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Influences of augmented reality head-worn display type and user interface design on performance and usability in simulated warehouse order picking

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ABSTRACT

Limited information is available regarding the effective use of workplace head-worn displays (HWD), especially the choices of HWD types and user interface (UI) designs. We explored how different HWD types and UI designs affect perceived workload, usability, visual discomfort, and job performance during a simulated warehouse job involving order picking and part assembly. Sixteen gender-balanced participants completed the simulated job in all combinations of two HWD types (binocular vs. monocular) and four UIs, the latter of which manipulated information mode (text-vs. graphic-based) and information availability (always-on vs. on-demand); a baseline condition was also completed (paper pick list). Job performance, workload, and usability were more affected by UI designs than HWD type. For example, the graphic-based UI reduced job completion time and number of errors by ∼13% and ∼59%, respectively. Participants had no strong preference for either of the HWD types, suggesting that the physical HWD designs tested are suboptimal.

1. Introduction

Augmented reality (AR) is a technology that can enrich physical reality by overlaying computer-generated information atop the real environment and/or annotating objects and environments (Azuma, 1997), and which has been suggested as having substantial potential for occupational applications (Behringer et al., 1999). Particularly in logistics, AR is viewed as a technology that could improve logistics processes (Cirulis and Ginters, 2013; Glockner et al., 2014; Stoltz et al., 2017). These processes often require frequent data interactions to complete physical work tasks, for example when planning a work path, identifying item locations and quantities, and arranging goods. AR head-worn displays (AR HWDs), or simply "smart glasses", are a wearable AR hardware platform that is attractive for occupational applications, since workers can freely use both hands and move about and easily access task-relevant information in a head-up fashion using either one (monocular) or two eyes (binocular). The potential benefits of AR HWDs have been demonstrated in diverse industrial applications, including warehouse operations (e.g., Iben et al., 2009; Reif and Günthner, 2009; Schwerdtfeger et al., 2009) and maintenance/assembly (e.g., Caudell and Mizell, 1992; Henderson and Feiner, 2011; Ke et al., 2005).

Order picking (OP) – retrieving a set of items from storage locations to fill customer orders – is a particular area of warehouse operations wherein HWD use has received growing attention. This attention may be because OP is often highly labor-intensive, representing up to 55% of all warehouse labor activities (de Koster et al., 2007), and using human pickers (i.e., manual OP) is prevalent in practice due to its simplicity and flexibility (de Koster, 2012; de Koster et al., 2007). Existing work has demonstrated that HWD use produces improved or similar task performance (e.g., fewer errors, faster picking speed) and perceived workload as compared to existing OP technologies such as light-directed (Guo et al., 2014), voice-directed (Wiedenmaier et al., 2003), and paper-based systems (Guo et al., 2014; Reif and Günthner, 2009; Weaver et al., 2010). Weaver et al. (2010) also noted that users found HWDs easier to use and learn than paper pick lists. Further, commercial HWD solutions for OP are being introduced to the market, such as UBiMAX xPick (www.ubimax.com) and KNAPP visual manual picking (www.knapp.com). DHL pilot-tested the former using two commercial monocular HWDs (Google Glass and Vuzix M100) and reported a 25% increase in efficiency (Deutsche Post DHL Group, 2015).

To support the effective and safe industry adoption of HWD technology, however, there is a need to develop evidence-based design practices for HWD use, since design practices can affect worker safety, health, and task performance. For example, using a monocular HWD may produce a situation in which the two eyes receive different visual stimulation; a phenomenon that occurs to varying degrees with different HWD types (Patterson et al., 2006; Patterson et al., 2007). Such a

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situation may cause user concerns including visual discomfort, eyestrain, headache, dizziness, and/or nausea (e.g., Kooi, 1997; Patterson et al., 2006; Wenzel et al., 2002). Regarding task performance, HWD users may also over allocate attention to HWD-based information and become less sensitive or able to detect unexpected environmental events and hazards (Krupenia and Sanderson, 2006; Liu et al., 2009). Users also can be slower at completing a visual scanning task when using a monocular HWD as compared to a binocular HWD (Laramee and Ware, 2002). Additionally, Bauman et al. (2011) showed, compared to a conventional paper pick method, that the number of OP errors can be reduced by 50% with a monocular HWD, depending on the colors and symbols used in a user interface. Overall, this previous work suggests that the choices of HWD types and UI designs can influence work performance, though presently there is only limited information regarding the effects of such choices.

This study had a primary aim to explore how different HWD types and UI designs affect perceived workload, usability, visual discomfort, and job performance during a simulated warehouse job involving OP and part assembly. Two commercially-available HWD types (one binocular and one monocular) were used to display information to participants about the simulated job. With respect to UI design, two basic but practical aspects were considered: information mode (i.e., graphics vs. text) and information availability (i.e., always-on vs. on-demand). Given results reported by Laramee and Ware (2002), we hypothesized that the binocular HWD would be associated with lower levels of perceived workload and increased job performance as compared the monocular HWD. No specific hypothesis was formulated for the effects of UI design, given a lack of relevant evidence (to our knowledge). As a secondary aim, we sought to confirm results of earlier studies (Guo et al., 2014; Reif and Günthner, 2009; Weaver et al., 2010) that using a HWD would reduce perceived workload and improve job performance, as compared to a conventional paper pick list.

2. Methods

2.1. Participants

A total of 16 gender-balanced participants completed the study, and were recruited from the University and local community as a convenience sample. Their mean (SD) age, stature, and body mass were 24.2 (4.8) yrs old, 179.0 (7.7) cm, and 86.3 (19.1) kg, respectively, for the males; and 22.5 (2.7) yrs old, 165.8 (4.8) cm and 68.5 (15.1) kg, respectively, for the females. All participants reported being healthy, having normal or corrected normal vision with contact lenses, and having no current or recent (past 12 months) musculoskeletal injuries that limited their normal daily activities. Note that those who used prescription glasses were excluded, as it was not possible to wear glasses along with the HWDs. Prior to any data collection, participants completed an informed consent procedure approved by the Virginia Tech Institutional Review Board.

2.2. Warehouse job simulation – order picking (OP) and part assembly

Order-picking and part-assembly tasks were simulated in a mock warehouse environment – one whole floor within the building in which the authors work (Fig. 1) – with tasks performed using a manual "picker-to-part" method. This method requires participants to walk through the warehouse to a fixed pick/part-assembly location and then retrieve/assemble items. The mock warehouse environment consisted of three pick zones, and had 29 pick and three part-assembly locations (Fig. 1). At each pick location, a mock bin was hung on the wall. The mock bin was a 4 × 3 grid, with each grid divided into four quadrants marked with numbers indicating an item's location (Fig. 2). Completing the simulated OP task required participants to tap on a certain quadrant of a certain grid for a given quantity; this was to minimize potential effect of physical fatigue. To simulate simple assembly tasks, two Purdue pegboards (Lafayette Instrument, Indiana, USA) and a wooden board with holes were placed at part-assembly locations (Fig. 2). Completing the part-assembly task required participants to assemble pins, washers, and collars (or bolts, nuts and washers) in a sequence and quantity as specified via the HWD (and paper in the baseline condition).

The simulated warehouse job was designed to include 71 OP and nine part-assembly tasks. To complete this job, participants needed to walk along a specified route (i.e., a sequence of bin and assembly locations) that was selected randomly from among seven routes predefined to have the same total walking distance. These routes were planned so that participants could travel to reach each bin in a reasonably logical way (e.g., no random bin assignments across different pick zones). For each OP or part-assembly location, we set the maximum pick or assembly quantity to be four. Upon completing the simulated job, the total number of picks and assembled parts were controlled to be 177 (i.e., the number of taps) and 23, respectively. We finalized these designs, both of the simulated warehouse job and warehouse environment, after consulting two subject matter experts. These experts confirmed that the simulated task processes and demands were a reasonable representation of those present in actual warehouses.

2.3. Experimental design and procedures

A three-way, repeated measures design was used to determine the effects of HWD type, information presentation mode, and information availability on job performance, usability, and visual discomfort. There were two levels of *HWD Type*, which were commercially available binocular and monocular HWDs (Fig. 3). The two levels of information presentation mode (*Info Mode*) were text-based and graphic-based UI designs (Fig. 4). Finally, the two levels of information availability (*Info Availability*) were constantly visible (i.e., always-on) vs. on-demand. In the latter condition, information was shown in the HWD initially for six seconds but not again until requested by participants. In addition to these eight combinations of *HWD Type*, *Info Mode*, and *Info Availability*, the warehouse job was simulated using a traditional paper pick list (Fig. 4), which served as a basis of comparison.

Information presented on each HWD was controlled using a "Wizard of Oz" approach (e.g., Henderson and Feiner, 2009; Kelley, 1983). As such, participants spoke the words "next" or "done" to see the next bin/part assembly location information, and said "again" to see the current bin/part-assembly location information repeated in the on-demand display condition. Note that it was emphasized to participants that no penalty would be given regardless of how often and/or many times they requested information. We presented the requested information using a tablet computer that was mirrored to the HWDs.

Participants completed both a training and a data collection session, which were done on separate days. In the training session, participants practiced all experimental conditions for ~1 h, and received an explanation of the outcome measures to be obtained. In the data collection session, one of the investigators first walked with participants around the mock warehouse environment to remind them of all pick and part-assembly locations and how to complete the order-picking and part-assembly tasks. Then, participants completed the simulated warehouse job using the paper pick list (baseline), followed by each of the eight experimental conditions. The presentation order of experimental conditions was counterbalanced using 8 × 8 Balanced Latin squares. A 3-min rest period, or longer if requested, was provided between each of the testing conditions.

Both subjective and objective outcome measures were obtained. Regarding the former, participants completed a set of questionnaires after completing each job simulation in a given condition. The questionnaires used are listed below (specific questions employed for the latter three are providing in online supplemental material):

- NASA Task Load Index [NASA-TLX; Hart and Staveland (1988)] to assess perceived workload.