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Revealing workload insights in virtual assembly processes: a case study

Revelando información sobre la carga de trabajo en procesos de ensamble virtual: un estudio de caso

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Abstract

The use of virtual reality continues to expand in industries to improve processes, but it may also increase workload and have a negative impact on the wellbeing of users. This research aims to assess the level of workload caused by industrial assembly training in a haptic-enabled virtual reality system. To do this, 30 inexperienced participants assembled a moderately difficult component consisting of eight pieces and were subsequently evaluated using the NASA Task Load Index. Results indicate that effort, mental demand, and frustration recorded the highest scores, while physical demand received the lowest score. Over 80% of participants experienced workload at high and very high levels, which suggests the need for immediate improvements in the training methodology.

Keywords: NASA TLX; human-computer interaction; haptic systems.

Resumen

La realidad virtual es usada en la industria cada vez con más frecuencia para mejorar procesos; sin embargo, esto puede conducir a un aumento en la carga mental de trabajo, afectando negativamente el bienestar del usuario. Esta investigación tiene como objetivo evaluar el nivel de carga de trabajo ocasionada por el entrenamiento de ensambles industriales en un sistema de realidad virtual con habilitación háptica. Para ello, 30 participantes inexpertos ensamblaron un componente de dificultad moderada de ocho piezas y posteriormente fueron evaluados mediante el instrumento NASA Task Load Index. Los resultados obtenidos muestran que el esfuerzo, la demanda mental y la frustración presentaron los mayores puntajes, mientras que la demanda física obtuvo el menor puntaje. Más del 80% de los participantes presentaron carga de trabajo en niveles alto y muy alto, sugiriendo mejoras inmediatas en la metodología de entrenamiento.

Palabras clave: NASA TLX; interacción humano computadora; sistemas hápticos.

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Introduction

Virtual reality (VR) is a valuable technology to achieve rapid comprehension and effective decision-making through visualization and experience in the product development process (Choi *et al.*, 2015). It is defined as a digital environment created by a computer in which a user can interact with system components, thereby obtaining a sense of immersion (Kim *et al.*, 2020). VR offers opportunities to enhance the learning of cognitive and psychomotor tasks (Xia *et al.*, 2013). Beyond its traditional applications in the entertainment industry, VR is now creating value in various sectors, including education, healthcare, and the industrial field. In the latter, VR has greatly enhanced worker training by immersing them in realistic scenarios where they can acquire knowledge about industrial processes while ensuring their safety. In this way, VR is a compelling technological solution in cases where real-life training poses challenges, such inaccessibility of physical components due to time constraints, the high manufacturing costs of physical prototypes, excessive dimensions, the need for specialized facilities, hazardous processes, or difficulties encountered during real-world training. These issues can significantly affect the overall cost of designing an effective product (Cooper *et al.*, 2021; Gallegos-Nieto *et al.*, 2017). VR is particularly evident in the automotive sector, where companies continually strive for quality improvement through the integration of VR techniques such as virtual prototyping, virtual manufacturing, and virtual training (Lawson *et al.*, 2016).

In industry, VR seeks to reduce risk, to improve and accelerate learning over traditional training schemes, and to transfer the information obtained in the simulation environment to the equivalent real work (Vanneste *et al.*, 2020). However, automated procedures can lead to levels of demand that go beyond human capabilities, specifically, cognitive and decision-making capabilities. The user is faced with a situation in which work performance requires a state of attention (the ability to "stay alert") and concentration (the ability to be aware of an activity or a set of activities for an extended period), which results in a workload when performed consciously and consistently (De Arquer & Nogareda, 2010).

There is no one widely accepted definition of workload; however, Hart & Staveland (1988) described workload as "the perceived relationship between the amount of mental processing capability or resources and the amount required by the task". Thus, the cognitive workload is an important factor that needs to be minimized or maintained at an engaging level to provide satisfactory user experience during human-computer interaction (HCI). Thus, the workload evaluation must consider both task characteristics and the conditions of its execution, according to De Arquer & Nogareda (2010). A constant high cognitive workload affects attention and concentration when there is an imbalance between the person's cognitive capacities and the task difficulty, thus distracting the person and producing errors (Kosch *et al.*, 2023).

Today, there is a research trend to analyze HCI in visual-immersive environments because they provide the user spatial awareness and depth perception through glasses (Andersen *et al.*, 2019; Bjørn *et al.*, 2024; Chessa *et al.*, 2019; Tcha-Tokey *et al.*, 2018). Since VR systems have different types of interaction with users and new devices are constantly being developed, more research is needed to investigate the HCI from different auditory, touch, and other senses perspectives. Adding more senses to the HCI gives a more immersive environment. Haptic-enabled VR systems, which fall into the classification of the sense of touch, improve simulation fidelity and provide augmentation during training (Huegel & O'Malley, 2014).

Research on VR systems from the haptic perspective is an emerging research area with less exploration than the visual perspective. Moreover, the existing studies on haptic–enabled VR systems have focused on the overall functionality of the system (Kim *et al.*, 2017), the software development (Li *et al.*, 2018), and the identification of computing components to make the experience more realistic (Tong *et al.*, 2023). In the industrial sector, the studies have focused on analyzing the functionality and performance of haptic-enabled virtual assembly (Gallegos-Nieto *et al.,* 2020; Gallegos-Nieto *et al.*, 2017). However, there is still lack of knowledge and a research gap on haptic-enabled VR systems, but from the HCI perspective. The evaluation of human factors is crucial to determine whether and how the virtual training process is assisting the operators in making the most use of their abilities (Brunzini *et al.*, 2021).

In order to contribute to knowledge and fill the research gap on VR systems, this paper focuses on the evaluation of a haptic-enabled VR system for industrial assembly training, but from the human factors perspective. In particular, the study focuses on evaluating the workload induced on the users during haptic-enabled virtual assembly training. The aim is to answer the following research questions: What level of workload is induced on new users during the first interaction with the haptic-enabled virtual assembly system? What are the dimensions that contribute most to the workload? What proposals or actions can be made to maintain or improve the workload levels? The research outcomes will serve as valuable insights to improve the user satisfaction and well-being during the use of VR technologies with haptic feedback.

Materials and methods

The sample consisted of 30 volunteers, all of whom had no prior experience with haptic virtual systems. The participants were single, with an average age of 22.73 $\pm$ 2.05 years (15 males of 23.60 $\pm$ 1.72 years and 15 females of 21.87 $\pm$ 2.03 years). Regarding their educational backgrounds, 90% (27) were studying bachelor's degrees, 6.6% (2) were pursuing master's degrees, and 3.3% (1) were enrolled in doctoral programs. They were all right-handed. Participants received class credits as compensation for their involvement in the research.

The research methodology comprised five stages, as shown in Figure 1. The participant selection and data collection processes adhered to the principles outlined in the declaration of Helsinki (World Medical Association, 2017). Participants were chosen in the first stage. Invitations were distributed to university engineering students through promotional fliers, posters, e-mails, social media posts, and personal meetings. Students who answered affirmatively were verified to confirm the inclusion criteria: a) to have a professional profile relevant to the manufacturing industry, b) to be in good general health (self-reporting), and c) to have no prior experience with assembly processes in VR systems with haptic feedback.

The second stage involved an informational session with the participants, where the objectives of the research and the testing procedures were explained. Participants who consented to take part in the study signed an informed consent form and completed a brief questionnaire to provide demographic information.

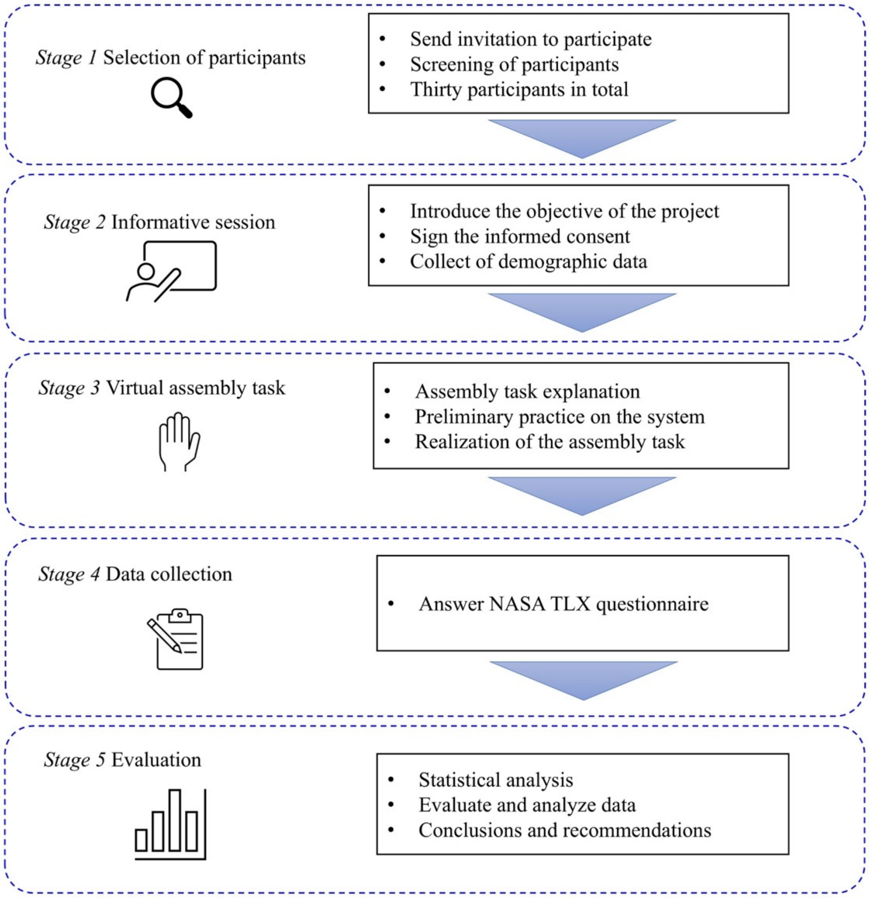


Figure 1. Methodology used to assess the workload in virtual assembly processes with haptic feedback.
Source: Autor's own elaboration.

In the third stage, participants were introduced to the haptic-enabled virtual assembly system, followed by a 10-minute orientation and practice session. They received instructions on the component assembly sequence. Later, the participants were tasked to train virtually the assembly process of a pneumatic cylinder consisting of eight parts while seated comfortably in front of a monitor, as shown in Figure 2.

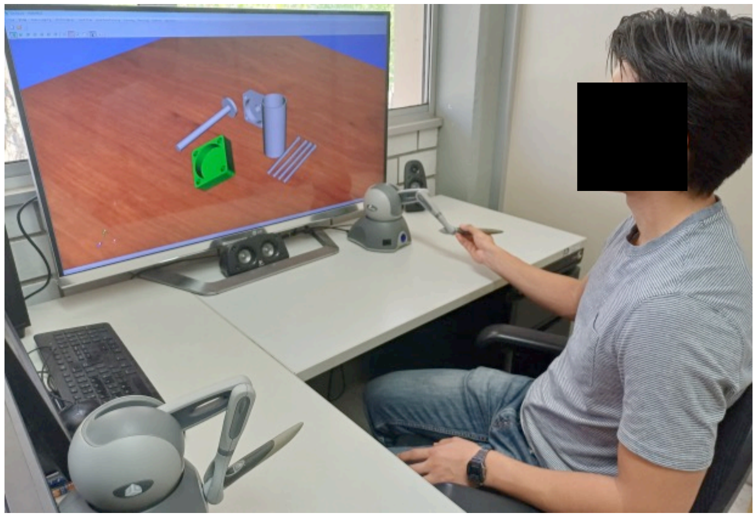


Figure 2. Participant executing the haptic-enabled virtual assembly task.
Source: Autor's own elaboration.

After completing the virtual assembly training, in the fourth stage, participants were asked to complete a printed NASA Task Load Index (NASA TLX) questionnaire. The SPSS® software was used to generate the database. Finally, the data were processed and analyzed in the fifth stage to make suggestions and draw conclusions.

Haptic-enabled virtual assembly system

The virtual assembly system used is the Haptic Assembly and Manufacturing System (HAMS), which includes haptic feedback (Gallegos-Nieto *et al.*, 2020). In the HAMS system, the user can feel, touch and manipulate the 3D virtual objects by means of a haptic device. Moreover, in the HAMS virtual environment, the objects have dynamic behavior as in real life, including collision detection and gravity.

The HAMS system was developed in Microsoft Visual Studio C++ using the Microsoft Foundation Class (MFC), the Visualization Tool Kit libraries (VTK 5.10) for the graphic rendering, the physics simulation engine PhysX v3.1 for dynamic behavior, and the Open Haptics v3.0 for the haptic rendering. In terms of hardware, the experimental setup featured a Smart TV 42" LG® with 3D Full HD capabilities, boasting a resolution of 1920 x 1080 pixels and a Geomagic® Phantom Omni device, with six degrees of freedom, as shown in Figure 3.

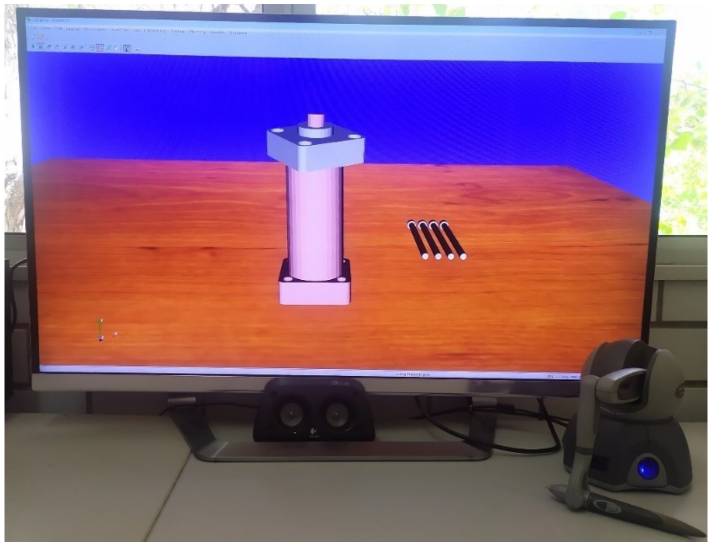
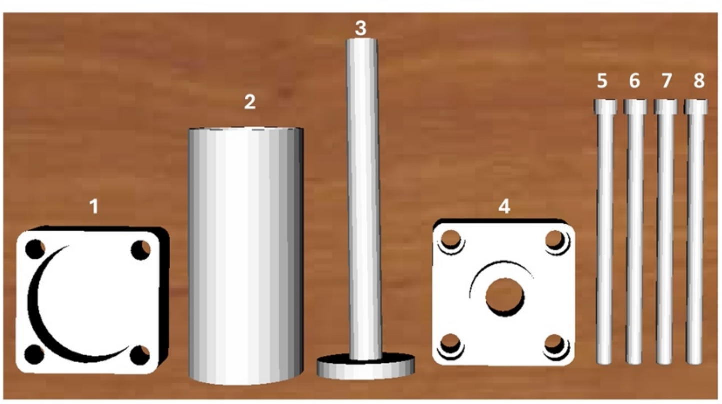


Figure 3. Haptic-enabled virtual assembly system for training.
Source: Autor's own elaboration.

Assembly task

The virtual assembly task involved the assembly of a pneumatic cylinder comprising eight parts, as shown in Figure 4. This assembly task is classified as a moderately complex industrial assembly. Based on preliminary pilot testing, a three-hour training session was proposed. The objective was not only for the user to practice and become familiar with the system, but also to ensure that, by the end of the session, the user would be able to complete the entire assembly. Unexperienced users were expected to reach an intermediate or advanced level in just one session. In addition, the system offers an intuitive, user-friendly experience with minimal physical strain, since no heavy lifting is involved.



Number	Parts
1	Rear cap
2	Cylinder
3	Plunger
4	Front cap
5,6,7,8	Screw

Figure 4. Virtual assembly task: pneumatic cylinder.
Source: Autor's own elaboration.

Evaluation instrument

The NASA TLX is one of the most widely used instruments to assess the workload (Hart & Staveland, 1988; Noyes & Bruneau, 2007; Tao *et al.*, 2019). It is a multidimensional instrument, which provides an overall workload score derived from a weighted average of scores across six subscales or subcategories. These subscales encompass mental demand (MD), physical demand (PD), temporal demand (TD), performance (PF), effort (EF), and frustration (FR). They can be categorized into those related to demands placed upon the individual (MD, PD, and TD), and those related to the individual's interaction with the task (EF, FR, and PF). The NASA TLX has been referenced in the ISO 10075 standard (De Arquer & Nogareda, 2010), and it has been used to assess virtual environments, including a virtual keyboard (Kung *et al.*, 2021), a virtual driving track scenario (Marucci *et al.*, 2021), and a driving simulator (Chihara *et al.*, 2020).

In this work, the NASA-TLX instrument was used to evaluate the workload during haptic-enabled virtual assembly training. According to the guidelines outlined in the instrument's manual (National Aeronautics and Space Administration [NASA], 2019), the data collection procedure was conducted in two phases. In the first stage, participants selected subscales in 15 pairwise comparisons (Table 1, green color), choosing the one they perceived as the greater source of workload for each pair. A weight was assigned to each dimension based on how many times it was selected in the comparisons. This weight ranged from 0 (if the dimension was not chosen in any comparison) to 5 (if the dimension was chosen in all comparisons in which it appeared).

Table 1. Pairwise comparison of subscales.

	MD	PD	TD	PF	EF	FR
MD						
PD						
TD						
PF						
EF						
FR						

Note. MD: Mental demand, PD: Physical demand, TD: Temporal demand, PF: performance, EF: Effort, and FR: Frustration.
Source: Autor's own elaboration.

In the second stage, participants were asked to rate the six subscales of workload. The rating given was subjective and based on how the respondent perceived each subscale. Scores ranged from 0 to 100, in intervals of five units. Using the data obtained in the two phases, a global index of the cognitive workload of the task was calculated. The weights and ratings for each subscale were multiplied, then summed, and divided by 15 (the number of pairwise comparisons). The score interpretation based on calculated workload are low (0-9), medium (10-29), rather high (30-49), high (50-79), and very high (80-100) (Sugarindra *et al.*, 2017).

Results

Workload evaluation

Before the assembly task, all participants received training to ensure that they fully understood the NASA TLX questionnaire, which they filled out immediately afterward. During the three-hour training session, the aim was for participants to gradually enhance their assembly skills, completing each round faster than the previous one. Notably, 67% of participants achieved multiple successful assemblies of the component, 10% completed the assembly only once, and 23% were unable to complete the assembly once.

The results of the pairwise comparisons are presented in the frequency graphs shown in Figure 5, which are based on the total count for each subscale. In this initial stage, participants chose the subscale they perceived as the primary source of cognitive workload through pairwise comparisons. The findings reveal that participants mostly attributed their workload to the frustration subscale, as it reached the maximum weight of 5 on eight occasions. The performance was the second most significant subscale, followed by the mental demand. Conversely, physical demand was the subscale that the participants found least significant, which was present in fourteen people with a value of 0 and a maximum weight of 5 in two participants.

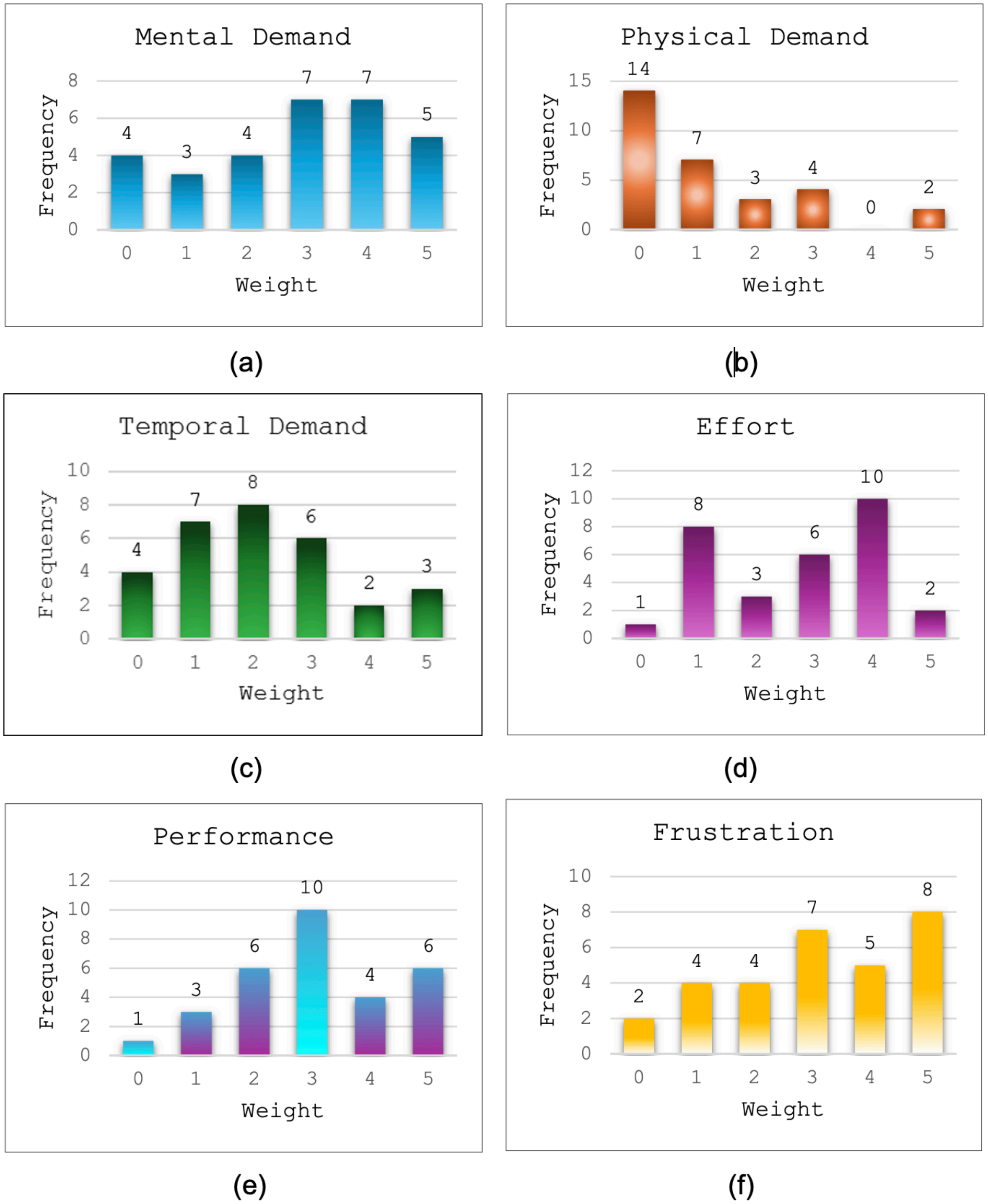


Figure 5. Frequency of weight on subscales: a) Mental demand, b) Physical demand, c) Temporal demand, d) Effort, e) Performance, and f) Frustration.
Source: Autor's own elaboration.

In the second stage, participants were asked to rate the six workload subscales on a scale from 0 (low) to 100 (high), based on the feelings they experienced.

The weighted scores obtained in this stage reflect the importance of each of the subscales as causes of workload (De Arquer & Nogareda, 2010). Figure 6 presents the average ratings for each subscale, as reported by the 30 participants. The subscales with the highest average ratings were effort in first place ($\bar{X}$ = 72.50), followed by mental demand ($\bar{X}$ = 69.66) and frustration ($\bar{X}$ = 62.66).

Notably, two of these subscales (MD and FR) also ranked highly in the first stage of evaluation. Once more, the PD dimension had the lowest average at this point.

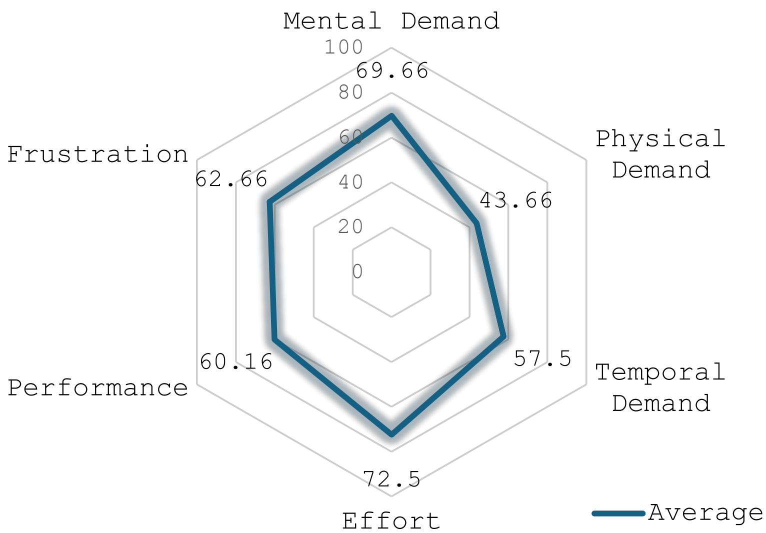


Figure 6. Average rating of subscales.
Source: Autor's own elaboration.

Lastly, the workload for the assembly task in the haptic-enabled virtual reality system was calculated. Figure 7 shows the final workload score for each participant. A total of 13.33% of participants experienced a rather high workload, while over half (70%) reported a high level of workload, and 16.67% were classified at a very high level.

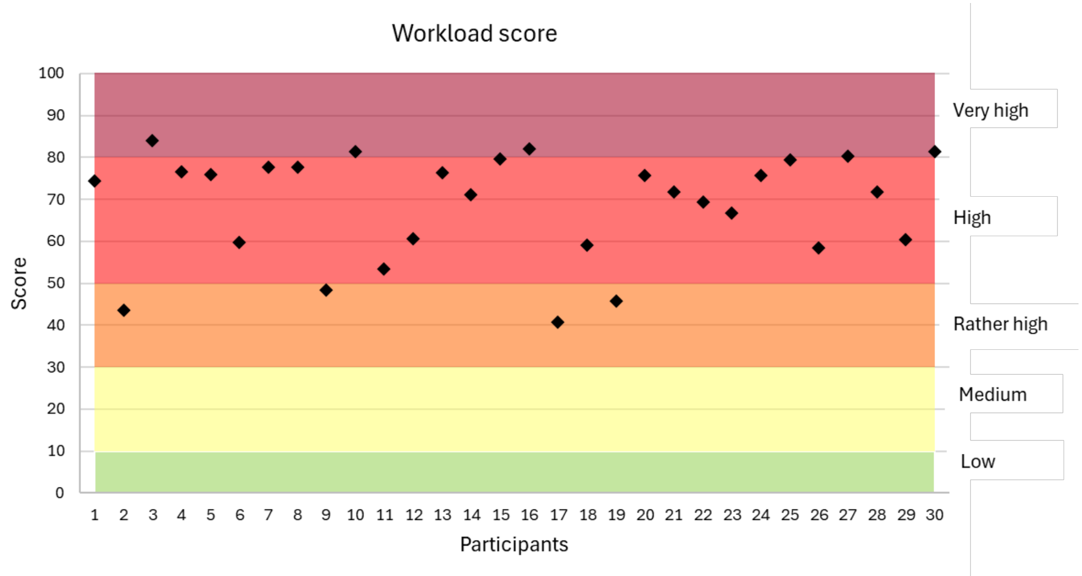


Figure 7. Score of workload and levels for each participant.
Source: Autor's own elaboration.

Discussions

The research questions can now be answered based on the results. The first research question was: What level of workload is induced on new users during the first interaction with the haptic-enabled virtual assembly system? The workload level resulted high: 86.67% of the participants felt high and very high levels of workload. Given that this was their first experience with the system, these results are unexpected, given that they were anticipated to remain at a low or moderate level, considering the system's ease of use. The high workload levels may be attributed to the precision required from users, as noted by Sugarindra *et al.* (2017), since the system allows no margin for error when assembling parts.

The second research question was: What are the dimensions that contribute most to the workload? It was observed that frustration and mental demand were the significant contributors to the workload as they received the highest scores in both the first and second evaluation stages of the NASA TLX instrument. Frustration, as MacKenzie (2013) notes, is closely tied to how users perceive their computing experiences, but it is crucial to ensure that these levels remain low. In this case, frustration arose during the assembly task because users were inexperienced, unfamiliar with the system, and unsure on how to handle the dynamic behavior of the parts. This interaction led to feelings of insecurity and discouragement. The other key dimension was the mental demand, which is formed by the nature of the task itself (De Arquer & Nogareda, 2010). According to the results, this suggests that the participants experienced significant mental fatigue while completing the task. It is important to consider that both the conditions and characteristics of the work will influence the results of the workload. This explains why frustration and mental demand were lower in studies like Huegel & O'Malley (2014). Despite the similarities in hardware, their study differed in terms of training time, task speed, and complexity, which likely influenced the lower workload levels.

In contrast, the physical demand subscale was the least relevant for participants. However, from the review of the physical demand definition and interpretation by NASA, it does not align well with the nature of the assembly task under investigation. This suggests that physical demand may not be particularly useful for assessing virtual assembly tasks enhanced with haptic feedback. The users did not perceive a significant physical effort during their first interaction with the system, and they did not experience fatigue from the extended use. Instead, the primary effort involved cognitive processes like thinking, remembering, and developing mental strategies for assembly. Thus, when assessing virtual environments, it is recommended to reevaluate or modify the subscale physical demand because research in such environments frequently reveals low values as those found in Harris *et al.* (2020) and Rivera-Flor *et al.* (2019).

The third research question was: What proposals or actions can be made to maintain or improve the workload levels? Given the high workload observed, the task context was reviewed, and based on the participants' final feedback, the following recommendations are made to improve their experience. During the training sessions, it was observed that some participants appeared hesitant to ask questions when they had concerns; thus, it is recommended to follow up the participants more closely during training to see if they have any questions or need clarification on any aspect of the system. It is also recommended to reduce the duration of the training session to two hours, including active breaks to mitigate participant strain. As mentioned before, it is recommended to modify the physical demand scale by adapting the question to the assembly activity in the haptic-enabled VR system. Finally, it is recommended to evaluate the users' workload from their first experience with the system, as a friendly and interactive HCI may still involve cognitive strain. A prior analysis will help to confirm whether the system is ready or if adjustments are needed to enhance the HCI, ensuring a positive user experience.

Conclusions

This investigation aimed to examine whether virtual assembly tasks with haptic feedback induce cognitive workload from the outset. The results revealed that participants experienced elevated levels of mental workload, mainly due to mental demands and frustration during their first interactions with the VR system.

Additionally, it was observed that the three-hour task duration was a primary contributor to the high levels of workload, which highlights the significant influence of the task duration on the cognitive workload. Thus, it is crucial to reconsider the methodology to make the appropriate adjustments in order to improve the HCI, to reduce the user's workload, and to provide positive user experience.

Acknowledgments

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Conflict of interest

The authors declare that there is no conflict of interest.

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