart block (HtBlk).

The BP object displays a simulated mean blood pressure that randomly deviates above and below upper and lower boundaries. The display objects have no “control surfaces” for direct user interactivity. Instead, users’ interpretations of displayed information are made verbally and captured by keyboard entries by the investigator. This strategy separates out the information communication performance of the system—the focus of this study—from the larger agenda of interface ergonomics.

3.2 Subjects

For this pilot study, physicians with routine responsibility for ECG rhythm interpretation were recruited. Seven subjects volunteered: three cardiology attendings, three cardiology fellows, and one emergency room physician.

3.3 Tasks

The intent of the study was to evaluate ECG monitoring performance in a simulated clinical setting. Two concurrent clinical tasks were constructed: the primary ECG task, and a secondary BP management task to provide cognitive loading and a second measure of user performance. For the ECG task, the subjects were instructed to name the ECG rhythm displayed. For the BP task, the subjects were told to state the proper corrective measure when the BP deviated outside its bounds; upon this command, the BP is reset to normal by the investigator. In both cases, the subjects must respond as rapidly and accurately as possible. Every event—both system-generated events (the onset of a new ECG rhythm or transition of the BP across a boundary) and user-generated events (an ECG rhythm diagnosis or BP “order”)—are captured as encoded timestamps, from which post-hoc analysis yields a variety of performance measures.

3.4 Experimental design

The study evaluated two main interface factors: “task presentation” and “display representation”. The *presentation* alternatives concern the visual separation of the two clinical tasks and include three conditions: 1) 90 degree separation (90-D); 2) 0 degree separation (0-D); and 3) Head-stabilization of the ECG object (HS). The 90 degree separation places the BP task to the side of the subject’s dominant eye. The *representation* alternatives concern the format of ECG information display and include two conditions: 1) waveform; and 2) 3D. All subjects performed the simultaneous ECG and BP tasks under all combinations of presentation and representation. The design is thus a 2x3 crossover factorial design. The order of trials is counterbalanced across subjects.

The protocol for each subject consists of these steps: 1) the subject read written instructions about the study and the simulated clinical tasks; 2) the subject watches a training video which showed the WF and 3D variants side-by-side through all the ten test rhythms; 3) the subject performs a short trial run twice to insure understanding of the task instructions; 4) the subject performs six study runs corresponding to the six test conditions.

Each condition consists of a randomly created but consistently used (across subjects) series of heart rhythms built from eight rhythm primitives (two rhythms from the instruction set are never used). Each abnormal rhythm is shown 5 times for between 2-4 seconds each time. Between each repetition of an abnormal rhythm, a stretch of NSR is displayed to disambiguate responses when the user's responses lag behind. Each entire study run per condition thus presents the subject with 35 abnormal rhythm episodes to interpret, separated by 36 normal rhythm episodes, and lasts between 3-4 minutes. Concurrently, the subject sees on average about 40 abnormal BP events, depending on how rapidly they deal with deviations. Between conditions, the subjects are allowed to remove the head mounted display if they desire.

3.5 Analysis

The system outputs data files consisting of encoded time-stamps of system events and user actions. A program was written which parses these files to link user responses to the system stimuli, creating "decision events" (DE) for which a variety of attributes are captured, including the "correctness" of a decision (correct, incomplete because no user action occurred, or incorrect because only incorrect user actions occurred), the "correct time" of a decision (the interval between the system stimulus and a correct user response), the "first guess time" of a decision (the interval between a system stimulus and any user response), and various parameters of a decision's "prior cousin" (i.e., the correctness and "correct times" of an ECG decision prior to an index BP decision, for example). These parsed DE data were imported into a database, a spreadsheet program, and SPSS for further analysis. For this small pilot study, only the correctness and "correct times" are evaluated, since they represent the chief end points of the study—the accuracy and speed of clinician interpretation, respectively.

4. Results

Seven subjects completed all six (2 representation x 3 presentation) test conditions. Because of the study's repeated measures design, the data set consists of a total of 4736 decision events (DEs). 2982 DEs were ECG decisions; 1754 were BP decisions. 1470 ECG DEs concerned abnormal rhythms, while 1512 ECG DEs were about NSR. The 2982 ECG DEs were evenly split between the WF and 3D representations—2354 DEs each—and among the 90-D, 0-D and HS presentation alternatives—994 each. The large number of repeated samples generated data that were nearly normal by inspection of histograms, even within subgroups, though because of the small number of subjects, formal tests of normality were not done.

4.1 Decision accuracy

The overall error rate for ECG DEs by all subjects was 17.0%. For NSR DEs, the rate was 14.3%, while for abnormal rhythms it was 19.7%. The BP DE error rate is zero because a deviated BP remained so until the subject "ordered" it to be corrected; BP mismanagement thus is measured in the time parameters of the next section.

ECG DE error rates varied considerably among the different rhythms and were higher for the 3D representation, as shown by Figure 2. Comparison by repeated measures 2-factor ANOVA showed a significant effects of rhythm [$F(7,144) = 8.2$, $p < 0.0001$], representation [$F(2,144) = 56.8$, $p < 0.0001$], and rhythm x representation interaction [$F(14,144) = 34.0$, $p < 0.0001$]. Across presentations (90 degree, 0 degree, and Head-stabilized task separations), there was no significant difference in error rates by representation [$F(2,2) = 0.9$, $p = 0.5$]; see Figure 3.

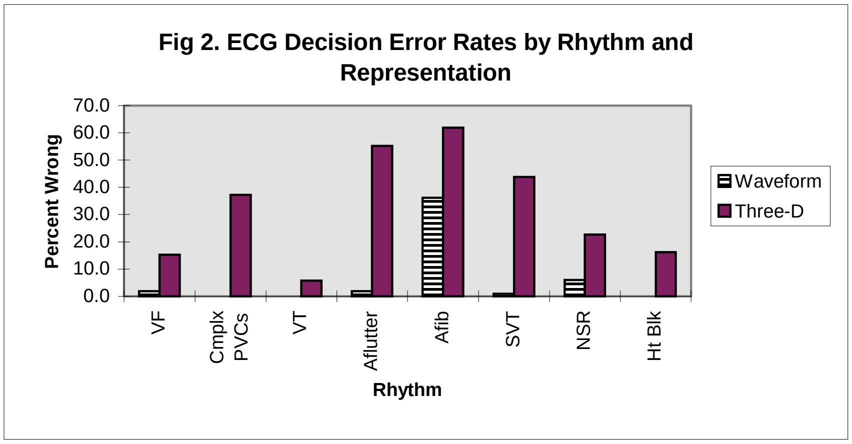


Fig 2. ECG Decision Error Rates by Rhythm and Representation
Percent Wrong
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
VF
Cmplx PVCs
VT
Aflutter
Afib
SVT
NSR
Ht Blk
Rhythm
Waveform
Three-D

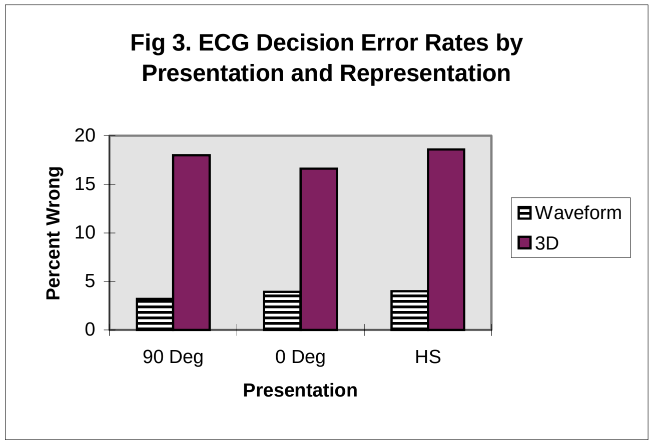


Fig 3. ECG Decision Error Rates by Presentation and Representation
Percent Wrong
20
15
10
5
0
90 Deg
0 Deg
HS
Presentation
Waveform
3D

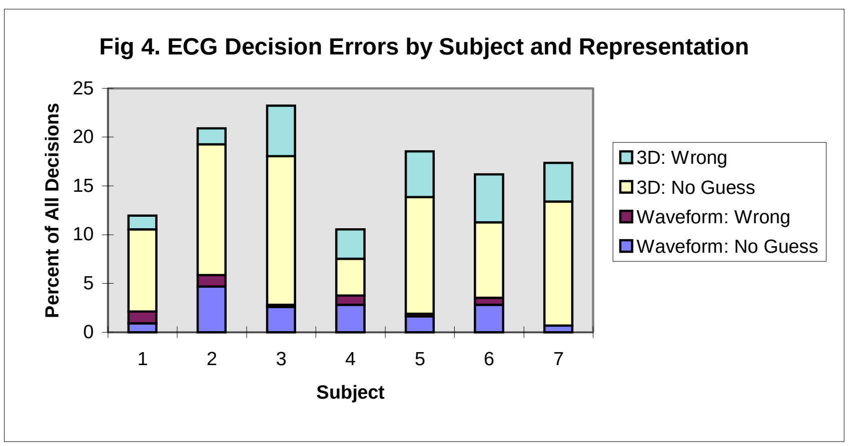


Fig 4. ECG Decision Errors by Subject and Representation
Percent of All Decisions
25
20
15
10
5
0
1
2
3
4
5
6
7
Subject
3D: Wrong
3D: No Guess
Waveform: Wrong
Waveform: No Guess

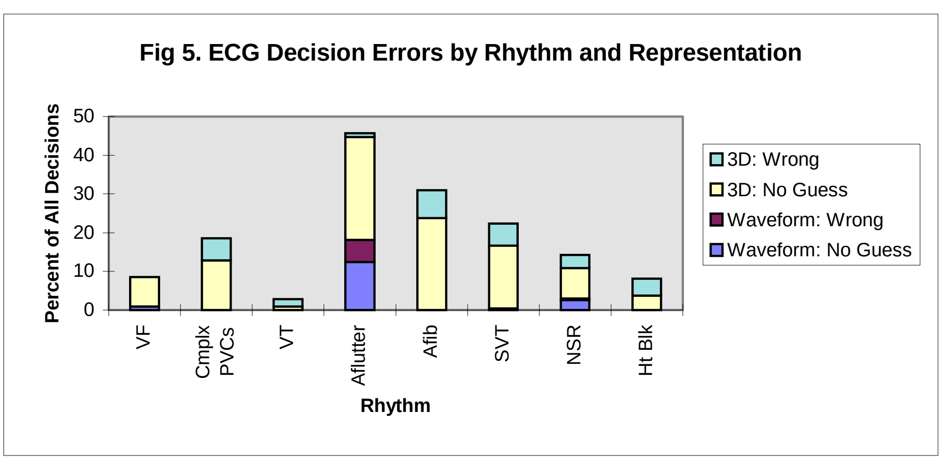
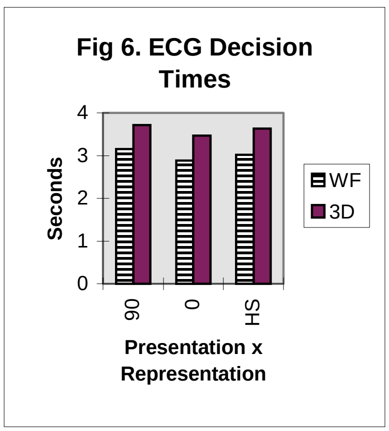


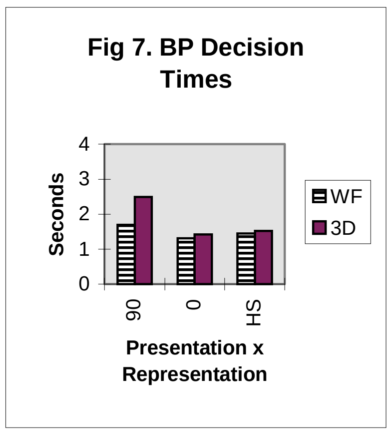
Fig 5. ECG Decision Errors by Rhythm and Representation
Percent of All Decisions
50
40
30
20
10
0
VF
Cmplx PVCs
VT
Aflutter
Afib
SVT
NSR
Ht Blk
Rhythm
3D: Wrong
3D: No Guess
Waveform: Wrong
Waveform: No Guess

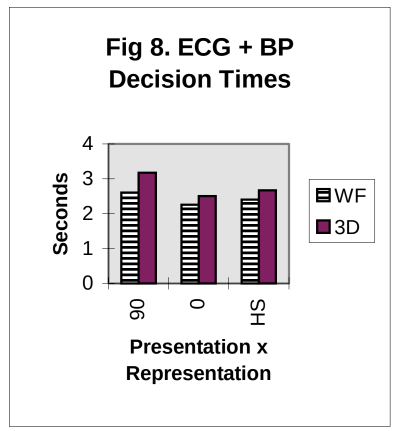
ECG DE errors could result from a subject either not making a decision at all (“no guess”) or by making only incorrect decisions (“wrong”). Of the 506 total ECG DE errors, 381 were “no guess” and 125 were “wrong”. Figures 4 and 5 show that the 3D representation was substantially more likely to cause “no guess” errors than the WF representation.

4.2 Decision speed

The chief measurement of interest was the time to a correct decision, “correct time” (CT). Two-way ANOVA comparisons of Presentation and Representation (2x3) were done on the ECG and BP DE subsets as well as the entire ECG+BP set. Significant effects of representation were seen in both the ECG [$F(1,36) = 45.4$, $p < 0.0001$] and BP [$F(1,36) = 11.6$, $p < 0.05$] DE sets; the 3D variant produced slower CTs (mean = 2.8 sec) than the WF variant (mean = 2.4 sec). The presentation factor was insignificant in the ECG subset [$F(2,36) = 2.9$, $p = 0.7$], but it was significant in both the BP subset [$F(2,36) = 22.4$, $p < 0.001$] and the total data set [$F(2,36) = 21.0$, $p < 0.001$]. These findings are shown in Figures 6, 7, and 8. This finding that the 90-D task separation resulted in significant deterioration of performance in the BP task compared to the other Presentation modes indicates that subjects attended more to the ECG task. Yet the combined ECG+BP DE data show that visual task separation caused overall slower performance in accomplishing a correct decision..

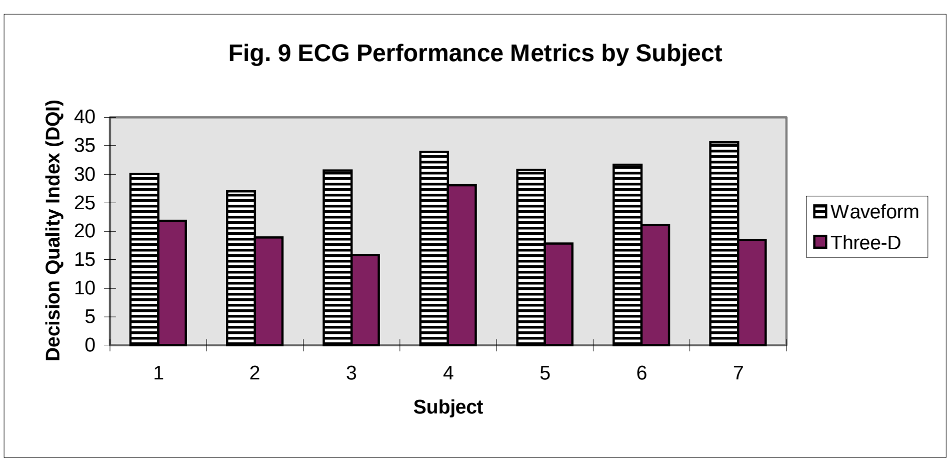


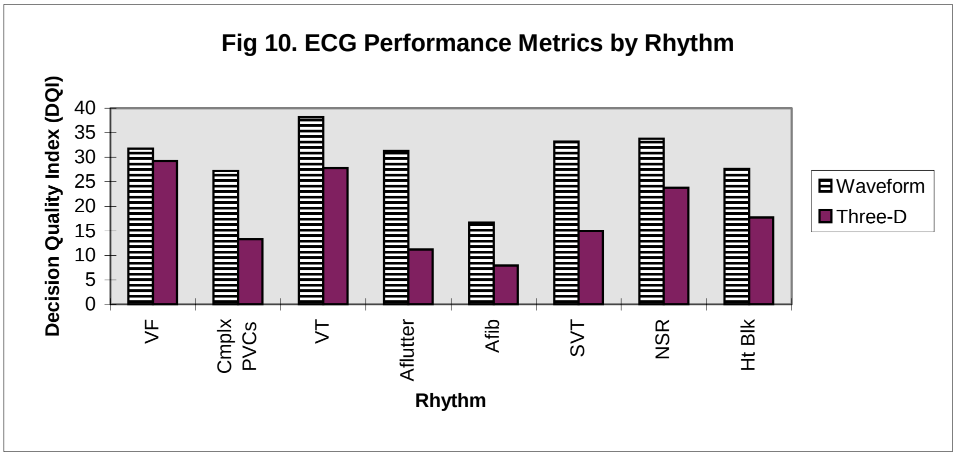


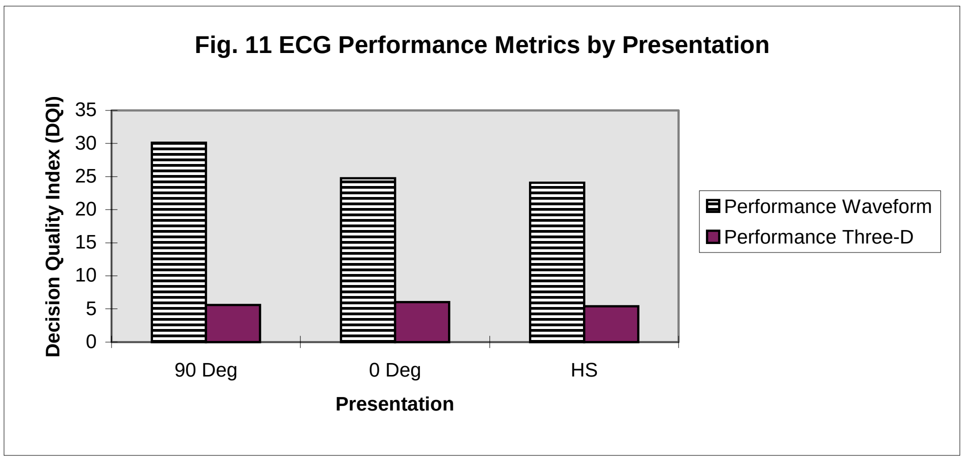


4.3 Combined “decision quality” performance metric

Combination of speed and accuracy measures is sensible because both metrics are important clinically. A “decision quality index” (DQI) parameter was defined as (100 - error rate / correct time). Comparisons across subjects, representations and presentation factors are shown in Figures 9. 10. and 11.







5. Discussion

Our work is preliminary and has a number of limitations. Our WARM interface objects are early prototypes and underwent substantially fewer design iterations than we would have liked. The test environment itself is a VR simulation of AR, and though we presume that our conclusions would transfer from the one setting to the other, this has not been demonstrated. The study itself was only a pilot study involving a limited number of mostly “expert” subjects. The study also involved only two, quite artificial simultaneous clinical tasks and thus provided only a limited reproduction of the target clinical environment.

Despite these limitations, our results show that WARM interfaces, by allowing concurrently performed tasks to be perceptually aligned, reduces the amount of time needed to perform the tasks correctly. This conclusion is not as foregone as it might at first appear, since there is an important trade-off between reducing visual scanning and adding visual clutter [36].

The clear failure of the 3D ECG object in all performance measures was not a great surprise; Merwin et al. in a different context found 3D representations to be less successful than more conventional variants [38]. Many additional design refinements such as further color and animation encoding were envisioned but couldn’t be implemented because of resource constraints; we think the 3D object would have fared better with them. On the other hand, a real-time object of this sort only accomplishes half of the two-phase decision task involved in interpreting an ECG rhythm. The first part—*event classification*—involves determining to which cardiac electrophysiological event each component of the ECG waveform pertains, and our 3D ECG model actually provides a higher-level interpretation of this phase. However, the second part of the interpretive task—*context recognition*—is not supported at all in a strictly real-time animation model. In contrast, the conventional ECG waveform shows at least a few seconds so the user can scan back in time. Further, the real-time model scales time 1:1, whereas the conventional waveform trace allows a user to scan the entire period virtually instantaneously, providing a huge magnification of time scale. Nevertheless, we believe real-time models probably have an appropriate use, and we're encouraged by similar work in "rapid serial visual presentation" interfaces such as that reported by Konrad et al. [37].

We believe that future work on WARM interfaces should focus on improved 3D information metaphors and visualization implementations, development of "control surfaces" for information interactivity, and continued formalization of performance testing methodologies.

6. Conclusions

"Wearable augmented reality medical" (WARM) interfaces may be central to a future generation of point-of-care clinical decision support systems. Interface metaphor creation and validation are critical tasks at this stage of development [33, 39]. Applications built from these new interface objects must be shown to provide functionality that previously was unavailable or to markedly enhance functionality that already is [40].

Our current efforts constitute preliminary work in this direction. Our results confirm that reduction of perceptual separation of simultaneous tasks can speed decision performance, though this enhancement is subject to visual clutter limitations. Three-dimensional representations of medical information are difficult to design and must be carefully evaluated for efficacy.

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