Towards a Predictive Framework for AR Receptivity

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Abstract. Given the sometimes disparate findings and the increasing application of AR in both training and operations, as well as increased affordability and availability, it is important for researchers, user interface and user experience (UI/UX) designers, and AR technology developers to understand the factors that impact the utility of AR. To increase the potential for realizing the full benefit of AR, adequately detailing the interrelated factors that drive outcomes of different AR usage schemes is imperative. A systematic approach to understanding influential factors, parameters, and the nature of the influence on performance provides the foundation for developing AR usage protocols and design principles, which currently are few. Toward this end, this work presents a theoretical model of factors impacting performance with AR systems. The framework of factors, including task, human, and environmental factors, conceptualizes the concept of "AR Receptivity", which aims to characterize the degree to which the application of AR usage is receptive to the technology design and capabilities. The discussion begins with a brief overview of research efforts laying the foundation for the model's development and moves to a review of receptivity as a concept of technology suitability. This work provides details on the model and factor components, concluding with implications for application of AR in both the training and operational settings.

Keywords: Extended reality · Virtual reality · Augmented reality · Receptivity

1 Introduction and Problem Statement

Augmented reality (AR) technologies augment the physical world by superimposing computer graphics and relevant data points onto a user's natural world view and have been purported to provide faster knowledge acquisition, improved retention, increased motivation and engagement, and more hands-on and immersive learning [1–3]. In operations, the technology is believed to provide visual supports that promote faster performance and reduce errors [4]. Past research evaluating AR with novices in an industrial context demonstrated that AR training produced faster learning of a memory-based assembly routine as compared to a 3-D manual [5]. Jung [6] found that when compared to the same 2D content, AR-based 3D projection mapping of a physical

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environment significantly increased recognition memory accuracy for pattern locations, and led to greater spatial presence, and provided a 25% more "satisfying" experience.

While these studies speak to the benefits of AR training, other research points out potential limitations, including negative effects of AR cueing (i.e., attentional tunneling [7]), trainee dependency on AR-features and instructional components [8], which are effects that could potentially lead to lack of transfer of skill from AR to real world tasks. Past research using a reading task has demonstrated that the focal distance and context switching that occurs when using AR and integrating information from both virtual and real elements negatively impacts task performance and leads to eye strain and fatigue [9]. Furthermore, there are perceptual issues such as the characteristics of head-worn displays (HWDs) like AR headsets - mismatches between visually displayed information and other senses, restricted field of view (FOV) or mismatched inter-pupillary distance (IPD), which can result in physiological maladaptation. Physiological effects such as shifts in visual function, degraded proprioception, cyber or sim-sickness, and ataxia can compound concerns associated with human information processing and undesirable psychological effects that can significantly negatively impact learning and skill transfer to reality.

Given the sometimes disparate findings and the increasing application of AR in both training and operations, as well as increased affordability and availability, it is important for researchers, user interface and user experience (UI/UX) designers, and AR technology developers to understand the factors that impact the utility of AR. To increase the potential for realizing the full benefit of AR, adequately detailing the interrelated factors that drive outcomes of different AR usage schemes is imperative. A systematic approach to understanding influential factors, parameters, and the nature of the influence on performance provides the foundation for developing AR usage protocols and design principles, which currently are few. Toward this end, this work presents a theoretical model of factors impacting performance with AR systems. The framework of factors, including task, human, and environmental factors, conceptualizes the concept of "AR Receptivity", which aims to characterize the degree to which the application of AR usage is receptive to the technology design and capabilities. The discussion begins with a brief overview of research efforts laying the foundation for the model's development and moves to a review of receptivity as a concept of technology suitability. This work provides details on the model and factor components, concluding with implications for application of AR in both the training and operational settings.

2 Past AR Research

A number of empirical studies have evaluated the potential benefits of AR on human performance outcomes, some of which also assess user perceptions of AR usefulness to the context. The results of these studies provide evidence that variations of task type, differences among individual users, and environment of usage can drive whether AR outcomes are superior to or surpassed by traditional experiences. Given that purported benefits of AR are expected to increase some skill types and improve upon training experiences, it is important to understand the conditions under which positive effects are observed and those for which negative outcomes are possible.

2.1 Nature and Type of Task

Schmidt-Daly et al. [10] evaluated the utility of an AR-equipped sand table for enriching training of military map reading and land navigation planning tasks. The Augmented REality Sand table (ARES), developed by the U.S. Army Research Laboratory (ARL), provides a projection of graphical imagery or visual augmentations over physical sand that can be shaped to mirror real terrain [11]. The system-delivered AR can automatically present augmented overlays that match the dynamic manipulations of the physical (e.g., contours mapped to sand elevation), and can provide visual representation of variable terrain features (e.g., roads, vegetation). ARES has been reported to provide improved training of spatial skills and spatial reasoning competencies as compared to traditional, 2-D maps [10]. In a study allowing trainees to use all map media formats to complete map reading and basic route planning tasks, authors found the ARES training condition to produce better results for distance estimation tasks and landmark identification tasks when compared to use of a 2-D paper map and use of Google Earth© to present map data. Participants were more accurate on both tasks with using ARES than they were with either of the other map delivery mediums. This finding is in line with past research that has found AR to be helpful in learning spatial skills and spatial concepts [12, 13]. Evaluation of individual differences in this study, collected via demographic surveys of game play and familiarity, revealed that individuals who reported moderate to high game play proficiency perceived ARES to be more useful than the other map training tool types [14]. While these performance and perceived utility results are positive, the same study produced inconclusive data on the utility of the AR supported training on higher-order map-based tasks such as situational judgement and route selection. Though participants, in theory, would use the same lower-level information elements such as position, elevation, contour data, and other terrain features to complete the situational judgement tests, as they did for distance estimation and landmark identification tasks, their performance on the judgement tasks did not gain the same AR benefits, as Schmidt-Daly et al. [10] found no significant difference between the map presentation medium on this performance measure. Furthermore, while ARES received higher scores on perceived utility overall and individuals reporting more game experience provided high ratings on utility for the conditions, these participants actually performed better when using the other digital medium, Google Earth© [10].

In a study comparing AR to Virtual Reality (VR) in re-training of activities for daily living for stroke survivors, researchers found AR training to be superior [15]. The motivation for the AR-based training was to provide a more "natural way to maximize learning" of common daily activities for those suffering impact to their motor skills [16]. Khademi and colleagues [15] designed a pick-and-place task representative of daily activities that required trainees to pick up a virtual cylindrical object and "place" it inside a virtual square appearing at random locations within VR or AR. The VR environment was presented through a computer monitor. The AR was presented using a projection device providing a virtual overlay of the target square. The task included psychomotor elements such as reaching, tilting, grasping, and positioning. A score of object placement (i.e., total target placements achieved in a 30-s time limit) was calculated for each condition. Results indicated that the AR condition produced better performance than VR; that is, AR resulted in significantly more objects placed within the allotted time period as compared to the VR condition.

Other evaluations of AR for practice of psychomotor skills produced different outcomes, with AR performance falling below that of real-world training. Researchers exploring the potential application of AR for guiding precision actions found negative effects possibly related to challenges associated with a phenomenon termed “focal rivalry”, the human limitations on simultaneously focusing visual attention on virtual and real objects [17]. The study investigated the impact of disparate focal cues on user performance and workload during an AR-guided task using the Microsoft HoloLens. The empirical task involved connecting dots, with and without AR support. Monocular (with one eye) and binocular (with both eyes) tests were performed and followed up with assessment of workload using the National Aeronautics and Space Administration Task Load Index (NASA-TLX). The results found no significant effects of the conditions on workload but did find better performance in the non-AR condition. When asked, participants reported feelings of comparable performance, however the data provide evidence of more errors with AR. On average the magnitude of error in lines drawn with AR guides was 2.3 mm in length, with the largest error at nearly 6 mm. Without AR, using just the naked eye, errors averaged about 0.9 mm. Errors in precision could be significantly detrimental to human performance outcomes in context such as AR-supported medical intervention, the context upon which this initial study of guided AR support was founded. Contrasting the study of AR benefitting the practice and execution of gross motor skills in a pick-and-place task [15], the results of this study indicates the influence of task type on AR utility. Such precision-based tasks may not be well-suited for AR application. This point is reiterated in an examination of studies evaluating AR for assembly-type tasks, which indicates training of complex and precise psychomotor skills may be limited in AR given the need to hone fine motor skills which are the result of years of practice [18].

Duration of the task will influence the duration of AR usage for either training or real task performance. Given the potential for visual discomfort, fatigue, headache, and nausea that has been observed in interactions with virtual environments and virtual content, longer exposures to AR to accommodate to task durations may be inadvisable. While research on aftereffects for AR are limited, past VR studies have demonstrated that the severity of psychological responses can be proportional to exposure duration [19]. Such effects may linger for hours or even days after exposure, which can impact user safety and the safety of others when symptomology influences user behaviors and performance outside of AR.

2.2 Individual Differences

In studies focused on individual differences, researchers have evaluated the potential for AR to attenuate the influence of individual differences on learning achievements. Zhang et al. [20] conducted research with elementary-aged students studying natural sciences. The research compared knowledge acquisition of natural science facts in AR supported training to learning achieved with traditional, non-AR supported training. Students using AR were able to download an AR application on their personal phones to use in the classroom. The application augmented their learning experience by providing additional information to them as they scanned their textbooks with the phones. The students in the non-AR group were provided supplemental information via traditional methods such as paper handouts and PowerPoint. The study results demonstrated that the non-AR group did not realize the learning gains observed with the AR-support group, which produced significantly better scores on an exam. Interestingly, the authors also reported that students in the AR-support group that were lower-performing in general, were able to perform closer to those considered higher-performing in general. These results provide evidence that AR-aided instruction can benefit the learning process and may help to lessen the impact of individual differences like proficiency levels. It should be noted that the quality of the instructional content might have some influence on the utility of the AR-supported approach.

Chen and Wang [21], also conducted research to evaluate the influence of individual differences, specifically on the impact of learning achievement in an AR-supported training protocol. The experimenters implemented a 3-part learning flow that moved from knowledge presentation with traditional methods, to learning with AR, to a reinforcement stage of learning during which students could elect to use AR while using a handout that guided reflection on their learning. They used questionnaires to evaluate two individual differences among the student-participants – learning style and competence with computer-based technologies. The researchers also assessed knowledge acquisition of the students comparing post-test results of knowledge with results obtained from a test administered prior to exposure to the training. The results of the study indicate that students were able to boost their knowledge of the science concepts covered during the 3-part training, with significant differences in the pre- and post-test scores. Evaluation of student perceptions of the AR training scheme indicated that the majority of participants preferred the AR portion of the learning protocol over the others. Over 90% of participants found the AR training “valuable” or “interesting”. The effort to evaluate the influence of individual differences, however, produced unexpected results. The researchers found no significant influence of these individual differences. The authors state that the findings are not consistent with past research that has demonstrated supporting learning preferences and increased experience or familiarity with computer-based technologies adds to learning gains.

Stanney, Fidopiastis, and Foster [22] examined the impacts of physiological and biological individual differences on the occurrence of simulation sickness. The goal of the study was to determine the drivers of gender-based differences in the experience of simulation sickness. Across two experiments, male and female participants were exposed to a 20 min virtual rollercoaster using a VR headset or a flatscreen TV. In the first experiment, Inter Pupillary Distance (IPD) was found to account for 42% of variability in simulation sickness experienced. The second experiment demonstrated that when female participants were within the IPD accommodated by a VR headset, they experienced simulation sickness in a manner similar to male participants.

Individual differences with respect to psychological states such as the sense of presence may also impact the utility of AR. Research has reported relationships between immersive tendencies and presence experiences, noting that individuals producing high immersive tendencies scores also report high presence scores [23, 24]. This may have a significant impact on AR experiences given the potential for AR to result in symptoms of cyber- or simulator sickness. Research has reported a negative correlation between presence and cyber-sickness [25, 26]. Their data from multiple studies demonstrate a large negative correlation between sense of presence scores and self-reports on the severity of cyber-sickness symptoms. Research describing the interrelated constructs of immersion, presence, and cyber-sickness suggest that individual propensity toward immersion or lack thereof can influence AR experiences. Individuals more likely to be immersed, and thus "feel" present, may be less likely to suffer sickness which can negatively impact AR experiences.

2.3 Environmental Issues

Researchers examining use cases for AR are evaluating its application beyond controlled, indoor spaces. Azuma [27] discussed a number of environmental challenges in making AR work well outside. The author discusses general ergonomic issues with use in an uncontrolled environment, such as size, weight, power, and durability. A key environmental condition discussed is lighting, which is highly variable in outdoor spaces. Azuma [27] states that most AR displays are not able to achieve the brightness levels required to match the range of lighting conditions along the spectrum from bright sunlight to pitch-dark night. This results in significant issues in user capacity to recognize and identify virtual objects in the augmented space. Ultimately, the negative impact is observed as perceptual and human information processing issues that are compounded by the fact that the resolution of the displays also fails to match human vision capability.

Internal research by the authors and colleagues evaluating AR application across indoor and outdoor conditions has provided a number of insights. For marker based tracking systems, performance has been observed to be better in diffuse and stable lighting. Lighting that is not flickering and remains stable (e.g., does not change overly in terms of brightness) leads to better results with regard to system tracking of AR markers. This kind of consistency in lighting leads to consistency in marker registration of the AR system, which can improve application outcomes. For infrared Simultaneous Localization And Mapping (SLAM) based tracking AR, performance is best when there are no significantly dark or very bright areas in the environment. Performance has also been demonstrated as better when other infrared radiation sources are limited or avoided. In addition, solid white, solid black, reflective, and transparent materials have been observed to cause issues with tracking with infrared SLAM. In a proof-of-concept development effort toward applying AR for outside use with unmanned systems, the display issues created substantial concerns with respect to viewing critical robotic system data through the display, greatly impacting the ability to build situation awareness on the robot and other aspects of the operational task. The solution was to develop "shades" for the AR technology, which were 3-D printed and applied over the viewing goggles.

Beyond lighting, environmental elements such as heat and noise have been observed as problematic for AR technologies. Some systems (e.g., the Microsoft HoloLens) are not actively cooled and, as such, they can overheat in warm spaces. Others have integrated and active cooling capabilities (e.g., Magic Leap), which helps to ameliorate issues with overheating. Mobile Phones equipped with AR have been observed as quite versatile in this regard, and can operate in higher temperatures, despite being passively cooled. Voice commands are currently considered a primary source of input for AR systems. Noise, then, can be problematic for applications of AR. Most systems do not include noise-cancelling features, so noise can negatively influence user performance in training or operational settings. This can be a significant detriment in operations where gesture input is limited due to the need to use hands for other operational tasks.

3 AR Receptivity

Results from these various studies indicate a need for additional study of how the implementation of AR influences the quality of outcomes. That is, studies need to systematically evaluate how, where, for how long, and for whom AR is being applied. There are limited studies that look at the different factors influencing AR utility. Cheng and Tsai [13], for example, stress a need for exploring learner characteristics as “sparse studies” examine human factors involved in AR-related science learning. [18] list limitations in studies evaluating AR application to various kinds of assembly tasks, noting the number of other contexts in which AR can and should be studied given the variability of task types and complexities. The kinds of systematic reviews the research suggest adding to the overall body of work describing AR utility and offers results toward the development of AR usage guidelines. This kind of effort must begin with defining the important factors in AR implementation - human factors (individual differences), task factors (type, complexity, etc.), and environmental factors (physical attributes). Multiple parameters associated with each can work together to influence psychological and physiological experiences with AR. Maximizing effectiveness and reducing negative results requires ensuring the factors and parameters appropriately match to the AR technology and system capabilities. As such, the current work considers the concept of AR Receptivity. The term is used as a means of describing the “goodness of fit” or suitability of AR for a given application based on the receptivity of the individual user, the tasks for application, and the environment.

3.1 Technology Acceptance and Receptivity

The concept of AR Receptivity comes directly from past work on technology acceptance research. In the context of technology innovation, transfer and acceptance, receptivity has been defined as the “extent to which there exists not only a willingness (or disposition) but also an ability (or capability) in different constituencies (individuals, communities, organizations, agencies, etc.) to absorb, accept and utilize innovation options” [28]. Studies evaluating receptivity have used approaches such as the Technology Acceptance Model [29, 30] and the Technology Acceptance Scale [31] to assess technology suitability. The Technology Acceptance Model, for example has been used to assess technology receptivity in educational settings on the basis of the three primary model factors–perceived usefulness, perceived ease of use, and behavioral intentions [32]. The Technology Acceptance Scale, similarly presents queries to users related to perceived usefulness and perceived ease of use of technology and has been used to assess user receptivity of a robot-based coach for smoking cessation [31].

Both questionnaire-based methods produce scores on component scales and for the overall measure, with higher scores indicating high acceptance or receptivity. The component areas provide some starting point on technology use, acceptance, and adoption based on common aspects of usability, but they do not take other key factors into consideration. Consideration of these additional factors facilitate increased understanding of the conditions producing immediate and persisting effects of AR on human psychology (e.g., perception, attention, learning, memory), human cognitive-affective states (e.g., stress, engagement), and human physiology (e.g., ataxia, gut responses). An expanded model will highlight human factors (individual user differences), task factors (characteristics and work design), and environmental factors (physical elements), and relate the same understanding mediating or compounding influences of AR system design (e.g., optical, display, graphics capabilities) to characterize AR Receptivity [33]. Figure 1 presents a graphical depiction of the theoretical model.

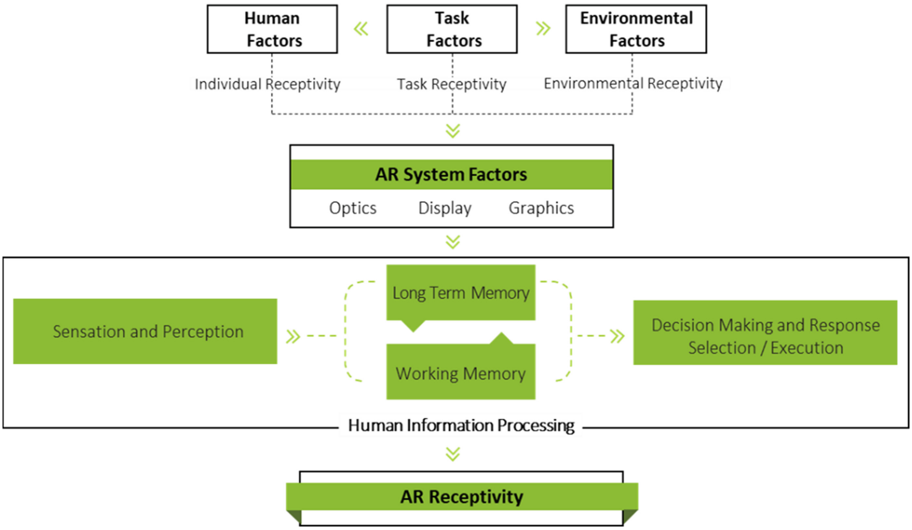

Fig. 1. Theoretical model of AR receptivity

3.2 Theoretical Model of AR Receptivity

The theoretical model includes three major "layers". The top layer presents three high-level factors that map to three proposed receptivity components. These components essentially describe the broad factor categories than can influence AR experiences, acceptance, and use. Human factors map to individual differences and Individual Receptivity. Task factors map to Task Receptivity, which focuses on the potential influence on task type and operational characteristics on AR outcomes. Environmental factors map to Environmental Receptivity, adding consideration for how the physical aspects of the environment impact ability to effectively use AR. For all three factors within the top layer of the model – human, task, and environment – receptivity is characterized by a willingness (of an individual) or inherent characteristic (of a task or environment), along with the ability (of an individual) or capability (of a task or environment) to absorb, convey, accept, implement, and/or effectively utilize AR technologies.

The three high-level factors in the top layer intersect with the AR system design factors, presented in the second layer. The way an AR technology is designed to work – its functional capabilities and limitation, its form factor, and the like – significantly influence the user's experience. Furthermore, as the system is applied to a specific user, for completing or learning a particular kind of task or competency, in a given application environment, the model must consider the influence of the system on overall outcomes. For AR, the system optics, display, and graphics are primary capability features that can present limitations to usage and utility. More specifically, system resolution, brightness, color fidelity, field of view, and capability for stereoscopy can influence the human perception and cognition when using AR. This leads to the intersection of the second layer of the model with the third layer which presents components of human information processing.

The quality of human information processing is critical to human performance in training or real-world operations. The degree to which a user can effectively and efficiently sense and perceive critical elements, comprehend and judge their meaning, encode relevant information in working and long-term memory, and further process the information for decision making directly impacts performance outcomes. The third layer of our theoretical model presents key aspects of human information processing – sensation, perception and attention, encoding into memory, decision making and response selection – as they are directly influenced by main and interacting effects related to human, task, environment, and system design factors. Theoretically, increasing receptivity associated with any factor would positively impact human information processing and performance, to the degree that the system capabilities do not degrade any receptivity element. There may, of course, be competing parameters or factors, as well as compounding and countering influences of each. The goal in AR application should be to provide the most advantageous conditions with respect to individual user, task application, and environment of use to optimize effectiveness of the selected AR technology. That is, the implementation and application should aim to optimize AR receptivity in order to maximize AR outcomes. Outcomes might be related to multiple aspects of overall system performance (e.g., objective task outcomes), training (e.g., efficacy, effectiveness, and transfer), acceptance (e.g., usage and adoption with the training or operational context), psychological responses (e.g., motivation, stress, engagement, task efficacy), or physical responses (e.g., sickness, dizziness, blurred vision). Designers, developers, and implementers may have differing goals with regard to which of the outcomes to prioritize for optimization. The authors contend, however, that consideration of the impact of all factors and how they interact to provide complementary benefits or compounding complaints is critical to understanding AR effectiveness.

3.3 Receptivity Factors: Human, Task, and Environmental

The theoretical AR Receptivity model can help guide considerations in regard to optimizing effectiveness of AR technology based on identified receptivity factors, as it links the AR system features and functional design capabilities to the deployment conditions of interest. Table 1, below, presents the factors impacting AR receptivity as outlines in the theoretical model. It should be noted, the list provides examples, and is not all-inclusive of the factor types or parameters.

Table 1. Human, task, and environmental factors impacting receptivity

Human factors	Task factors	Environmental factors
• Past experience • Mental models • Task proficiency • Perceptual and attentional skills and abilities (visual acuity, contrast sensitivity, color matching, stereo-acuity, dark focus, attention switching) • Cognitive, spatial, psychomotor skills • Personality traits and predispositions (engagement, self-efficacy, locus of control, immersive tendencies, mood, stress) • Attitudes and beliefs • Neural conditions	• Type of task (cognitive, psychomotor) • Duration • Complexity or level of difficulty • Sensory/perceptual needs (auditory, visual, haptic, etc.) • Psychomotor skill requirements (gross motor, fine motor and precision) • Cognitive skill requirements • Spatial skill requirements • Information requirements • Collaborative requirements • Temporal requirements • Task interface and interaction design	• Lighting • Noise • Temperature • Weather • Interference • Stability, vibration, perturbation • Complexity, distractions, dynamics

In general, human performance is affected by numerous user characteristics, at both the individual and the team level. Each human user has his or her own experiences, competencies and proficiency levels, aptitudes and attitudes, and personality traits and dispositions. Differences in motivation, capacity for engagement, ability to cope with stress, along with commonly considered characteristics such as age and gender can impact user learning and performance learning [34]. Attention allocation and capacity for switching attention between contexts and task elements, both AR and real-world, significantly affects user information processing and decision making [24]. It is, therefore, important to consider human factors inherent to the AR user when applying the technology and predicting the outcome of application. As an example, individuals with positive attitudes toward AR are more likely to be accepting of the technology and open to using AR when applied to work or training. Users with high quality perceptual, attention switching, or spatial skills might be expected to exhibit better task performance in AR than those lacking the same skills and abilities. In contrast, one might see negative AR acceptance, physiological responses, and task performance for persons, with low immersive tendencies, physical sensitivities to immersive technologies, or degraded perceptual skills. The key is that variable parameters or levels associated with human factors can directly influence AR experiences, usage, and utility. As such, human factors impact individual receptivity which is described as the willingness and ability of an individual to process information in, accept application of, and effectively use AR technologies.

- Individual Receptivity: The willingness and ability of an individual to process information in, accept application of, and effectively use AR technologies.

Task factors, both training-based and operational, influence user information processing and performance. Stanney [35] indicated that task characteristics affect user outcomes in AR applications. Task characteristics also determine the level of realism, immersion, and overall detail necessary to achieve the desired training or performance effect. Some task characteristics will be more or less suited to AR environments. The parameters of the task, the number and type of sensory cues and information elements that need to be represented or supported for the task, along with the variable cognitive or physical requirements and constraints of the context, are important to AR application. Task complexities can influence AR utility for learning. Long duration tasks may result in physiological aftereffects that are persistent and impact user safety. Poorly designed task interfaces may fail to provide needed sensory cues in the right formats which limits information processing performance. Tasks that are highly cognitive in nature, with little need for psychomotor skill or spatial reasoning, may result in low utility for AR. Tasks that rely on or prioritize sensory cues, knowledge, or skill sets that cannot be accurately represented, replicated, or completed in AR are not conducive to the application of the technology. As with human factors, implementers should aim to maximize utility of AR by applying it to tasks for which the characteristics of AR are highly suitable.

- Task Receptivity: The degree to which the characteristics, requirements, and constraints of tasks to be performed (in training or operations) can be effectively represented in AR technologies.

Many environmental factors directly relate to the reliability and durability of the AR technology. High temperature environments lead to low reliability in system performance in systems that rely on passive cooling. Noisy environments will result in poor voice input performance. Interference, lighting, and wet weather will all result in performance issues. In general, control of environments will increase control over reliability. That doesn't mean that all uncontrolled spaces should avoid AR usage. It means that implementers should consider the impact of environment when designing an application or implementation protocol. For example, if outdoor use is desire, timed exposure to heat or selection of cooler areas should be implemented. The goal is to optimize physical elements of the environment as much as possible to promote reliable system functioning.

- Environment Receptivity: The degree to which environment (training or operational) characteristics and constraints facilitate effective information delivery and AR utilization.

3.4 AR Technology Design Factors

One can easily conclude that increasing the match between AR capabilities and parameters of any single factor increases the potential for effective human information processing and performance with AR. However, assessment of receptivity and predicting the outcomes for AR receptivity go beyond single-factor assessment. It is highly probable and projected that factors and parameters of factors interact, given the nature of interrelationships among factors, to produce more complex outcome potentials. Some combinations are expected to produce better outcomes than others, but the specific effects of those combinations and the degree to which each factor and component influence and weigh on the outcomes are not well known. The theoretical model of AR Receptivity provides a foundation upon which to structure and roadmap a systematic empirical approach to examining these interrelated influences.

The review must consider the AR technology to be applied to the given context, as AR capabilities and features drive the level of immersion experienced and influences how and where the system can be applied for individual or collaborative tasks [36]. As such, the theoretical model presents the AR System Factors in the second layer of the model. Features and capabilities of the AR will either moderate or exacerbate the influence of the receptivity factors, in isolation or in combination, ultimately impacting the quality of human information processing and user experience in AR. As an example, the form factor (e.g., tablet, phone, or head display) is expected to influence overall AR Receptivity, with some forms projected to be better suited to some tasks than others. Task requiring hands to be free for completing task steps will be less receptive to tablet- or phone-based AR unless some device is applied to hold the platform for the user. Similarly, some forms will be better suited to some individual differences and environmental characteristics. Users that suffer negative physiological or psychological impacts from a high degree of immersion, may not be well-suited for head-worn displays, but better able to sustain performance with non-immersive AR. These same non-immersive deployment tools, like phones, may be best suited for use in uncontrolled environmental lighting and temperature when AR usage must be sustained for longer periods of time.

As another example, use cases for AR will require variable levels of or amounts of virtual content or assets to achieve specific experiential and functional goals. The amount of virtual content necessary to convey meaningful (context relevant) information for training or operational performance has been termed as the “weight” of the AR. Light AR conveys fewer virtual elements than “heavy” AR, which presents more virtual content as compared to real-world content. Mobile form factors may be best suited for light AR contexts, while head-mounted displays, which are more immersive, may be better for heavy AR contexts [37]. Researchers, such as Wu, Lee, Chian, and Liang [38] evaluating application of AR to training, suggest that the key is to implement the technology in such a way that it best supports meaningful use in context.

AR technical capabilities such as the quality of system optics, display, and graphics impact human visual perception in AR. Resolution, brightness, color fidelity, field of view, and stereoscopy capabilities vary across AR technologies. Mobile AR technologies for example typically provide good visual acuity, but lower stereo-acuity than head-worn technologies which are improving in the area of depth mapping, stereo-acuity and 3-D representation of information. It is important to note, however, that limitations in AR optics and graphics can result in image effects such as grainy or blurred images, limited visibility of various colors, and distortion of depth cues. Distorted scenes and misrepresented cues can impact information processing and cause immediate or persistent psychological effects, as well as physiological effects. Poor presentation can impact feelings of presence, perceptions of utility and task efficacy. Mismatches to the human visual system can lead to sickness. If the system capabilities are not adequate for the context (i.e., that is, the capabilities cannot provide meaningful information effectively and accurately), detection, recognition, and identification are hindered. This is highly detrimental when training in contexts where target/object detection are critical, as it may cause negative transfer or lead to reliance on false cues. These limitations and decrements would be compounded for users who have inherent limitations to perceptual systems, and environmental contexts that further degrade visuals.

4 Receptivity Use Case

The examination of the results from the authors' past and current efforts defines factors, examines relationships among factors, and devises a framework for examining AR technology receptivity. As an example, a specific AR platform might match all of the psychological sensation and perception requirements for a task yet misalign from a physiological perspective. Or, a platform might lead to few physiological effects, but misalign psychologically causing a mismatch between AR cues, multi-modal cues, and user interactions required for knowledge transfer or operational task performance. Additionally, an AR technology may simply fail in regard to the optics and graphics needed for accurate and precise visual perception and discrimination. A consideration of relevant receptivity factors and technology factors helps to lay the foundation for optimization. Consider the below use cases and relevance of AR Receptivity.

There is interest in applying Augmented Reality to medical training, in particular tactical combat casualty care (TC3). AR is expected to provide high-fidelity, hands-on training on battlefield injury states by presenting critical sensory cues and trainee task interactions for rapid repeated practice of trauma interventions. The application of use is intervention training for observed tension pneumothorax (TP), a condition in which air is moving into the space between the lungs and the chest wall. The trainee will use AR to practice needle decompression for releasing the pressure caused by the leaking air. As the training is for battlefield care, conditions should mimic that environment. A headset application is desired.

Individual receptivity should consider evaluations of conditions such as neural conditions and perceptual impairments that can exacerbate psychological or physiological effects. These individuals may need to be excluded from head-worn AR training. Psychological effects related to AR's capacity to influence human attention allocation should be considered in the training task design and interface design. Prolonged attention and required switching of attention between multiple AR elements and real-world element that drive decision making during the intervention could potential impact cognitive loading, as well as visual system aftereffects from long term exposure for an extended or repeated scenario. Similarly, as AR has been found to elicit higher cognitive activity (as compared to non-AR task situations) assessment of stress and engagement should be considered with human factors and individual differences, to ensure they don't persist following exposure. Trainees may need significant down time prior to returning to daily activities or normal duties. Individuals with lower skill levels might also experience higher loading as they are coping with using AR while also trying to learn skills. As such, their learning in AR headsets may need to be guided and focus on building of basic knowledge of TP to ensure they can absorb knowledge in AR and transfer that to future training or reality, before trying to integrate more complex skills.

Task receptivity can be linked to the task type. TP interventions requires fine motor skill application to place a needle in a specific location for relieving pressures in the chest cavity. Perceptual limitations can be caused when AR overlays don't correctly align with body landmarks and locations. Misperceptions of the correct location to place the needle and aligning with the intercostal space through the headset, can lead to negative transfer and impact real-world performance. Further, if there is not a one-to-one correspondence between such needle placement in the AR headset and the real world, this can lead to a shift in the kinesthetic position sense, which could lead to degraded hand-eye coordination in the real world. Prolonged exposure to perceptual mismatches can also lead to nausea, so exposure time should be evaluated.

Given the battlespace environment, implementers should consider where the training will occur, to avoid overly bright conditions and too-high temperatures. Shades, if available for the technology, might need to be applied during implementation to ensure the critical cues learned in the training are appropriately salient.

The training scenario implementation must ensure that the technological features of the AR headset that is selected can accurately convey critical multi-modal sensory cues. Depth cues relevant to the task (e.g., needle placement, needle depth, chest position and movement, etc.) should be adequately conveyed to ensure proper skill development. Technologies incapable of providing correct cues, including color, should be avoided.

This use case demonstrates a number of receptivity concerns that should be considered to promote effective human information processing and AR outcomes, including performance, psychological effects and physiological effects. So, while AR technology has the potential to advance the TC3 training, there is a critical need to identify any receptivity limitations that could compromise user states, training effectiveness and performance, and safety.

5 Implications for AR Usage Guidelines

Organizations interested in application of AR and realizing its full potential need to understand the human factors concerns with AR, the capacity to acquire and transfer skills in AR, and the ability to mediate negative effects of AR exposure for maximizing training and performance gains. The work presented here describes a theoretical model of AR Receptivity that can guide empirical studies systematically examining AR effects. The goal of the model is to define interrelated factors driving the suitability and utility of AR. Characterization of a receptivity construct will ultimately support stakeholders unfamiliar with AR platforms in moving beyond simple review of technical specifications and cost, to consider the relative "goodness of fit" or optimal implementation of the technology for the context and environment of use and the target user. It helps us better answer the questions around the best implementations for AR to promote acceptance, adoption, and effectiveness. Ultimately, the results of studies guided by and underlying framework provide evidence for development of implementation and usage protocols. Target areas that will benefit from usage and applications guidelines include, but are not limited to:

- Design guidelines of interfaces and interaction mechanisms to address task factors and AR system factors, including form factor and capabilities
- Implementation guidelines related to AR system selection addressing individual differences
- Implementation guidelines related to AR system selection and implementation to address task factors related to sensory cue needs and information presentation needs
- Implementation and usage guidelines relevant to environmental factors such as lighting, noise, temperature, size/space, when the environmental context for meaningful task application is critical to AR usage
- Implementation guidelines to address individual differences in contexts with important collaborative task requirements and/or team processing
- Application guidelines with respect to best fit of technology capabilities (i.e., optics and graphics) are critical to training or operational performance when paring those capabilities with the human visual system
- Usage guidelines on protocols for duration of usage to address physiological and psychological aftereffects
- Application guidelines on best fit of technology based on nature and type of tasks, including cognitive tasks (on continuum from basic to high-order decision making) and psychomotor tasks (ranging from gross motor skills to fine motor skills)
- Design and implementation guidelines for information presentation when context switching in AR is task driven; guidelines for appropriately balancing virtual and real objects in usage context.

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