Enhancing Early Cognitive Engagement in Human–Robot Communication Through Neurodiversity-Aware Human Digital Twins

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Synopsis

This study proposes a human digital twin (HDT) system to enhance early cognitive engagement of workers with Attention-deficit/hyperactivity disorder (ADHD) during human–robot communication in future construction. The HDT integrates multimodal sensing, real-time analytics, and haptic feedback to identify attention challenges and deliver timely alerts. An MR bricklaying experiment with drone interactions demonstrated that HDT-supported workers showed greater prefrontal cortex activation during the initial communication phase than in the non-HDT condition. These findings highlight the potential of HDT-enabled interventions to support neurodiverse workers by improving situational awareness and cognitive readiness in future construction.

Background

Future construction is expected to become more inclusive for workers with various backgrounds by incorporating autonomous technologies (e.g., robots) to accommodate individual limitations while boosting their strengths (Chang et al., 2024). This accommodation mechanism requires an intelligent system that understands workers' distinctive characteristics, continuously monitors their behaviors, and provides timely interventions when needed. This study identifies the potential of a human digital twin (HDT) to enable real-time monitoring, analytics, and adaptive support. HDT, representing bi-directional communication between a physical human and its virtual replica, has primarily been discussed in theealthcare and medicine domains (He et al., 2024). Its integration holds strong promises for enhancing inclusivity in future construction.

Among various types of neurodiversity, ADHD was targeted in this study because of the alignment between the physical nature of construction activities and ADHD individuals' preference in hands-on tasks (Cerezo et al., 2019). Considering that over 15 million people in the U.S. meet the criteria for an ADHD diagnosis (Schiavone et al., 2019), and they experience a 10-15% higher unemployment rate (Fletcher, 2014), this critical issue should be addressed by enhancing workplace inclusivity to improve their quality of life and well-being. Meanwhile, ADHD workers may experience attentional challenges (Scholz et al., 2023) and impaired cognitive engagement (Weinhardt et al., 2025), potentially compromising their performance in dynamic, demanding construction environments. unemployment rate (Fletcher, 2014). It is envisioned that future construction will become more inclusive for workers with ADHD by incorporating autonomous teammates into construction workplaces. However, in future construction jobsites, ADHD workers are at risk of not noticing approaching robots (e.g., drones), which may undermine their engagement during human-robot communication. Therefore, this study aims to advance inclusive construction by developing and validating an HDT-enabled system that identifies workers with ADHD and delivers proactive feedback to foster earlier cognitive engagement with autonomous robots, reducing interaction risks and enhancing human–robot collaboration.

Methods

A mixed-reality (MR) bricklaying immersive environment envisioning future construction jobsites was built to investigate the impact of the developed HDT system on enabling ADHD workers to engage earlier in human-robot communication, as shown in Figure 1. During the experiment,

participants were asked to perform bricklaying with a semi-automated tool (i.e., MULE) while interacting with three types of drones (i.e., inspection, surveillance, and delivery drone). Participants were required to detect approaching drones and initiate the appropriate communication or response in a timely manner. Two experimental stages were implemented: without HDT (Stage I) and with HDT (Stage II).

Figure 1 presents the seven layers in the HDT system. The physical layer refers to the deployment of devices (i.e., HTC Vive Pro Eye, EmbracePlus, fNIRS (Brite 23, Artinis), and TackSuit Pro). The sensing layer collects real-time neurophysiological data (e.g., prefrontal cortex (PFC) activation) and transmits them to the communication layer. The perception layer focuses on developing a Generative Adversarial Network (GAN) model to identify whether workers had attentional deficits outside the normal range (workers with ADHD) using physiological signals collected during resting-state (Chang et al., 2026). The model achieved an accuracy of 82%, with a precision of 87%, a recall of 72%, and an F1-score of 79%. The digital layer visualizes aggregated data, and the control layer identifies a need to provide alerts for ADHD workers. Finally, the vibration is activated in the device layer, capturing their visual attention in the physical layer.

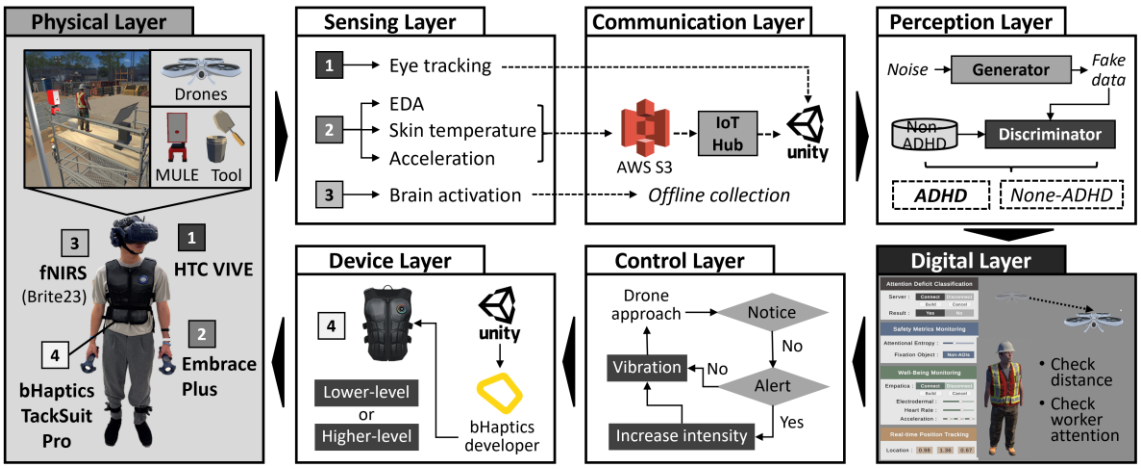


Figure 1. Graphical overview of the developed HDT system.

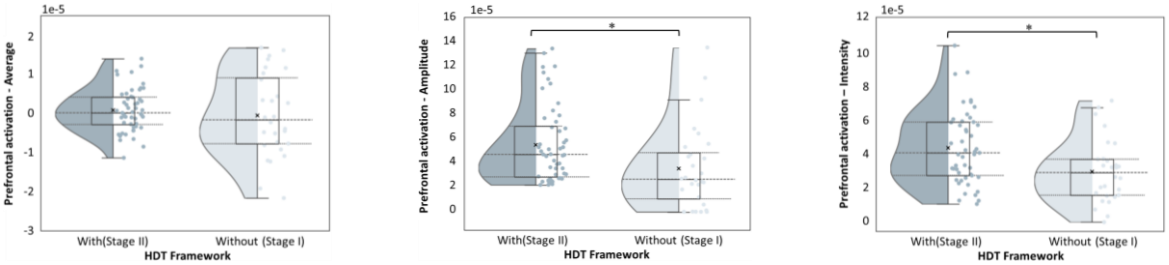
This study recruited 81 workers (Mean $_{age}$ = 22.802, STD = 3.389) for Stage I and 69 participants (Mean $_{age}$ = 25.514, STD = 7.192) for Stage II. Stage I participants were asked to undergo a Structured Clinical Interview for DSM (SCID) ADHD assessment conducted by a licensed psychologist. The results showed that 18 of 81 participants met the criteria. The Stage I data was used to train the GAN detection model. In Stage II, 24 out of 69 participants were identified as individuals with attentional deficits outside the normal range (e.g., possibly ADHD).

To validate the effectiveness of HDT in cognitive engagement, participants identified with attentional deficiencies in stages I and II were compared. Thus, PFC brain activation was quantified and compared using three complementary metrics within the first 10 seconds of the communication phase : (1) *average* (the mean PFC activation), (2) *amplitude* (the peak PFC activation), and (3) *intensity* (the positive area under the activation curve). The selection of the first 10 s was based on the assumption that the drone conveyed its core intent within this interval, representing the workers' initial decoding phase of the communication.

Results

Figure 2 presents a graphical representation of PFC activations in participants with attentional deficits during the first 10s of communication across two stages. The results suggest elevated cognitive engagement in the experiment with HDT ($Mean_{average}$±STD = 1.849e-6±9.352e-6; $Mean_{amplitude}$±STD = 6.459e-5±5.104e-5; $Mean_{intensity}$ ±STD= 5.333e-5±4.463e-5) than without HDT ($Mean_{average}$±STD = -6.914e-6±2.633e-6; $Mean_{amplitude}$±STD = 5.602e-5±6.534e-5; $Mean_{intensity}$

±STD= 3.527e-5±2.444e-5). Mann–Whitney U tests further showed the significant differences in amplitude (U=1109, p=0.044<0.05) and intensity (U=1008, p=0.032<0.05), indicating that participants in the HDT condition experienced significantly stronger early PFC engagement during human–robot communication. These findings validate the effectiveness of the proposed HDT system in facilitating earlier attentional and cognitive engagement among workers with attentional deficits in future dynamic construction environments. Beyond its immediate cognitive benefits, embedding neurodiversity-aware intelligence into construction workflows of the future broadens job opportunities for workers with ADHD, and the HDT framework offers a pathway to safer and more inclusive jobsites and expanded employment access for workers with ADHD.



(a) Average (b) Amplitude (c) Intensity

Figure 1. PFC neural activations of workers with ADHD during the first 10s of communication.

Discussion

This study developed HDT system to identify ADHD workers and deliver timely haptic alerts to enhance early cognitive engagement during human–robot communication. The findings indicate that these alerts not only increased workers' awareness of the drone's approach but also facilitated mental preparedness for upcoming communications, enabling more prompt engagement compared to workers without HDT support. The contributions of this study lie in supporting the effectiveness of the HDT to address ADHD workers' unique challenges in cognitive engagement.

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