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Human-Autonomy Teaming in the Battlespace: Trust and The Role of Neuroimaging

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***Abstract*— An effective Human-Autonomy Team (HAT) is integral to the development and integration of robotic and autonomous systems (RAS) into the battlespace. The use of intelligent decision support systems will bring an inevitable shift in the interaction paradigm between the human and RAS, which needs to be understood in order to design the HAT effectively. There are a variety of different tools and techniques to assist in the design and evaluation of such systems, however many fall short of providing design features for the human, with limited applicability for these techniques to measure key aspects of the HAT, including trust. Neuroimaging modalities, such as functional near infrared spectroscopy (fNIRS), present an opportunity to assess the underlying higher cognitive functions associated with the HAT and could assist in guiding the design of an effective team. However, these techniques require validation to ensure their reliability in real-world applications. This paper discusses some recent studies that take steps towards the systematic validation of fNIRS in the context of the HAT, with a particular focus placed on the feasibility of measuring trust. These studies demonstrate the ability to measure key regions of the prefrontal cortex associated with decision-making, and implicate these changes in activity as neural correlates of trust. The findings present a step towards developing an effective toolkit to help design future systems that facilitate an effective HAT.**

Keywords—Human-Autonomy Teaming, Robotic Autonomous Systems, Neuroimaging, fNIRS, Trust

I. INTRODUCTION

Human-Autonomy Teaming (HAT) has the potential to influence the way humans interact with robotic and autonomous systems (RAS) on a fundamental level. The increasing use of RAS presents an opportunity to improve efficiency and effectiveness of operators across all human-system domains, including the battlespace. However, the increasing need for intelligent support to be integrated into different solutions does not imply that the user is absent, but merely alters the nature of the interaction dynamic between the human and RAS. Perhaps inevitably with this evolving shift in interaction paradigm, in both authority delegation and supervising tasks carried out by the machine, there is a greater need to understand the human component of the team in terms of design, evaluation, and effectiveness. This approach becomes even more important when considering the high-risk, dynamic environments across the battlespace, where outcomes of decisions can impact combatants and non-combatants alike [1]. As the use of RAS and intelligent decision support lends itself to higher levels of delegated authority it would be unsurprising to expect the role and responsibility of the human to change also. Sometimes this delegation of authority may be variable, fixed, or a dynamic mixture of the two; suggesting a symbiotic partnership between the human and RAS. Designing for an effective partnership will be fundamental in determining the effectiveness of the HAT in achieving its tasks and goals, thus understanding the framework upon which it is designed is integral to the success of HAT [2,3].

In order to create effective HAT the design team will likely need to be composed of individuals with a mix of different disciplines (e.g. Software Engineering, Artificial Intelligence (AI), Human Factors (HF)). Further to this, with the lack of agreed standards for design approaches in this domain, the design team will often utilize a variety of different tools and techniques to assist in the design and evaluation of such systems. However, while there may be differences in approaches to designing the HAT, most will start the project by defining the problem space and begin to identify requirements. Indeed, the battlespace is not without its significant challenges, requiring rapid and efficient response to increasingly complex situations whilst all the time aligning to specific rules of engagement and ensuring the safety of operators, allied forces and non-combatants [4]. In order to design an effective HAT it is essential to consider both human and RAS requirements, rather than focusing on solely one. Identifying this information will not only allow for an effective design for the human and RAS, but also identify the nature of information required to be shared between the two. Traditionally the focus has tended to be on the need to display information to the human, in terms of the behaviour intent or decision rationale, but we can equally weight the nature of information that the RAS will require from the human also; as this can assist in the machine learning or defining constraints and limitations imposed by the human on the system(s). With advancing AI techniques and applications of autonomy, the existing techniques and tools used currently may very well be suited to generate behaviours but somewhat fall short for providing design features for the human. Richards and Stedmon [5] suggest that a joint approach to human-machine design is required – especially when there are distributed systems involved.

With this in mind we suggest that, while there are many tools and techniques available to the design team, the nature of these tools tend to be focused on satisfying only one of the disciplines within the design team. Further to this, there are subsequent gaps in the design of eliciting human-autonomy requirements in terms of the unique design aspects involved within a HAT. Key to this problem is not only the pursuit of new and innovative tools and techniques, but the need to validate these in the context of the HAT. Thus, the very nature of what we are assessing within the HAT becomes difficult to define – let alone measure for validating the effectiveness and

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the robustness of a new approach. This paper examines an innovative technique for use within the HAT design toolset that could assist with evaluating the effectiveness of the human as they interact with the RAS team members. Within HF research several techniques have begun to show promise in assessing the underlying cognitive functions associated with the human interacting within such HATs. However, there is still a need to validate these tools to ensure their reliability in real-world and applied domains, and to de-risk future research and development activities that apply these tools.

II. NEUROIMAGING AND HUMAN-AUTONOMY TEAMING – FUNCTIONAL NEAR INFRARED SPECTROSCOPY

A key aspect of human performance when considering their interaction within a HAT is the cognitive state of the individual. This will dictate a number of key cognitive factors that will determine not only how the human interacts within the team, but also their perception of how effective the team is. The ability to understand and assess changes to a person's 'cognitive state' related to task performance has been examined extensively. Techniques such as subjective questionnaires like the NASA Task Load Index (NASA-TLX) [6], or physiological measures such as Heart Rate Variability (HRV) have been used across a vast range of human-system interaction (HSI) studies to explore the nature of these interactions and how they impact the human [7]. However, the increased use of RAS technologies not only prompts the consideration of a new interaction paradigm, but raises known issues such as automation bias and mode confusion [8]. It also raises the need to understand the nature of human trust with these systems – a key barrier to achieving the full potential of autonomous systems [9]. Apart from subjective and qualitative metrics, it is difficult to quantify measures of trust – especially when requiring a tool for providing validation of such a construct. However, advances in neuroimaging techniques show the potential to address this issue.

A. *Functional Near Infrared Spectroscopy*

Whilst there are several techniques that have been used in recent years, one technique called functional near infrared spectroscopy (fNIRS) has gathered support and has shown promise in providing an appreciation of this related to HAT. fNIRS, whilst not a new technology in itself, is a relatively novel approach to measuring cognitive functions associated with human-autonomy interaction. fNIRS is a functional imaging modality that can measure changes in cortical blood oxygenation as a direct result of changes in cognitive activity – a relationship termed 'Neurovascular Coupling' [10]. fNIRS monitors neurovascular coupling simultaneously across multiple regions of the brain by measuring real-time changes in the concentration of cortical oxygenated (oxy-Hb) and deoxygenated (deoxy-Hb) haemoglobin. Infrared light is emitted from a series of light sources to irradiate cortical tissue. Most biological tissues are relatively transparent to infrared light with a wavelength between 700-900nm (referred to as the optical window – Fig. 1); however, oxy-Hb and deoxy-Hb are amongst the main chromophores within this optical window that absorb infrared light within this wavelength range [11].

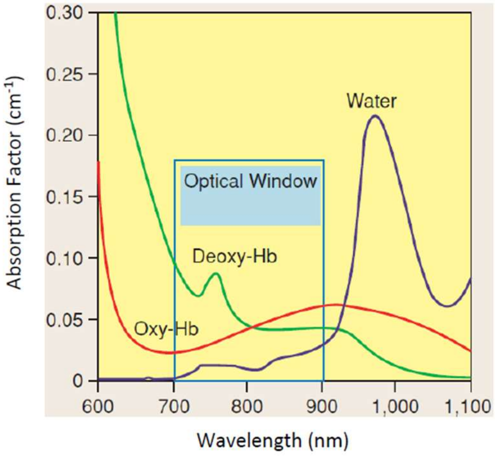


Fig. 1. A graphic representation showing the absorption wavelength and absorption factors of oxy-Hb and deoxy-Hb, referred to as the optical window [11].

The light travels a "banana-shaped" pathway to the surface capillaries of the brain where the photons are either scattered by the extra- and intracellular boundaries within the head (such as the skin, skull, and cerebrospinal fluid), or are absorbed by oxy-Hb and deoxy-Hb. Photodetectors are placed in close proximity to receive that light after it has interacted with the organic tissue (Fig. 2). The mobilization of oxy-Hb and deoxy-Hb is directly related to changes in cortical blood flow associated with a specific event or stimuli, and the absorption spectra of each is significantly different which allows for spectroscopic separation using variable wavelengths.

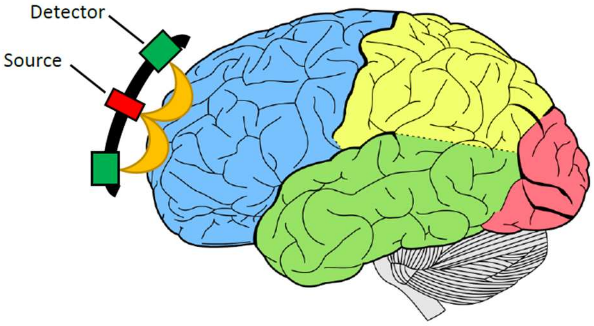


Fig. 2. A schematic diagram of the brain showing the pathway that photons travel, emitted from a central light source and detected by a series of photodetectors placed in close proximity [12].

fNIRS has some advantages over other neuroimaging modalities such as increased temporal resolution, portability, and reduced cost over techniques like functional Magnetic Resonance Imaging (fMRI). However, the most notable advantage is that it is not impacted by electromagnetic interference or movement artefacts, which significantly increases its feasibility in real-world studies over other portable modalities like Electroencephalography (EEG) [12]. This is important because real-world testing of RAS technologies is vital in ensuring they operate appropriately, are trusted by the human member of the HAT, and ultimately facilitate an effective partnership. However, the question still remains as to whether fNIRS is indeed able to provide sufficient data for designers to create these systems. Therefore, fNIRS must be validated in the context of the HAT in a safe, controllable, and perhaps most importantly, a repeatable environment, before it is deployed in real-world scenarios. This presents an opportunity to utilize simulated environments as a validation method, not just for the design of RAS technologies but also for the use of fNIRS as a robust method to assess human-autonomy interaction. We discuss the recent application of fNIRS in the context of the HAT, and explore the potential benefits it has to developing effective human-autonomy interaction in relation to battlespace situation awareness and decision-making.

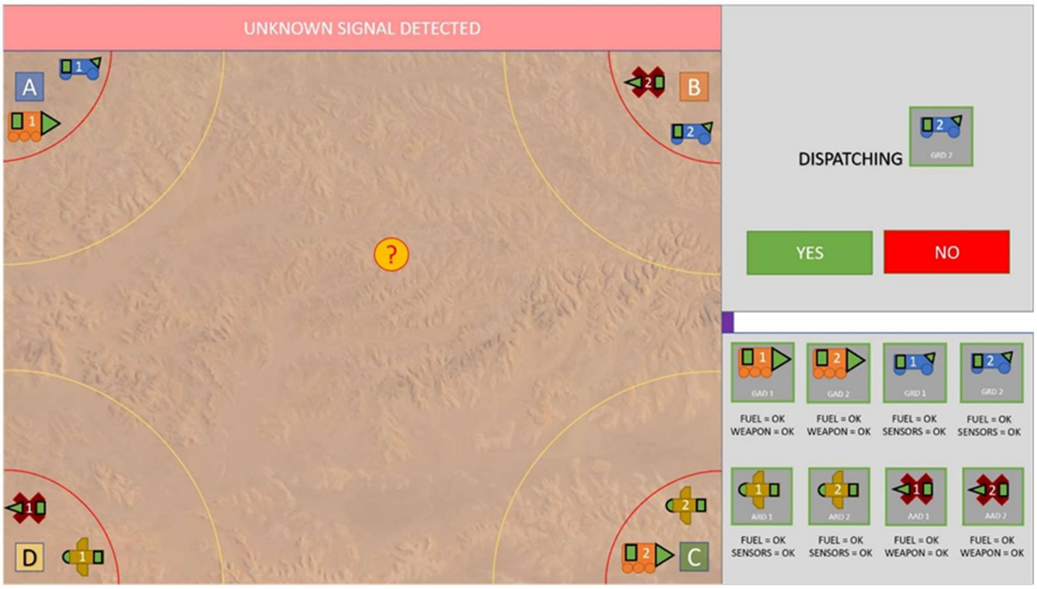
III. STUDIES

A. *Study One: Using fNIRS to Measure the Neural Correlates of Trust*

In a recent study by Palmer et al. [12], fNIRS was used to measure cognitive function during human interaction with systems that had varying levels of delegated control. Participants interacted with a ground control station (GCS) shown in Fig. 3 to supervise and monitor a set of air and ground RAS assets with either sensor or weapons capabilities. Four different scenarios were created whereby the level of delegated control was adjusted to assist the participant in completing the task. The GCS display was adjusted to reflect the level of support afforded to the participant. The participants were tasked with using the GCS during each scenario to control the RAS assets and to interrogate unknown tracks that appeared on the GCS display, and act accordingly to defend four areas of interest referred to as "bases" from enemy combatants whilst protecting and escorting civilian and VIP targets to safety.

The level of autonomy provided to the participants was defined in a number of different conditions; referred herein as 'systems'. The "assisted manual mode" (AMM) system provided the participant with several command inputs they could choose from, based solely on the RAS assets closest to the target, whilst not considering the asset state (e.g., remaining fuel and ammunition) or sensor/weapon capability. The "assisted autonomous mode" (AAM) system was designed to provide the participant with the best calculated response to the unknown track, considering all aspects of the situation such as distance to target, RAS asset sensor or weapon capabilities, and asset state including fuel level, ammunition level, and whether the asset was damaged or operational. The AAM system also utilised a scan-first approach to determine the nature of the track before deciding on the appropriate response, but still requiring approval from the participant before engaging. Two "full autonomous mode" (FAM) systems were also provided. Both of these systems had full operational capability and required no interaction from the participant. However, to separate the two systems, the decision-making approach was adjusted. One of the systems (referred to as the "correct" system) took the same scan-first approach as the AAM system to determine the nature of the track before engaging, ensuring that enemy combatants were identified before engaging with weapons systems, whilst protecting civilians and VIP tracks from accidental harm. In contrast, the other FAM system (referred to as the "incorrect" system) was designed with an attack-on-site approach to eliminate all unknown tracks without first interrogating them to determine their nature. This meant that during this scenario, the system engaged a civilian track and the mission ended in failure. The aim of creating a system with this approach was to try and elicit a change in trust from the participant, to determine whether there were neural correlates associated with trust or distrust that could be recorded using fNIRS.

The fNIRS device used during this study measured changes in oxyhaemoglobin levels in the prefrontal cortex, as this region of the brain is strongly associated with executive cognitive functions such as decision-making and problem solving [11,13]. This region is also associated with increased oxygenation during higher levels of mental workload when interacting with manual control systems compared with systems that provide autonomous support [14]. Looking across the conditions, the data began to show emerging trends of increased cognitive activity related to decision-making when participants used the AMM system, which is to be expected as participants were given minimal support and were required to interrogate the system to determine which of the choices provided presented the best approach to the situation. However, similar activity was also recorded when participants used the "incorrect" FAM system. This system was fully autonomous and therefore required no decision-making input from the participant. Furthermore, the changes in cognitive activity were observed over the duration of the scenario. This suggests that participants were attempting to



FUEL = OK
WEAPON = OK

FUEL = OK
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Fig. 3. A screenshot of the GCS used for the AAM system scenario

monitor the system as it progressed through the scenario, potentially to try and understand the decision-making processes of the system. Indeed, whilst the supporting evidence is scarce it has been shown that increased activity in certain sub regions of the prefrontal cortex – namely the mid-ventrolateral prefrontal cortex – is driven by uncertainty during the decision-making process [15]. In addition, Dimoka [16] suggests that the neural correlates of trust are associated with prediction and uncertainty processing in the brain, observing that the lack of cognitive activity associated with uncertainty may indicate an increase in trust. This may suggest increased cognitive activity relating to uncertainty in decision-making of the autonomous system, and could thus be indicative of a lack of trust from the participants.

B. Study Two: The Impact of System Transparency on Trust

In another recent study by Palmer et al. [17], fNIRS was used to observe the impact of system transparency on human-autonomy trust. Participants completed a series of simulated manual and autonomous driving tasks which aimed to firstly determine the how autonomous systems can aid in reducing cognitive workload, but also to determine if adjusting the level of information presented to the user impacted human-autonomy trust. Participants were asked to complete several driving scenarios using the simulator shown in Fig. 4.

Fig. 4. A screenshot of the driving simulator

Two of the conditions in this study involved participants using autonomous vehicles with varying levels of system information displayed on an in-vehicle information system (IVIS) that was placed in the centre of the dashboard, over the top of the infotainment system. One of the IVIS displays (Fig. 5) was designed to show higher levels of detail relating to the external environment and the decision-making processes of the autonomous system. This was used to represent a more intelligent system that was able to observe the surrounding environment, but also to represent a system with high transparency of information. In contrast, the other IVIS display (Fig. 6) was designed to show minimal detail relating to the environment and no information on the decision-making process other than the next action (e.g. emergency braking). However, both autonomous systems used with the different IVIS displays were identical in their operational capabilities, and both were able to complete the driving task safely. This design aimed to ensure that changes in cognitive activity that may be associated with the neural correlates of trust were as a result of the change in the transparency of the autonomy, and not the actions of the vehicle as it completed the driving task.

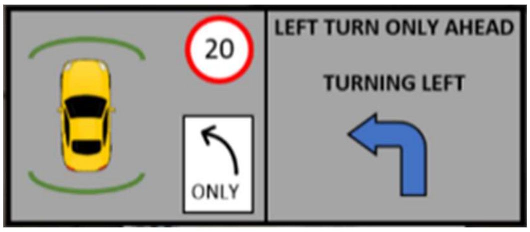

Fig. 5. A screenshot of the high transparency IVIS

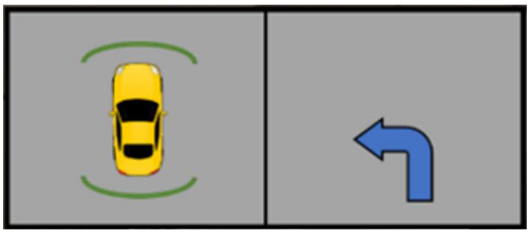

Fig. 6. A screenshot of the low transparency IVIS

The results revealed emerging trends of increased cognitive activity related to decision-making during the conditions with the low transparency IVIS. Increased activity in the ventrolateral prefrontal cortex during this condition further suggests that cognitive activity associated with decision-making during human-autonomy interaction may be an important neural correlate of trust. The findings also align with the analysis in the previous study and show that whilst a system may be functionally operational and able to complete a given task, the user's ability to understand the decision-making process may be a key component in whether the user trusts the system. Furthermore, whilst the study was based on human-autonomy interaction in the context of civilian driving, it demonstrates the fundamental need to ensure that these interactions are understood in complex and continuously changing environments such as the battlespace, and are developed in such a way that the HAT facilities a symbiotic, trustworthy partnership between the human and RAS.

IV. DISCUSSION

The findings of these studies present a compelling glimpse of how fNIRS can be used to measure interactions within the HAT. It demonstrates the ability for fNIRS to measure factors such as decision-making which, in the context of the human-autonomy interaction, may be closely associated with the neural correlates of trust – a key component of the HAT. However, the limited evidence surrounding these neural correlates and the use of tools such as fNIRS to assess them means that continuous and systematic validation of tools like fNIRS is integral to the examination of its use in HAT evaluation and development. The lack of understanding about how humans interact with a rapidly evolving technology such as autonomy is difficult to pin down – particularly in complex environments such as the battlespace, where one size will certainly not fit all. As these systems become more intelligent and the interaction paradigm shifts to a more collaborative one, it becomes increasingly difficult for humans to understand the processing behind the system's output [18]. Therefore, the nature of the technology being assessed, and the context in which it will be used, will need to be carefully examined prior to approaching the use of fNIRS to determine what neural correlates can be isolated and measured – particularly when looking to measure and assess trust within the HAT. Furthermore, a recent review on approaches to measuring human-autonomy trust demonstrates that changes in trust are reflected in neural activity, yet neurological assessment has yet to be substantially leveraged in this context [19]. This further shows that whilst there is a significant opportunity for HAT designers to exploit novel technologies like fNIRS in the development of an effective RAS, these technologies must continue to be systematically validated. The studies detailed in this paper demonstrate the first steps to leveraging neurological assessment in the context of HAT, but they also illustrate this need for further validation of these techniques and the requirement for assessment frameworks that identify which methods are appropriate for the type of assessment being conducted. With such a framework, HAT designers could determine the most effective tools and techniques to help inform their design process and ensure that future RAS technologies can be safely and efficiently integrated.

Finally, it is also worth considering the wider implications that this research has for ensuring automated and autonomous systems are built on a foundation of trust. Trust plays an important role in the integration of new technologies, particularly in the acceptance of automation [20]. However, it is also important to ensure that trust is *calibrated to the capabilities of the system* to ensure safe and appropriate use, especially in safety-critical situations like those that occur in the battlespace. In fact, [21] suggests that trust should be calibrated both to the capabilities of the system but also to the experience and confidence of the user, suggesting that those who are less experienced may choose to use an automated system more than those who are more experienced and trust more in their own abilities. This is further considered by Parasuraman et al. [22], who suggest that the calibration of trust is important to prevent both misuse, where operators may utilise the system in environments beyond its capabilities, but also disuse, in situations where operator trust is low and the system is not used to its full potential. This places a key reliance on ensuring that there is an understanding of trust within the HAT, and shows that there must be a way of effectively, and more importantly, objectively measuring trust.

V. SUMMARY

RAS technologies have the potential to enhance the capabilities of operators across all aspects of the battlespace, and are becoming an increasingly important part of the future development of defence and military capabilities. Indeed, many studies such as those described in this paper have demonstrated the benefits that the HAT could provide to complex operational environments within the battlespace. However, the shift in the interaction dynamic between human and RAS presents a challenge that requires a new approach – one that seeks to improve our understanding of dynamic human-autonomy interaction and ensures safe and effective operations. We must also understand that the HAT does not remove the responsibilities of the human operator. Indeed, UK Defence has seen a significant push towards HAT and the integration of RAS to enhance operational capabilities. The British Army RAS Strategy shows integration of RAS as early as 2025, whilst the UK Ministry of Defence (MoD) Defence AI Strategy describes HAT as being foundational to the development and integration of all intelligent systems in UK Defence. However, one of the foundational elements that these frameworks share is the requirement for human-in-the-loop development of RAS technologies and their integration into the battlespace, across all levels of delegated control. Therefore, we must endeavor to find reliable, repeatable, and robust methods to assess human-autonomy trust, such as fNIRS, to allow HAT designers to ensure their systems are not only effective in the HAT, but are take a human-centered design approach to ensure safe operations whilst allowing for efficient integration into real-world use. Future investigations of the HAT should consider utilising novel approaches such as fNIRS, ensuring that factors such as human-autonomy trust are understood and designed for, whilst also further validating these tools in the context of the HAT.

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