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Integrating smart glasses in a hybrid manufacturing system: towards a better understanding of impacts on productivity, quality and ergonomics/human factors

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***Résumé* – La production s'éloigne de l'automatisation complète pour se tourner vers des systèmes hybrides. Le travail manuel assisté par une technologie intelligente, surtout pour les processus à faible volume, est prometteur. Cette étude vise à mieux comprendre les impacts sur la productivité, la qualité et l'ergonomie, lorsque des lunettes intelligentes sont introduites dans un système hybride.**

10 participants ont été invités à faire quatre assemblages complexes avec 15 répétitions en utilisant des clés à cliquets manuelles et pneumatiques avec et sans lunettes intelligentes. Les données ont été recueillies au moyen de caméras, d'un système d'oculométrie, de chronométrage, du questionnaire NASA-TLX et de photos.

Les résultats montrent que le temps d'exécution est plus court avec les lunettes intelligentes et, avec la répétition de l'assemblage, les participants omettent de suivre des instructions. Les indices NASA-TLX globaux sont élevés pour la charge physique et l'effort. Les évaluations individuelles montrent toutefois des différences importantes. Tous les participants ont commis des erreurs d'assemblage (alignement du support ou serrage des boulons). Les outils utilisés ont eu un impact sur la qualité.

Une analyse plus fine des données de cette étude est nécessaire pour mieux comprendre comment intégrer les technologies conventionnelles, automatisées et intelligentes comme les lunettes intelligentes.

***Abstract* – Production process is progressively shifting away from fully automated towards hybrid alternatives. Technology-assisted manual labor in manufacturing, more specifically low-volume processes, promises increased job productivity and is expected to support the workers. This study aims to gain a better understanding of the impacts on productivity, quality and ergonomics/human factors, when smart glasses are introduced in a hybrid system.**

10 recruited participants were asked to do four complex assemblies each with 15 repetitions using manual and air ratchets with and without smart glasses. The data was collected through cameras, an eye-tracker, time measuring, NASA-TLX for task workload and quality control with documented pictures of each finished assembly.

Results show that completion time was shorter with the smart glasses and, with assembly repetition, participants skipped reading some instructions. Globally, the weighted and unweighted NASA-TLX were high for the physical and effort indicators. Participants' individual scores however show important differences. All participants made assembly errors, whether bracket alignment or loose bolts. The tools used (manual and air ratchet) had an impact on quality.

This paper presents preliminary results. More refined analysis of this study's data is needed to better comprehend how to integrate conventional, automated, and intelligent technology like smart glasses.

***Mots clés* – accessoires intelligents, lunettes intelligentes, systèmes d'assemblage, assemblage manuel.**
***Keywords* – intelligent wearables, smart glasses, assembly systems, manual assembly.**

1 INTRODUCTION

Intelligent wearables have a wide range of potential applications (e.g. aircraft maintenance with speech recognition) [Siyaev and Jo, 2019; Chen et al., 2019], according to research. But compared to conventional, completely manual procedures, semi-manual assemblies could lead to an increase in complexity [Naeini and Nadeau, 2022]. Researchers have shown that the widespread industry use of intelligent technology will cause the use of intelligent wearables to rapidly increase [Dimitropoulos et al., 2021]. Additionally, flexible human-computer interaction, such as intelligent wearables, can offer greater user experiences in comparison to conventional rigid and heavy interactive equipment [Yin et al., 2020].

More precisely, wearables gather information from their surroundings, conduct essential data processing and output the processed data, as well as operate as a component of a larger smart system [Fernández-Caramés and Fraga-Lamas, 2018]. Wearables can be used to assist humans in, for example, monitoring work situations, activities and processes [Pokorni and Constantinescu, 2021] and in this way, can support occupational health and safety (OHS). Among others, they can provide timely alarms and crucial visual information for assembly, improvement and conformance verification, helping thus to reduce human errors [Torres et al., 2021; Nadeau et al., 2022].

Making sure wearables are accepted and used correctly in real work situations is a crucial component of practice, as for any tool or system [Nielsen, 1993]. It is imperative to make sure any technology is user-friendly and useful (e.g necessary to enter a site or operate a specific equipment) [Barata and Cunha, 2019] before being put into operation.

1.1 State of the art

Smart glasses are wearable devices with multiple sensors, an embedded processor, and a digital display for viewing and interaction. For example, to assemble a product, workers can receive instructions, taken from an assembly database through smart glasses. In this way, workers can easily adapt to different product types, and the training time of employees to assemble new product types is reduced [Torkul et al., 2022]. The main challenges with smart glasses are hand and eye coordination with complex tasks [Kreutzfeldt et al., 2019], the need to balance performances with usability measures for high mobility tasks [Chua et al., 2016], higher accuracy and device's cybersecurity when use of gesture is integrated in the smart glasses [Yi et al., 2016]. It has been identified that when the hands are occupied, receiving information through smart glasses does not lead to an increase of task performance [Theis et al., 2015]. Computer Vision Syndrome [Blehm et al., 2005] could be observed after prolonged use. Ongoing use of eye-sensitive technology has been found to have an impact on users' brain and eyes [Mann, 2013]. These challenges have been studied and are still studied in the literature and we invite the readers to consult the review of Nadeau et al. [2022] on that behalf. Finally and moreover, most studies like [Laun et al., 2021 & Laun et al., 2022] used toys as experimental object to assemble. There is a clear need for studies where the object assembled and the assembly conditions are more realistic and closer to industrial working situations. The Applied Human Factors Lab of École de technologie supérieure's unique assembly test bench has specifically been designed and materialized for that purpose.

1.2 Research contribution and perspective

We are aiming to achieve a better comprehension of how industry can use intelligent wearables in hybrid systems. As smart glasses, and their impacts on operational indicators (time and quality) and on ergonomics/human factors (mental, physical and temporal demand perception, as well as performance, effort and frustration) have not been explored as much as they should.

In this study we employed an experimental method as the objective is to understand the usability of smart glasses, according to Nielsen's (1993) framework. The fact that similar studies have been done with toys or in a virtual environment encouraged us to take this path. Practical work closer to what is being done in the industry seemed to us an important path towards a better comprehension of the usability of these new devices.

The methodology of this study (experimental protocol and data treatment process) is presented in section 2. Preliminary results are presented in section 3. Section 4 discusses our preliminary findings, compare them with what can be found in the literature, presents the limitations of this study and gives perspectives for future work.

2 METHODS

2.1 Experimental process

A laboratory experimental research was chosen for this study. The protocol was approved by the Ethical Committee of *École de technologie supérieure* in July 2022.

10 individuals participated in the study, aged between 22 and 51 years old, from the academic environment and outside of academic environment regardless of experience. An equal chance of participation was given to both genders when recruiting and the study was carried out with equal numbers of both genders. Participants were recruited through ads on campus and were invited to attend an information meeting. Participants interested completed a consent form and the 2022 Par-Q+/2022Q-AAP+ questionnaire. Data was gathered during a two-week timeline in autumn 2022.

The tools used in the scenarios were a manual ratchet and an air ratchet (Figure 1). Participants were asked to assemble L-shaped brackets with bolts with and without wearing smart glasses in an ergonomic standing posture (adjustment of the jig's height). More precisely, four distinct scenarios were designed:

1. manual ratchet without Vuzix M400 glass;
2. air ratchet without Vuzix M400 glass;
3. manual ratchet with Vuzix M400 glass;
4. air ratchet with Vuzix M400 glass.

All scenarios had the same tasks, with the same assembly and brackets configurations. They consisted of 15 repetitions, each requiring about a minute to complete. A 10 minutes break was provided to the participants in between each scenario. The participants were not given any time limits in the study.

All the bolts were delivered to them at once, at the start of each scenario, in a box, on a conveyor near the assembly jig illustrated in (Figure 2). Before beginning with each participant, a brief tutorial on how to use the tools and components was provided. The participants had to select the appropriate bolts between the two types provided based on the instructions. For the first two scenarios, both the instructions and an image of the final assembly were printed on paper and attached to the jig above the plate they needed to work on. For the third and fourth scenario, the same instructions and image of the final assembly were only provided in smart glasses. During all scenarios, participants were filmed for upper limb movements with 2 GoPro Hero 3+ cameras which were located on the jig on both sides of the participant, and the time was measured with a chronometer and confirmed by the cameras. A Pupil-labs core eyetracker was also used to track eye movements.

Figure 1. Assembly of brackets on a simulated plane engine using smart glasses

Each participant completed a NASA-TLX survey at the end of the experiment which assessed the subjective workload experienced while doing tasks. Also, each participant's specific comment on the tasks and usage of smart glasses were documented.

In this study, it is hypothesized that introducing smart glasses in a hybrid and complex assembly system will reduce assembly time and increase quality. Assembling in a hybrid and complex assembly system environment increases the perceived workload.

2.2 Data processing

In this paper, preliminary experimental results were obtained by analysis of:

1. the time indicator collected with the chronometer and the Go-Pro Hero 3+ cameras, to check if any time difference was a result of the usage of smart glasses.
2. the subjective assessment of the workload using the NASA-TLX scoring worksheet, to permit an analysis of the overall workload of the participants.
3. the error/quality indicator with documented pictures and tightness check of each bolt of the finished assembly after each scenario. This verification was made to gain an understanding of how smart glasses would affect the quality aspect of the assembly.

More in depth analysis for this experimental data remains to be done and will be presented in a peer reviewed journal paper in writing.

Figure 2. Assembly jig designed at ETS

3 RESULTS

3.1 Completion times

The total experiment took on average 125.4 minutes with a standard deviation of 12.49 to complete. The total scenario completion time was shorter (mean 35.4 minutes, STD 6.63 without glasses; mean 33.6 minutes, STD 6.72 with glasses) when using the smart glasses and participants were less likely to go back to read instructions repeatedly. Results in Table 1 show the completion times for each assembly scenario. Some participants stated that they were not fully reading instructions on the glasses, since the steps were the same as previous scenarios, they simply skipped them.

Table 1. Scenarios' completion times

		Average time (minutes)	**STD (minutes)**
Without glasses	Manual ratchet	19.4	4.73
	Air ratchet	16.1	4.54
With glasses	Manual ratchet	19	4.07
	Air ratchet	14.6	3.13

3.2 NASA-TLX

Results of the weighted and unweighted NASA-TLX in Table 1 demonstrate that, globally, participants were feeling more physical demand and effort than mental demand and frustration from the tasks. However, individually, (Figure 3) shows that subjective results vary between participants.

Table 2. Weighted and raw global NASA-TLX

Group Score Results			
Weighted		Raw/Unweighted	
Overall	35.67	**Overall**	25.00
Diagnostic Subscores		Diagnostic Subscores	
Mental	75.00	Mental	27.00
Physical	137.22	Physical	41.50
Temporal	73.13	Temporal	33.00
Performance	99.50	Performance	33.00
Effort	108.50	Effort	36.50
Frustration	85.63	Frustration	23.50

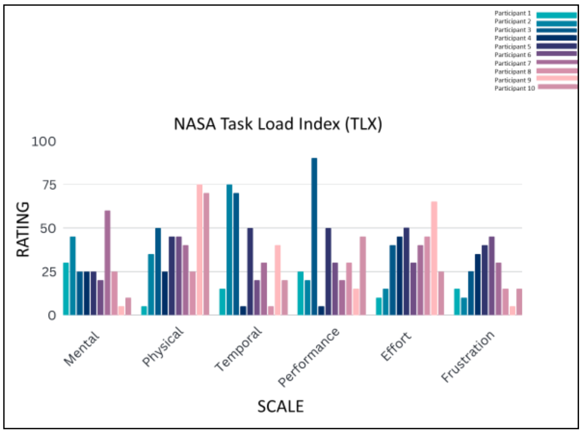

Figure 3. Individual NASA-TLX scores for the 10 participants of the study

3.3 Quality

Quality of the finished task was documented for each participant by checking alignments of installed brackets and the tightness of the bolts. The brackets were supposed to be aligned with the top and bottom of the plate that they were being installed on.

Without glasses:

1. None of the participants completed the assemblies without any mistakes. 9 out of 10 participants did not read instructions completely, resulting in missing details such as aligning the brackets and picking up the bolts' box from the conveyor.
2. 3 out of 10 had left bolts loose.
3. 7 out of 10 were not able to align the bracket properly.

With glasses:

1. None of the participants completed the assemblies without any mistakes. Some participants stated that they were not paying attention to the instructions on the smart glasses because of the repetitiveness of the tasks.
2. 5 out of 10 had left bolts loose.
3. 6 out of 10 were not able to align the bracket properly either due to lack of attention to instructions or difficulty handling the air ratchet as they testified.
4. 3 participants complained that the text in the glasses was small or unclear.

As the analysis of this experiment's data remain to be refined, none of the hypothesis can be rejected at this preliminary data treatment phase.

4 DISCUSSION AND CONCLUSION

As the use of smart glasses was introduced after two times of doing the same task without the glasses, the presence of a learning curve might need be taken in consideration in our more in depth data treatment analysis. The impact of this learning curve might explain partly why the completion times of the scenarios with the smart glasses are shorter.

A substantial amount of data provided on a device for human-machine interaction leads to visual complexity, which increases the user's cognitive load [Kiangala and Wang, 2019]. This could increase fatigue and decrease user's attention [Tsutsumi et al., 2020]. Furthermore, two cognitive stress factors have been reported for users: complexity of product parts and complexity of the environment [Ansari et al., 2020]. Eye tracking measurements and upper limbs movements will be analyzed in a subsequent paper. This analysis should objectify changes of strategies in reading instructions with repetitions and differences in eye movements in scenarios with and without smart glasses as well as might explain partly individual NASA-TLX differences.

The tools seem to have an impact on the alignment and bolt looseness quality indicators with and without smart glasses. It seems easier to control and hold the brackets when using a manual ratchet. Most participants were able to align brackets better with it. Bolts were left loose more when the air ratchet was used which could be a result of the hand not feeling the tightness as much as when using a manual ratchet.

Our team has been modeling analytically (using Functional Resonance Analysis Method known as FRAM and Systems Theoretic Process Analysis known as STPA) (Naeini and Nadeau, 2022) the impact of integrating an intelligent device (in our past study a data glove) in a hybrid system. This first laboratory experimental study is meant to shift our developments from TRL3 to TRL4 by providing original data simulating a realistic assembly task. This study also answers to usability testing questions.

It needs to be noted that the model of glasses is important in a study and the results of this study are only based on one model (Vuzix M400 smart glasses) with specific characteristics. The number of participants is small but adequate according to Virzi's (1992) recommendations. 8 out of 10 volunteers were inexperienced in using the tools. As the NASA-TLX survey was given to the participants at the end of their participation session and was based on the whole work done, the results cannot be used as an interpretation of the differences between tasks with and without smart glasses. Also, due to the design and production method of the jig used, cross-threading of some nuts were problematic and made it hard for participants to tighten some bolts. Repairs were done between participant's experiments. No testing of the participants' eyesight was done before experiments, some participants expressed concerns and slight eyesight difficulties. For participants already wearing prescription glasses, the smart glasses were attached to a cap. Moreover, battery life is a critical matter in using smart glasses. The model used in this study was able to perform for around one hour for the specific input. A battery charging station and back-up batteries were available.

Smart device's usability and usefulness both have tremendous value for industrial deployment and integration in hybrid manufacturing systems. Further studies should explore other assembly scenarios, including scenarios where a supervisor delivers verbal instructions/support and scenarios integrating more than one intelligent wearable.

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