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Tell me, show me, involve me: Supercharging Collaborative Diagnosis with Augmented Reality

Zeyuan (Stephen) Hong
Nanyang Technological University, ZEYUAN002@e.ntu.edu.sg

Chun Fung (Ben) Choi
Nanyang Technological University, benchoi@ntu.edu.sg

Boh Wai Fong
Nanyang Technological University, awfboh@ntu.edu.sg

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benchoi@ntu.edu.sg

Boh Wai Fong
Nanyang Technological University
awfboh@ntu.edu.sg

ABSTRACT

Augmented reality has been broadly employed to help remote individuals communicate and coordinate. In this study, we develop and test a model that explains how augmented reality can facilitate collaborative diagnosis on an unexpected technical breakdown involving two complete strangers. Drawing on the affordance theory, we integrate the dual-task interference literature to reveal frustration valence and arousal as the underlying mechanisms. We tested our hypothesis in a laboratory experiment involving a custom-built augmented reality environment and physiological measurements. Overall, this study contributes to information system literature, human-computer interaction literature, and dual-task interference research by unearthing the effects of augmented reality characteristics on enhancing collaborative diagnosis performance.

Keywords

Augmented reality, collaborative diagnosis, affordance, dual-task interference, physiological measurements.

"Tell me and I will forget,

Show me and I may remember;

Involve me and I will understand"

Xunzi (est 316BC to 235BC), Ruxiao, Chapter 23

INTRODUCTION

The advancement in automation has fundamentally transformed business operations. Automation involves highly advanced and niche hardware, software, and technical knowledge of technologies. Adequate investment can largely overcome the demand for automation hardware and software. Yet the demand for technical talent is ahead of supply by leaps and bounds. Consequently, recruiting and retaining employees with technical expertise costs businesses a premium (Gartner, 2023). Unanticipated breakdowns are often inevitable, despite regular maintenance and routine checks. The talent gap further aggravates both tangible and intangible costs in unanticipated breakdowns. Overall, delays in resolving unanticipated breakdowns are highly likely to hurt a company's performance.

Information system (IS) research has progressed significantly in expanding our understanding of telecommuting, virtual collaborations, and remote diagnosis to mitigate the shortage of technical talents (e.g., Dennis, Fuller, & Valacich, 2008; Ma & Agarwal, 2007). For instance, Zhu, Benbasat, and Jiang (2010) examined synchronized digital collaboration using shared screens and audio communications among dispersed shoppers. Although IS research deals with numerous aspects of digital collaboration, to the best of our knowledge, no research has been done to understand how digital collaboration can mitigate issues with technical knowledge, such as effective and efficient remote diagnosis. Furthermore, it remains largely unknown whether digital collaboration can facilitate technical training and learning to address the talent gap.

Drawing from the affordance literature, this study considers two specific characteristics of collaborative diagnosis in the augmented reality environment: area reference and actional demonstration. Area reference, often through superimposed colored overlays, has been broadly applied to draw individuals' attention to specific areas in the augmented reality space. In particular, scholars opine that foreground-background contrast, a core interface design principle, is essential for attracting attention to specific on-screen areas (Hou, Zhang, & Zhang, 2022).

We conducted a laboratory experiment using a custom-built augmented reality environment to test our hypotheses and make multiple contributions. First, we extend digital collaboration to illustrate the efficiency of augmented reality for remote diagnosis. Second, we refine the understanding of area reference and actional demonstration in the Human-Computer Interaction (HCI) literature. Third, we advance knowledge of dual-task interference in augmented reality and identify the underlying psychological processes that explain the effects of augmented reality on collaborative diagnosis performance. Finally, this study enriches the collaboration literature by demonstrating collaborative performance in multiple manifestations.

THEORETICAL FOUNDATIONS

Digital Collaboration and Collaborative Diagnosis

Digital collaboration presents an intricate technology-augmented environment through which complex interpersonal interactions between two agents are facilitated to accomplish mutual goals (Thomson, Perry, & Miller, 2009). Past IS research examining digital collaboration has focused on understanding the two key aspects of collaborative communications: contextual communications (i.e., communications to establish common understanding and/or common perspective) and actional communications (i.e., communications to instruct a remote agent to perform specific tasks).

The IS literature has also robustly examined collaborative diagnosis, through which remote agents work together to analyze the cause or nature of a problem, in various contexts, such as telemedicine, software development, and information security (Fruhling & Vreede, 2006; Jensen, Wright, Durcikova, & Karumbaiah, 2022; Serrano & Karahanna, 2016). Collaborative diagnosis presents unique challenges to digital collaboration. Digital collaboration is oftentimes conducted to facilitate routine communication and coordination for long-term productivity tasks, through which agents can gradually establish communication norms and accumulate mutual understanding. Collaborative diagnosis, by contrast, considers impromptu, one-off troubleshooting of technical breakdowns attended by agents who are complete strangers.

The Affordance Perspective and Digital Collaboration

Human-Computer Interactions (HCI) literature has made notable progress in advancing the designs and implications of digital collaboration in a broad spectrum of digital environments, such as open-source software communities, group decision-making, and teleconsultation (Jung, Schneider, & Valacich, 2010; Khurana, Qiu, & Kumar, 2019; Lindberg, Berente, Gaskin, & Lyytinen, 2016). Our literature review uncovers two important technological features pertinent to digital collaboration: area reference and actional demonstration features.

Area Reference and Collaborative Diagnosis

Area reference affords communication clarity between remote agents by steering the counterparts' attention with visual cue augmentations (Serrano & Karahanna, 2016). Past HCI research has broadly demonstrated the benefits of area reference, typically administrated using superimposed graphical elements on the visual depiction of an actual working area or object, in enhancing remote communications and coordination. For instance, Fussell et al. (2004) pointed out the importance of pointing cues that refer to task objects and locations. The results suggested that pointing cues led to an effective grounding process and improved collaborative task performance. Considering the importance of area reference, this study considers *area-emphasis-only* and *area-emphasis with traversal guidance* in collaborative diagnosis.

Area-emphasis-only has been widely employed in map-based visualized narratives, where attention to specific visual elements is directed using colored highlights. In collaborative diagnosis, area-emphasis-only offers a succinct mechanism alerting individuals to align their visual attention to a focal component from the overall working area in the augmented reality environment. Yet, area-emphasis-only is most applicable to digital collaboration where a single visual overlay is utilized to coordinate one's visual attention. The complexity of collaborative diagnosis often demands multiple overlays to ensure clarity.

By contrast, area emphasis with traversal guidance incorporates additional graphical linkage to harmonize agents' visual attention traversing between the text instruction overlay and the component highlight overlay. The application of traversal guidance is rooted in the law of unified connectedness, which states that visual elements connected using lines, frames, or other shapes are perceived as a single unit compared with other graphic elements not linked in the same manner (Palmer & Rock, 1994).

Actional Demonstration and Collaborative Diagnosis

Recent advancements in collaborative diagnosis have begun incorporating virtual bodily actions to complement instructional descriptions. Digital actional demonstration, which illustrates precise bodily actions in high fidelity, has shown substantial promise for comprehending and learning fine-grained actions (Mayer, Hegarty, Mayer, & Campbell, 2005). Considering the importance of actional demonstration, this study focuses on two modes of actional demonstration: actional-description-only and actional description with virtual illustration. Actional-description-only conveys specific bodily actions using text descriptions for the on-site agent. Understanding actional-description-only requires substantial cognitive efforts in information processing. The on-site agent must accurately comprehend the text content and mentally construct, if not simulate, the bodily actions to fully understand the steps to be performed. Consequently, the on-site agent is likely to struggle to understand actional-description-only fully.

By contrast, actional description with virtual illustration supplements detailed, descriptive instructions with virtual illustration complement text descriptions with superimposition of real-life bodily actions to convey diagnosis instructions. The superimposition of real-life bodily actions affords the off-site agent direct utilization of their hand gestures to demonstrate the natural hand actions in collaborative diagnosis. By doing so, the on-site agent can be relieved from effortful mental simulations.

Dual-task Interference

The dual-task interference literature postulates that simultaneous tasks can interfere with each other, leading to suboptimal performance in both tasks (Ketelaars, Khan, & Franks, 1999; Schmidt, Lee, Winstein, Wulf, & Zelaznik, 2018). Past research examining dual-task interference reveals that the human cognitive system is predominately constructed for serial processing, through which only a single task can be worked on at a time (Pashler, 1994). In cases of simultaneous tasks, the literature offers two major explanations for dual-task interference: capacity sharing and task-switching bottlenecks.

The capacity-sharing perspective assumes that one's mental resources are shared to process multiple tasks concurrently. Since mental resources are inherently a finite, scarce pool of processing capacity, with more than one task performed at any given moment, individuals would have fewer resources for each task, and performance can be impeded. Dual-task interface can occur when the resource demand of a subsequent task cannibalizes the processing capacity required by an initial task, therefore impairing the performance of the initial task. For instance, in operating automobiles, drivers must maintain consistent attention to the dynamic road conditions and make rapid corresponding driving decisions. A simultaneous phone call during vehicle operations would inevitably curtail the mental resources necessary for safe driving, contributing to sub-optimal driving decisions, and at worst, fatal road accidents.

Recent advancement in cognitive research reveals that dual-task interference can be exacerbated when one interacts with multiple tasks through a shared sensory channel (e.g., concurrently engaging in two conversations) (Matthews, Sparkes, & Bygrave, 1996). Theorists offer that interaction channel overlaps can introduce confusability across tasks, further degrading task performance, even when the interactions are compatible or complementary across tasks (Oliveros, Pieczykolan, Pläschke, Eickhoff, & Langner, 2023). Similarly, the IS literature has corroborated the issues of oversaturating one's visual attention with multiple on-screen messages. For instance, Jenkins, Anderson, Vance, Kirwan, and Eargle (2016) examined interpretive security messages and found that individuals would experience elevated interference when popup security messages were displayed when they were visually engaged in ongoing tasks, such as typing, online payment, and mouse cursor navigation.

Frustrations In Dual-task Interference

Although the dual-task interference literature has enriched our understanding of mental resource depletion, past research has focused predominately on examining performance outcomes of task interference, with only a few studies investigating the impact of interference on psychological consequences (Vance, Anderson, Kirwan, & Eargle, 2014; Weinert, Maier, Laumer, & Weitzel, 2022). Evidence suggests that when individuals must confront dual-task interference to complete an important, compulsory task, they can experience various frustration emotions (DeBellis & Goldin, 2006; Goldin, 2000). This study examined frustration valence and arousal triggered by dual-task interference in collaborative diagnosis. Frustration valence describes the extent of negative emotions the on-site agent experiences using augmented reality for remote communication and coordination. Frustration arousal refers to the strength of the frustration state experienced by the on-site agent during collaborative diagnosis.

HYPOTHESES DEVELOPMENT

Through integrating the affordance theory and dual-task interference theory, we propose the research model as presented in Figure 1.

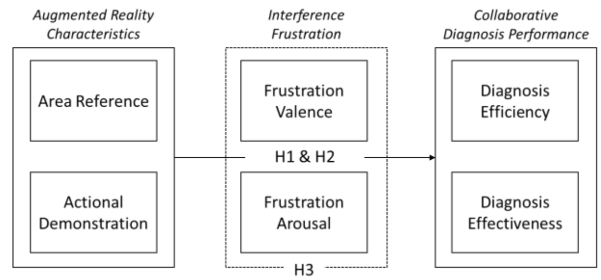

Figure 1. Research Model

Collaborative Diagnosis Performance

Following the digital collaboration literature, we consider collaborative diagnosis performance in two aspects: diagnosis effectiveness and diagnosis efficiency. Diagnosis effectiveness refers to the extent to which the on-site agent has identified the series of abnormalities in performing the diagnosis procedures. Low diagnosis effectiveness indicates mediocre, superficial diagnoses, whereas high diagnosis effectiveness implies that the diagnoses are rigorous and meticulous. Diagnosis efficiency refers to the amount of communication and coordination required to identify the abnormalities. While low diagnosis efficiency underscores the incompetent support and guidance for collaborative diagnosis, high diagnosis efficiency marks the on-site agent's diagnosis competence facilitated by augmented reality.

Area Reference and Collaborative Diagnosis Performance

The HCI literature has extensively documented how area emphasis with traversal guidance can improve collaboration performance by sharpening synchronized attentions and expediting re-calibration when disruption occurs. The graphical elements employing the principles of foreground-background contrast and unified connectedness are visual salient features that can powerfully lead to attentional synchrony, whereby individuals' attention can be directed and regulated. It is worth noting that when information presentation is conveyed with color contrast and unified connectedness, individuals' visual attention and information acquisition can be cognitively outsourced to the visual elements, streamlining their understanding and comprehension to optimize mental capacity utilization.

Applied to our context, when the collaborative diagnosis is facilitated through area emphasis with traversal guidance, the on-site agent can better align the diagnosis instructions with the augmented reality illustration. Collaborative diagnosis presents a double cognitive integration challenge that demands individuals to integrate and understand various visual presentations on the digital environment, and simultaneously, stipulate individuals to infuse and extend their understanding to the physical, at times visually separated, environment. Area emphasis with traversal guidance reduces the mental capacity required for the on-site agent to understand the diagnosis instructions and eases the efforts in extending the understanding to actual diagnosis actions. Consequently, area emphasis with traversal guidance can expedite the on-site agent's understanding and reduce errors in performing specific diagnosis activities, leading to enhanced collaborative diagnosis performance. Therefore, we propose the following hypothesis:

H1: Compared with area emphasis only, area emphasis with traversal guidance will increase collaborative diagnosis performance.

Interaction between Area Reference and Actional Demonstration

Past dual-task interference research has utilized channel competition and complimentary to explain the interactions between collaboration over multiple sensory channels. Channel competition occurs when multiple digital collaboration activities are simultaneously conducted through a common communication channel. Applied to our setting, in the case of actional description only, diagnosis instructions are conveyed through text descriptions to coordinate the specific bodily actions of the on-site agent. Understanding actional-description-only requires substantial attention in acquiring visual information, dominating the on-site agent's visual sensory channel. Area emphasis only introduces a separate visual overlay in addition to the actional description, to align the on-site agent's visual attention to a focal component from the overall working area in the augmented reality environment. The additional visual overlay aggravates the saturation of the on-site agent's visual sensory channel, contributing to interference between the two collaboration mechanisms. By contrast, area emphasis with traversal guidance builds on the law of unified connectedness, utilizing additional graphical linkage to reduce the on-site agent's cognitive efforts to traverse between the text instruction overlay and the component overlay. The overall reduction in mental capacity demand enables the on-site agent to comprehend better and perform the specific diagnosis actions. Thus, we predict the following effect:

H2a: Under the actional description-only condition, area emphasis with traversal guidance will lead to better collaborative diagnosis performance compared with area emphasis only.

Virtual illustrations complement text descriptions with superimposition of real-life bodily actions to covey diagnosis instructions. While the superimposition of real-life bodily actions reduces the on-site agent's mental efforts in simulating the physical gestures, actional description with virtual illustration requires concurrent presentations of two visual overlays, constituting substantial demand for the on-site agent's visual attention. With area emphasis with traversal guidance, the on-site agent provides additional graphical linkage to visually connect the text instruction overlay and the virtual illustration overlay. As a result, the on-site agent's mental capacity can be severely saturated by the visual competition between multiple visual overlays and the attention split between text-based information acquisition and observational learning. Area emphasis only, however, draws on foreground-background contrast to direct the on-site agent's visual attention, without utilizing additional visual overlay. Consequently, the overloading of the visual sensory channel can be reduced, enabling the on-site agent the mental capacity to comprehend better and perform the specific diagnosis actions.

H2b: Under the actional description with virtual illustration condition, area emphasis with traversal guidance will lead to worse collaborative diagnosis performance compared with area emphasis only.

Mediating Role of Frustration

Recent development in dual-task interference suggests that individuals' frustration psychology mediates the degree of interference and interference frequency on collaborative performance (e.g., Baer, Vasavada, & Cohen, 2022; Mikulincer, 1989). In other words, frustration responses can be influenced by the technological characteristics of digital collaboration, through which remote communication and coordination can be affected. For instance, Choi, Kim, and Jiang (2016) showed that individuals' cognitive and emotional responses could be simultaneously determined by various fairness information presentations after an online security breach. It is also consistent with previous behavioral studies that considered individuals' psychological responses as the determinants of behavioral changes. For instance, Liang, Xue, Pinsonneault, and Wu (2019) proposed that individuals' cognitive appraisal of information technology risk and emotions aroused by security breaches influenced their motivations to take corrective actions.

Extending the relationship between technological characteristics and psychological responses, we postulate that the two characteristics of collaborative diagnosis (i.e., area reference and actional demonstration) affect the on-site agent's frustration psychology, i.e., frustration valence and frustration arousal. Empirical evidence underscores the critical role of frustration psychology in digital collaboration. For instance, in a study examining the design of online collaboration environments, Trammell, Morgan, Davies, Petrunich-Rutherford, and Herold (2018) found that suboptimal communication and coordination features could substantially elevate the frustration experienced by collaborators.

Regarding the relationship between frustration psychology and collaboration performance, we argue that the on-site agent's frustration valence and arousal affect their understanding and execution of the diagnosis instructions. The IS literature has demonstrated the impact of frustration on task performance. For instance, de Guinea, Titah, and Léger (2014) found that frustrating system usage experience would draw users' attention to criticizing abysmal system usability and usefulness, inhibiting meaningful system usage for productive performance.

Collectively, we propose that area reference and actional demonstration would elevate the on-site agent's frustration valence and arousal, influencing their collaborative diagnosis performance. Therefore, we hypothesize:

H3: The effects of area reference and actional demonstration on collaborative performance will be mediated by frustration valence and frustration arousal.

RESEARCH METHODOLOGY

Experimental Design

A laboratory experiment with a 2 (area reference, area emphasis only versus area emphasis with traversal guidance) × 2 (actional demonstration, actional description only versus actional description with virtual illustration) between-subjects factorial design was conducted to test the proposed research model. Area reference in the experiment was manipulated by incorporating area emphasis overlay (i.e., emphasis on a focal area with color highlights) or area emphasis overlay with superimposed references in the augmented reality environment. Actional demonstration was manipulated by varying the presence or absence of the virtual projection of hand actions using an additional overlay.

41 subjects participated in the main experiment. They were randomly assigned to one of the four experimental conditions. The GSR sensors were attached to the subject's hand and put on a eye-tracking glasses. Subjects first completed the familiarization task using the augmented reality environment.[1] Afterwards, subjects were presented with a scenario asking them to imagine that they were a junior on-site IT technician tasked with troubleshooting and accessing hardware issues. To ensure timely service recovery, subjects were put in contact with a remote server engineer through the augmented reality environment to perform collaborative diagnoses. After completing the collaborative diagnoses, subjects were asked to complete an exit survey and thanked.

DATA ANALYSIS AND RESULTS

Subject Demographics, Manipulation Check, and Operationalizations

Among the 41 subjects, 20 were female. The age of the subjects ranged from 25 to 38. No significant differences were found among subjects randomly assigned to the experimental conditions concerning age, gender, and computer knowledge, indicating that subjects' demographics were quite homogeneous across different conditions.

Manipulation checks were conducted and were shown to be successful. This study employed automatic facial expression analysis (FEA) using computer vision to operationalize emotional valence. Galvanic skin response (GSR) has been shown to be an objective, valid, and reliable measure of physiological arousal. Therefore, to operationalize frustration arousal, we collected subjects' average GSR scores during the time period when they were performing collaborative diagnosis. We utilized the algorithm proposed by Benedek and Kaernbach (2010) to filter, extract, and smooth GSR data.

The Effects of Augmented Reality on Collaborative Diagnosis Performance

ANOVA with collaborative efficiency as the dependent variable reveals the significant effects of area reference ($F(1,37) = 1858.33$, $p < 0.01$) and actional demonstration ($F(1,37) = 39.08$, $p < 0.01$). Second, results on collaborative effectiveness as the dependent variable reveal the significant effects of area reference ($F(1,37) = 42.03$, $p < 0.01$ and actional demonstration ($F(1,37) = 579.85$, $p < 0.01$). Collectively, area emphasis with traversal guidance leads to lower time duration for collaborative diagnosis and less collaboration decoupling instances than does area emphasis only. Therefore, H1 is supported.

Since the interaction effects on collaboration efficiency ($F(1,37) = 61.12$, $p < 0.01$), we further conducted the simple main effect analysis. Results of the simple mean effect analyses suggest that (1) area emphasis with traversal guidance is associated with significantly lower diagnosis time duration ($F(1,18) = 42.13$, $p < 0.01$) than area emphasis only under the actional description only condition, and (2) area emphasis with traversal guidance and area emphasis only are not different from each other in affecting collaboration duration under the actional description with virtual illustration condition ($F(1,19) = 0.00$, $p = 0.99$).

The interaction effect on collaboration effectiveness is also significant ($F(1,37) = 26.13$, $p < 0.01$). Results of the simple mean effect analyses suggest that (1) area emphasis with traversal guidance is associated with significantly less communication decoupling ($F(1,18) = 330.26$, $p < 0.05$) than area emphasis only under the actional description only condition, and (2) area emphasis with traversal guidance and area emphasis only are not different from each other in affecting communication decoupling under the actional description with virtual illustration condition ($F(1,19) = 1.21$, $p = 0.28$).

Overall, under the actional description-only condition, compared with area emphasis only, area emphasis with traversal guidance leads to better collaborative diagnosis performance. By contrast, the interaction effects are less pronounced under the actional description with virtual illustration condition. Therefore, H2a is supported, but not H2b.

[1] The AR environment consists of a high-definition resolution camera (i.e., a 4K web cam), a portable computer (which is invisible to the subject), and a 14-inch high-definition resolution flat-screen (i.e., a 4K portable screen) mounted on an adjustable monitor arm.

The Mediating Role of Frustration Valence and Frustration Arousal

To test the hypothesized mediation effects, we utilized the procedure proposed by Preacher and Hayes (2004). Results suggest that the effects of the independent variables (i.e., area reference and actional demonstration) on the mediators are significant. Furthermore, frustration valence and frustration arousal significantly mediate the direct effects. Therefore, H3a and H3b are supported.

Discussion of results

Our results supported most of our hypotheses, with one exception. Contrary to our expectations, the results showed that the joint effects on the outcomes were not significant. A plausible explanation is that virtual illustration presented vivid demonstrations of not only bodily actions for specific diagnosis steps but also naturally exhibited the specific locations for the actions to be carried out. Furthermore, since virtual illustration essentially presented the specific actions in the natural bodily form, individuals might predominately utilize observational learning to acquire the necessary knowledge for the diagnosis step. Consequently, less cognitive capacity might be required to understand actional description, enabling individuals with adequate mental capacity to overcome issues with interpreting areas emphasis only, leading to the indifferentiable interaction effects.

IMPLICATIONS

This paper informs the information systems literature, HCI literature, and dual-task interference research. First, we contribute to the IS literature by unearthing the effects of different augmented reality features on digital collaboration. Increasing IS research has paid attention to the potential of augmented reality in supporting remote communication and coordination. Despite the promises, evidence suggests that augmented reality might not consistently yield favorable collaboration outcomes. Such inconsistent findings have prompted fundamental questions on the design of augmented reality for digital collaboration. We thus make an important contribution to the IS literature by illustrating how area reference and actional demonstration can be utilized to improve collaborative diagnosis performance.

Furthermore, we offer that collaborative diagnosis requires substantial communication and coordination between the off-site and on-site agents, which can lead to substantial cognitive workload. Consequently, augmented reality features that contribute to dual-task interference can inhibit diagnosis performance. We further illustrate the importance of area reference in enabling foreground-background contrast and traversal guidance in facilitating unified connectedness. Overall, our findings suggest that area reference and traversal guidance are important features for collaborative diagnosis. We thus demonstrate how augmented reality can be designed for optimal digital collaboration performance.

CONCLUSION

This study examines the effects of augmented reality on collaborative diagnosis performance. Our results show that area emphasis with traversal guidance increases collaborative performance compared with area emphasis only. We also show the impact of the interactions between area reference and actional demonstration of diagnosis effectiveness and efficiency. Furthermore, we reveal that the effects of augmented reality on collaborative diagnosis performance are mediated by frustration valence and frustration arousal. This study provides theoretical explanations for the underlying mechanics of diagnosis performance through augmented reality designs and proposes recommendations for practice.

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