

**Assessment of Warning Modalities for Remotely Supervised Autonomous  
Agricultural Machines**

**By**

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## ABSTRACT

As autonomous systems gain traction in agriculture, effective human-computer interaction (HCI) frameworks are essential for safe and efficient remote supervision. While autonomous agricultural machines (AAMs) improve productivity, human operators remain vital for monitoring, interpreting warnings, and intervening during system failures. The design of warning systems within human-machine interfaces (HMIs) directly affects operator performance and situation awareness (SA), including perception (Level 1), comprehension (Level 2), and projection (Level 3).

This research investigates how visual, auditory, and tactile warning modalities, used alone or in combination, influence operator awareness and responsiveness during remote AAM supervision. Through simulated field scenarios, participants engaged with unimodal and bimodal cues, with objective measures (reaction time, comprehension, and projection accuracy, CSUQ usability scores) and subjective ratings collected and analyzed.

Bimodal cues enhanced perception. Visual-tactile warnings led to shorter response times than visual-auditory cues in quiet (close-to-field) environments, though no significant difference was found under noisy (in-field) conditions. Both modalities received high usability ratings, with farming participants preferring visual-tactile cues. Among non-farming participants, response times were significantly faster with visual-auditory warnings,  $t(24) = 3.16, p = .004$  (saccadic), and  $t(24) = 3.56, p = .002$  (manual). Projection accuracy was lower for farming participants using visual-auditory cues (86.7%), though not statistically significant,  $\chi^2(3, N = 540) = 5.37, p = .147$ .

Among unimodal cues, visual warnings were most effective across comprehension, urgency perception, and response time, earning the highest user preference (84%). Auditory cues showed moderate performance; tactile cues were least effective. Correlation analysis showed faster comprehension and predicted higher usability, with task accuracy aligning with CSUQ ratings.

Together the findings support the development of adaptive, user-centered HMIs that align warning modality with cognitive and environmental demands. The results of this research contribute to safer, more effective human-robot collaboration in agricultural automation.

## **DEDICATION**

This thesis is dedicated to the University of Manitoba community, whose supportive and enriching environment has played a vital role in my academic growth and success.

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## CONTRIBUTION OF AUTHORS

The thesis is organized as a "sandwich" or grouped-manuscript thesis with chapters 3, 4, and 5 containing material from journal articles that have been published and are awaiting publication. Following are the titles of the prepared research articles, the manuscript review status at the time of submission of this thesis, the authors' contributions, and relevant chapters of the thesis:

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**Danny Mann**: Conceptualization, Methodology, Supervision, Writing - review & editing

**Cheryl Glazebrook**: Conceptualization, Methodology, Writing - review & editing

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**Sebastian Lorenz:** Methodology, Writing - review

# 1. GENERAL INTRODUCTION

## 1.1 Introduction

The advancement of automation in agriculture is revolutionizing field operations by reducing manual labor, enhancing precision, and improving productivity. Autonomous agricultural machines—such as self-driving tractors, planters, sprayers, and harvesters—now perform complex tasks with minimal human intervention. As these technologies become more widespread, the role of the human operator is shifting from direct manual control to remote supervision, where responsibility lies in overseeing system performance, detecting anomalies, and intervening when necessary. This transformation introduces new cognitive demands, particularly in how operators maintain situation awareness (SA) and interact with system alerts and warnings.

Effective human supervision of autonomous systems depends heavily on an operator's ability to perceive, comprehend, and project information about the machine and its environment—components formally defined as the three levels of SA by Endsley (1995). Level 1 (Perception) involves noticing relevant system cues; Level 2 (Comprehension) is the understanding of those cues given; and Level 3 (Projection) refers to anticipating future system states and potential outcomes. In remote agricultural operations, maintaining all three levels of SA is essential but more challenging due to limited sensory immersion, increased mental workload, and reliance on mediated communication through interfaces.

To support SA effectively, warning systems must deliver critical information in a manner that is not only accurate and timely but also cognitively compatible with human perception and decision-making processes. This makes the modality of warnings—whether visual, auditory, or tactile—a critical design consideration. Each modality has distinct strengths and limitations in

terms of perception, interpretability, urgency conveyance, and user preferences. Visual cues are typically dominant for spatial tasks and offer persistent representations (Wickens 2002). That said, visual cues can be missed when attention is diverted (Muhammad et al. 2022). Auditory warnings are effective for rapid attention redirection but are prone to masking by background noise (Li et al. 2025). Tactile cues allow for hands-free operation and are useful in high-noise or visually overloaded environments, yet often suffer from interpretive ambiguity without training or related grounding (Rizza et al. 2018; Khaliq et al. 2021).

While prior studies have examined the effectiveness of different warning modalities (Edet and Mann 2021; Kallioniemi et al. 2021; Zhu et al. 2025), no study has addressed their usability alongside their ability to support all three levels of SA, particularly in the domain of remotely supervised agricultural automation. Usability considerations—including intuitiveness, clarity, user preference, and trust—are crucial for ensuring that warning systems not only function technically but are accepted and effectively used by human operators in critical, time-sensitive conditions.

This thesis investigates the assessment and usability of warning modalities—visual, auditory, and tactile (single and combination)—in their capacity to support perception, comprehension, and projection during the remote supervision of autonomous agricultural machines. The study employs a mixed-methods approach, combining quantitative performance metrics (e.g., accuracy, response time, usability score) with qualitative usability feedback (e.g., subjective ratings, user comments), to evaluate the cognitive and experiential effectiveness of each modality. By situating the analysis within the framework of SA and emphasizing the human-centered dimensions of system interaction, the research seeks to inform the design of adaptive, intuitive, and context-aware warning systems that better support operators in modern agricultural environments.

Ultimately, this work contributes to the growing field of human-automation interaction in agriculture by identifying which modalities are most effective and usable in supporting full-spectrum situation awareness. The findings will guide future development of multimodal interfaces and alert systems for safer, more efficient, and operator-friendly autonomous machinery.

## **1.2 Objectives**

The general aim of this study was to investigate the design, effectiveness, and usability of unimodal and bimodal warning modalities—visual, auditory, and tactile—for enhancing operator performance and supporting all three levels of situation awareness (perception, comprehension, and projection) in the remote supervision of autonomous agricultural machines (AAMs). Hence, the specific objectives of this study were to:

1. To perform a preliminary experimental study within a controlled laboratory setting to evaluate the effectiveness of literature-identified, high-performing multimodal warning combinations—specifically visual-auditory and visual-tactile—in enhancing the remote supervisor’s ability to detect system abnormalities. This objective focuses on measuring noticeability and response time, thereby aligning with the assessment of Level 1 SA (Perception).
2. To determine the most effective unimodal warning method—visual, auditory, or tactile—for conveying system state comprehension to the remote supervisor of an autonomous agricultural sprayer during emergency scenarios. This objective addresses the enhancement of Level 2 SA (Comprehension) in the supervisory task.
3. To evaluate the capacity of individual warning modalities—visual, auditory, and tactile—to facilitate the projection of system status during field conditions requiring operator monitoring and intervention in remote supervision contexts. This objective involves

analyzing the operator's perceived urgency and decision-making, thereby targeting Level 3 SA (Projection).

4. To conduct a comprehensive usability assessment of the implemented warning modalities within a prototype human-machine interface (HMI) developed in another research lab. This objective aims to examine the integration of warning methods in terms of user experience, functional effectiveness, and interface design standards, in support of safe and efficient remote supervision.

### **1.3 Thesis Structure**

This thesis has been written and structured in a paper format. Chapter 1 is the general introduction. Chapter 2 includes a detailed review of the supervision of autonomous agricultural machines (AAMs), focusing on remote supervision, automation interface design, situation awareness (SA), and the role of warning modalities literature pertinent to the objectives of this thesis. Chapters 3 to 5 are presented in paper format, and the status of each paper is shown in Table 1.1. Chapter 3 describes the perception of bimodal warning cues during remote supervision of autonomous agricultural machines. Chapter 4 describes modality-specific support for comprehension (Level 2 SA) and projection (Level 3 SA) during remote supervision of autonomous agricultural machines, extending the knowledge from a previous foundational study where perception (Level 1 SA) was evaluated. Chapter 5 investigates the usability of warning cues for remotely supervised autonomous agricultural machines. The overall conclusions and recommendations are discussed in Chapters 6 and 7, respectively.

**Table 1.1 Status of the manuscripts.**

<b>Chapter</b>	<b>Status of the manuscript</b>	<b>Journal</b>
3	Published, Vol.71 (X): 0–0. April 2025.	Research in Agricultural Engineering
4	Submitted in June 2025	Canadian Biosystems Engineering Journal
5	Submitted in August 2025	Journal of Agricultural Safety and Health

## **2. REVIEW OF LITERATURE**

### **2.1 Autonomous Agricultural Machines**

Autonomous Agricultural Machines (AAMs), also referred to as agricultural robots or AgBots, represent a transformative technological innovation aimed at addressing the growing need for productivity, labor efficiency, and sustainability in modern farming. These machines include a wide range of field-deployed robotic systems, such as self-driving tractors, automated weeding robots, autonomous harvesters, and sensor-integrated platforms for precision crop management. Their development and implementation are increasingly viewed as key strategies for overcoming challenges related to labor shortages, operational costs, and the need for greater accuracy in agricultural tasks (Edet and Mann, 2020; Mann et al., 2021).

AAMs rely on the integration of several advanced technologies to achieve autonomy and task-specific functionality. Core components include perception systems (e.g., LiDAR, stereo and RGB cameras, multispectral imaging), which provide environmental awareness and facilitate navigation through dynamic and unstructured farm environments. In addition, environmental sensors are used to monitor soil properties, plant health, and weather conditions. Control systems are often powered by artificial intelligence, particularly deep reinforcement learning and adaptive control algorithms, which enable these machines to learn from the environment and optimize their behavior accordingly (Liu et al., 2023; Zhao et al., 2024). Mapping and localization are commonly achieved through LiDAR-based simultaneous localization and mapping (SLAM) systems that are specifically adapted for rough and unpredictable terrain.

The application domains of AAMs continue to expand rapidly. In the area of weed control, systems such as Carbon Robotics' LaserWeeder G2 utilize computer vision and AI to identify and

selectively eliminate weeds with high precision, thereby reducing the need for chemical herbicides (Carbon Robotics, 2025). In horticulture, robotic platforms are being developed for the tasks of fruit picking, vine pruning, and branch thinning. These systems often employ sophisticated vision algorithms for object detection and manipulation planning, allowing them to operate with minimal human intervention (Taylor, 2006; Wong et al., 2017). Moreover, fully autonomous cropping systems, exemplified by the “Hands Free Hectare” project, have demonstrated the feasibility of automating the entire production cycle—from drilling and crop care to harvesting—without human presence in the field.

The economic and policy environments surrounding AAMs are also evolving in favor of broader adoption. The global market for autonomous agricultural equipment was valued at approximately USD 7.3 billion in 2024 and is projected to grow to USD 18.8 billion by 2030, with a compound annual growth rate (CAGR) of nearly 17% (ResearchAndMarkets, 2024). This growth is being fueled by advancements in autonomous navigation, the availability of cost-effective retrofit kits, and governmental incentives aimed at encouraging sustainable agricultural practices. Autonomous tractors, in particular, are gaining traction due to their compatibility with existing farm infrastructure and their ability to perform a range of tasks with high accuracy and reliability.

Despite these advancements, several challenges continue to hinder the widespread adoption of AAMs. Technical barriers include limitations in generalization across different crops and field conditions, difficulties in navigating complex or uneven terrain, and the lack of robust safety certification standards. Additionally, high capital investment, concerns about job displacement, and the need for farmer training and system interoperability remain significant hurdles (Bechar and Vigneault, 2016; Adamides et al., 2017). Public acceptance and regulatory

clarity are also critical to ensuring the safe and ethical deployment of these technologies on a large scale.

Current research directions are increasingly focused on developing modular, scalable, and interoperable systems that can integrate with traditional farm equipment. IoT-based platforms are emerging as key enablers of multi-machine coordination, providing functionalities such as real-time diagnostics, route optimization, and remote supervision from farm offices or mobile devices (Zhao et al., 2024). Empirical studies at agricultural research centers, such as Olds College in Canada, have demonstrated the practical benefits of AAMs, including improvements in fuel efficiency, reduced overlap during field operations, and increased productivity when compared to conventional methods (Bahmutsky et al., 2025).

Overall, AAMs are transitioning from experimental concepts to operational technologies with the potential to redefine the future of agriculture. Continued innovation in perception, control, and human-machine collaboration, along with the development of policy and economic models that support accessible deployment, will be essential to maximizing the potential of autonomous systems in agricultural production (Edet and Mann, 2020; Mann et al., 2021).

## **2.2 Supervision of Autonomous Agricultural Machines (AAMs)**

Supervision is an activity that is undertaken for the purpose of ensuring that a task is done in such a way that it meets our approval (in terms of safety, in accordance with rules, etc.). Autonomous machines, though independent, still require human supervision (Scholtz, 2003; Berenstein et al., 2012) to help minimize any catastrophe that may arise in case of unexpected situations such as system failure or malfunction that exceeds the capability of the machine (Bechar and Vigneault, 2016). Furthermore, since it is currently difficult to automate high-level reasoning

and tasks, it is also beneficial that the human remains in the decision-making loop to assist with planning field operations, allocating resources, and coordinating the autonomous machines. Generally, involving the human (as a supervisor) in an autonomous system has been reported to increase the overall reliability and performance of the system (Adamides et al., 2017).

Supervision can be carried out in proximity (where the supervisor and the system being supervised are collocated) or remotely (where supervisors perform their roles from a distant location without being physically present in the work zone) (Mann et al., 2021). Currently, supervision of agricultural field machines is mainly performed in proximity (i.e., with the operator seated in a cab on the machine), but it is envisioned that future AAMs will be supervised remotely due to farm labour shortages (i.e., enabling one person to supervise multiple AAMs) and to enhance the overall efficiency of the farmer (i.e., enabling the farmer to complete other farm management tasks while supervising AAMs in the field) (Javaid et al. 2022; Armstrong et al., 2023).

Remote supervision enables operators to oversee autonomous agricultural machines (AAMs) from a distance using interfaces such as desktops, tablets, or smartphones. These setups vary based on the proximity of the supervisor to the machines and the level of interaction required (Edet and Mann, 2020; Mann et al., 2021). This method addresses current labour shortages and increases operational efficiency by allowing one person to monitor multiple machines while also engaging in other farm-related activities.

Remote supervision has long-standing use outside of agriculture, including in military operations, industrial inspections, and space exploration (Taylor, 2006; Cubber et al., 2017; Kabir et al., 2025). For instance, pipeline inspection robots are monitored remotely due to inaccessibility

issues (Wong et al., 2017), and search and rescue robots or military drones are managed from control centers (Cubber et al., 2017; Cummings, 2004).

In agriculture, remote supervision has been implemented in both crop and livestock management. Examples include the use of drones to identify weed-infested areas and sensor systems in hog barns that monitor animal health and environmental conditions remotely (Senoo et al., 2024). These technologies enable farmers to make informed decisions without being physically present.

Academic research and industry developments have proposed various remote supervision concepts. Edet and Mann (2020) categorized them into four types based on the supervisor's location: (1) in-field, (2) edge-of-field, (3) farm office, and (4) off-site supervision. The in-field model typically involves a human-driven machine supervising an AAM nearby. Edge-of-field supervision allows the farmer to handle logistics while observing the operation. Farm office supervision supports multitasking, at the same time it can delay responses to in-field issues. Off-site supervision allows oversight from remote locations, possibly outside the farm, expanding flexibility. Each model has strengths and limitations. For example, in-field supervision ensures rapid response but can halt the operation if issues arise. Edge-of-field supervision offers short reaction times and logistical support, making it preferable to farm-office setups for certain scenarios (Mann et al., 2021).

Key technologies supporting remote supervision include real-time video feeds, sensor data integration, and advanced interfaces. For example, Carbon Robotics (2025) developed an AutoTractor system that supports 24/7 monitoring via low-latency video. Research by Liu et al. (2025) and Zhao et al. (2024) highlights the role of immersive teleoperation and IoT-based platforms that offer precise control, mapping, and status alerts. Alert mechanisms are critical to

successful remote supervision (Zhao et al. 2024; Cornet et al. 2024). Recent findings suggest that visual–tactile cues outperform audio–visual ones in terms of prompt operator responses during machine anomalies (Kaber et al. 2006; Bicevskis et al. 2016). Additionally, cost-effective supervision strategies consider farm size, labour availability, and economic constraints (Eliseu et al., 2024; Ibikunle et al., 2025).

Remote supervision provides a scalable and adaptable approach for managing autonomous agricultural machines. It improves operational efficiency, lowers the need for manual labour, and maintains safety through continued human oversight. The success of this method relies on well-designed user interfaces, effective communication systems, and timely access to real-time machine data.

### **2.3 Automation Interface**

The automation interface plays a pivotal role in enabling effective supervision of autonomous agricultural machines (AAMs), serving as the primary medium through which human operators initiate, monitor, and intervene in machine operations. As agricultural automation advances, the demand for interfaces that support intuitive interaction, reduce cognitive workload, and promote timely decision-making has grown significantly (Mann et al., 2021; Edet, 2021).

Edet (2021) outlined seven core functions of an automation interface: initiating operations, monitoring telemetry, displaying real-time status, tracking spatial position, receiving alerts, querying machine intentions, and issuing override commands. These functions are critical in agricultural contexts, where autonomous systems operate in dynamic and often unpredictable environments. Interfaces must not only communicate machine state effectively but also support situational awareness, especially during periods requiring human intervention (Endsley, 2017).

Human factors and ergonomics research has long emphasized the importance of clear display design and intuitive controls. Johnson et al. (2009) and Moorehead (2012) demonstrated that while direct commands from operators may diminish as autonomy increases, continuous feedback remains essential to maintain operator confidence and oversight. Key interface elements identified across multiple studies include real-time telemetry dashboards, geospatial visualization tools, and event-triggered alert mechanisms (Blackmore et al., 2002; Stentz et al., 2002; Karimi et al., 2011; Rakhra et al. 2020).

Technological advances are now redefining the automation interface. AI-driven perception systems, such as John Deere's SmartDetect™, combine cameras, radar, and machine learning to detect obstacles, display predictive paths, and autonomously halt machinery, effectively closing the feedback loop between machine and supervisor (Deere and Company, 2024; The Robot Report, 2024). Edet and Mann (2022) demonstrated that multimodal alert systems—especially visual-tactile combinations—significantly improve operator response time during critical events, enhancing situational awareness.

In parallel, emerging frameworks like edge-centric IoT and digital twins are influencing interface design by enabling context-sensitive adaptation of telemetry and alerts. Zhang et al. (2025) and Otto (2024) highlighted how digital models of crop fields and reinforcement learning algorithms are being used to prioritize data streams and tailor interface behavior to environmental and operational demands.

These innovations point to a convergence of intelligent perception, user-centered design, and adaptive feedback mechanisms in next-generation automation interfaces. Collectively, they ensure that AAM supervisors retain high situational awareness and can intervene efficiently, supporting safe and productive deployment of autonomous systems in modern agriculture.

## 2.4 Situation Awareness and Its Evaluation

Situation Awareness (SA)—the perception, comprehension, and projection of environmental elements—is essential in modern agricultural operations, especially with the integration of advanced machinery and precision farming technologies. Endsley (1995, 2000) defined SA as the perception of elements in the environment within a span of time and space, the comprehension of their meaning, and the projection of their future status. The most widely accepted framework for understanding SA is the three-level model proposed by Endsley, which systematically categorizes SA into three hierarchical stages. Level 1, perception, refers to the detection of relevant cues in the environment, such as visual or auditory signals. In agriculture, this might involve noticing a warning light on a tractor dashboard or hearing a change in engine tone. Level 2, comprehension, includes interpreting the significance of those cues in relation to task objectives—for example, realizing that a certain alert indicates low hydraulic pressure or that a deviation in GPS guidance could affect planting accuracy. Level 3, projection, represents the operator’s ability to anticipate future states or outcomes based on current understanding. For instance, a farmer might predict that a malfunctioning sprayer will lead to uneven pesticide distribution and proactively stop to make repairs. This model underscores that SA is not static but a dynamic cognitive process that evolves as tasks progress, making it critical for high-risk, high-efficiency domains such as agriculture (Salmon et al., 2009).

From a farming perspective, SA begins with the operator’s ability to detect and perceive critical environmental cues using sensory inputs. For example, a tractor operator may rely on visual displays for GPS alignment, tactile feedback from the steering wheel, or auditory signals from the machinery. This foundational stage of awareness is essential for accurate and timely decision-making. Challenges such as information overload, poor system design, or distractions can impair

the ability to perceive necessary information, leading to reduced operational performance (Endsley and Garland, 2000; Panfilov, 2017).

Once the relevant data are perceived, the operator must then comprehend the information in relation to the task at hand. In farming, this could involve understanding the implications of irregular GPS data or engine noise that might indicate overheating. This stage requires prior knowledge, experience with equipment, and contextual understanding of farming goals. Misinterpretation or lack of system knowledge can hinder comprehension, even if the cues are accurately perceived (Endsley et al., 2003).

The most advanced stage of SA in agriculture involves projecting future states based on the current understanding. For instance, an operator might anticipate field terrain challenges or identify patterns that suggest upcoming machine malfunctions. This enables proactive decision-making—adjusting machine settings or routes in anticipation of obstacles or hazards. However, reaching this level of awareness is difficult without extensive experience, system familiarity, and cognitive resources. High mental workload or unfamiliarity with new agricultural systems may prevent operators from forming reliable predictions (Endsley et al., 2003).

To evaluate SA in agricultural settings, various assessment methods are used, generally categorized into indirect and direct methods (Endsley et al., 2003; Salmon et al., 2006; Bolstad et al., 2010). Indirect methods infer SA from observed actions or processes. Process measures, such as verbal protocols, involve asking operators to think aloud while performing tasks. This method reveals the decision-making process and level of awareness during operations like planting or harvesting. Communication analysis serves a similar function but is used in team-based operations, evaluating verbal interactions between co-workers. Psychophysiological measures like eye tracking and heart rate monitoring are increasingly applied in agricultural simulators to assess

attention and stress levels. These are particularly effective when combined with tools like the Situation Present Assessment Method (SPAM) and Situation Awareness Rating Technique (SART), as demonstrated in recent studies (Pan et al., 2025; Jeon et al., 2024).

Behavioral and performance-based measures assess the actions or outcomes of the operator's work. For instance, behavioral indicators such as accurate row planting or steady machine navigation suggest good SA. Performance outcomes like yield uniformity or application efficiency may also be analyzed. However, such measures can be affected by external factors like soil variability or operator skill, making it difficult to isolate SA as the sole determinant (Salmon et al., 2006).

Direct methods aim to assess SA more precisely, often using subjective or objective tools. Subjective methods include SART, which asks operators to rate aspects such as attentional demand, resource supply, and understanding. This approach has been tailored to agricultural machinery by focusing on operational tasks and system interfaces. Other subjective tools like the Situation Awareness Rating Scale (SARS) and SA-SWORD offer similar insight and can be adapted to evaluate system design and operator SA in specific farming contexts (Endsley et al., 2003; Vidulich, 2000). Objective measures include the Situation Awareness Global Assessment Technique (SAGAT), where simulations are paused, and operators are questioned about system status to determine their awareness. This method is widely used in simulator-based agricultural training and has been validated as a reliable and flexible technique (Endsley, 2000; Hultin et al., 2019; Bashiri and Mann, 2014). SPAM, by contrast, uses real-time questions during active task performance to measure awareness without interrupting the workflow. These methods have shown strong validity, especially when combined with physiological data collection in agricultural technology evaluations (Endsley, 2021; Pan et al., 2025).

Given that situation awareness hinges on the timely and accurate perception of environmental cues, the modality through which information is conveyed becomes critically important—especially in dynamic, high-load agricultural environments. Effective warning systems play a central role in supporting SA by enabling operators to detect, interpret, and anticipate hazards or system states. Thus, exploring the design, effectiveness, and usability of different warning modalities is a natural progression in understanding how to enhance SA in agricultural machinery and remote supervision settings.

## **2.5 Warning Modalities and their Effectiveness**

In autonomous or semi-autonomous agricultural systems, human supervisors retain critical responsibilities: task planning, resource allocation, performance monitoring, and emergency intervention (Schreckenghost et al., 2008; Berenstein et al., 2012; Edet et al., 2018). To effectively intervene in emergencies, supervisors must quickly recognize and interpret abnormal system behaviour (Peryer et al., 2005). Interfaces therefore need well-designed warning systems capable of alerting supervisors to hazardous conditions while prompting rapid, reasoned actions (Laughery and Wogalter, 2006). Importantly, these warnings should be attention-grabbing without inducing stress or being prematurely dismissed (Peryer et al., 2005). Achieving this balance requires careful modality selection and signal design.

Current systems predominantly use visual, auditory, and tactile (haptic) cues—sometimes in multimodal combinations. Visual warnings (text, flashing lights, graphical displays) are ideal for stationary users, noisy environments, or when messages are complex or persistent (Van Cott and Kinkade, 1972; Elbert et al., 2018). Auditory alerts—tones, icons, verbal messages—are omni-directional and effective for mobile users, brief messages, or visually obstructed conditions (Wogalter et al., 2002; Elbert et al., 2018; Edet, 2020). Haptic cues, which bypass auditory and

visual channels, offer silent, non-intrusive alerts—particularly useful when operators’ vision or hearing is occupied or impaired (Gaffary and Lécuyer, 2018; Smith et al., 2009).

Warning effectiveness is commonly evaluated by metrics like noticeability, reaction time, comprehension, recall, perceived urgency, risk, and compliance likelihood (Wogalter et al., 1999; Wogalter et al., 2002; Edet and Mann, 2021). Of these, reaction time—the interval from stimulus onset to the initiation of the operator response—is the most frequently used measure, with shorter times indicating superior performance (Wogalter et al., 2002; Whelan, 2008; Mann et al., 2021). Individual factors such as age, gender, experience, education, culture, personality, and cognitive ability can influence reaction times (Ng and Chan, 2012; Jain et al., 2015). Effectiveness is also assessed through subjective methods (e.g., Likert scales, pairwise comparisons, interviews) and other objective performance outcomes (Wogalter et al., 1999; Edet and Mann, 2021).

Numerous studies support the benefits of multimodal warnings over single-modal signals, especially in contexts where sensory overload may occur. For example, Politis et al. (2014) found faster driver responses to combined audio-visual-tactile alerts versus unimodal signals. Murata et al. (2009) observed younger adults react faster than older adults to both tactile and auditory warning signals. Scott and Gray (2008) noted tactile warning signals yielded the shortest reaction times in simulated driving scenarios. Ng and Chan (2012) reported that tactile responses were fastest, followed by auditory and then visual cues. Edet and Mann (2021) found that, under field-noise conditions, combined visual-tactile warnings enabled quickest supervisor responses—surpassing auditory or unimodal methods. However, unimodal warnings can perform as effectively as bimodal ones when well-designed (Politis et al., 2015). The variability in the performance of different cues likely stem from differences in study design, user traits, or modality placement.

As agricultural machinery trends toward full autonomy, remote supervisors must effectively receive and interpret warnings from afar. Edet and Mann (2021) evaluated seven warning configurations—visual, auditory, tactile, and their combinations—across four remote supervision scenarios. They found that visual-tactile combinations were most effective under noisy, in-field or close-to-field conditions, yielding the fastest response times. Combinations involving auditory cues were less effective under tractor noise. The study emphasized that while tri-modal signals can increase cognitive load, well-chosen bimodal configurations can optimize response speed without overwhelming the operator.

These findings underscore the importance of aligning warning cue design with the operational environment and user context. Machines in agricultural settings operate in dynamic, noisy environments where operators heavily rely on sensory feedback (Edet, 2020). Visual cues dominate—estimated to provide over 80% of information needed during machine operation (Lee et al., 2015; Karimi, 2008; Macadam, 2003). Common warning systems include haptic steering feedback (vibrations indicating misalignment or steering adjustments) and LED lightbars signaling lateral deviation (Janosi and Kis, 2011; Ima and Mann, 2003). Auditory cues also convey critical information: variations in threshing sounds can indicate blockages, while engine noise fluctuations may signal mechanical stress (Edet, 2020; Bilski, 2013).

In agricultural settings, where noise, motion, and visual demand are high, the modality through which warnings are delivered must not only attract attention but also support immediate and intuitive responses. As such, usability becomes a function of how seamlessly the warning integrates into the operator’s sensory and cognitive workflow. This makes it crucial to assess which modality or combination of modalities ensures consistent recognition and response under real-

world agricultural conditions—especially as human oversight becomes more remote in autonomous systems.

## **2.6 Usability and Its Evaluation**

The International Organization for Standardization defined usability as ‘extent to which a product or system can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use’ (ISO 2018). Additional work has defined several characteristics of usability within the above definition. Although variations abound, a common definition of usability includes five key characteristics: effectiveness, efficiency, error tolerance, ease of use, and engagement (Quesenbery, 2001). Effectiveness, efficiency, and error tolerance all refer to the users’ ability to complete tasks with the system or interface. Effectiveness refers to overall ability to accomplish the task, efficiency refers to the speed and accuracy of completion, and error tolerance refers to the ability to minimize errors. They are typically measured objectively via usability studies in which subjects complete a task and metrics related to overall performance (effectiveness), time to completion (efficiency), and number of errors (error tolerance) are evaluated (Lewis 1995). Ease of use refers to the ability of a user to learn and use a system or interface; it is sometimes broken into sub-characteristics of learnability and memorability (Nielsen 1993). Engagement refers to whether a system or interface is pleasing and satisfying to use. As both ease of use and engagement are inherently subjective, self-report is the primary form of data collection for these characteristics. These two variables have been determined to be particularly important in predicting the degree to which people accept and use particular information technologies (Davis 1989).

People are likely to discontinue using an autonomous machine if its usefulness is questioned, particularly if its warning system is questioned (Lee and See, 2004; Hoff and Bashir,

2015). Usability evaluation of warning signals allows analysis and evaluation of the impact of the warning system design on the supervisory experience of the human supervisor during remote supervision of these autonomous systems. A number of survey instruments have been developed to evaluate the usability of a system, assessing a number of characteristics related to usability, including perceived efficiency, learnability, and satisfaction. A list of these scales is presented in Table 2.2. These scales have been shown to predict similar responses for user satisfaction; the System Usability Scale (SUS) has been found to correlate with both the Software Usability Measurement Inventory (SUMI) ( $r=0.86$ ) and the Usability Metric for User Experience (UMUX) ( $r=0.96$ ) (Finstad 2010). Among them, the System Usability Scale (SUS) is by far the most cited and utilized scale in the HCI literature (Bangor et al. 2008; Lewis and Sauro 2009). It consists of 10 Likert-scale items that ask respondents to agree or disagree with given statements on a 5-point scale. Odd-numbered items are worded positively, and even-numbered items are worded negatively. SUS has been shown to be cost effective for evaluating usability across a wide variety of systems, including cell phone equipment, modems, voice response systems, and websites (Bangor et al. 2008). It has been shown to outperform other scales at small sample sizes, has been found to be easy to administer and score. However, the major limitation of the SUS is that it only addresses the whole system rather than a particular feature of the system (Bangor et al. 2008). No psychometric analyses on SUS were initially published and it was originally thought to be a unidimensional scale (Brooke 1996). Subsequent researchers assessed the measure (Bangor et al. (2008); Lewis and Sauro (2009); Borsci et al. (2009)) and found “inconsistent results regarding the factorial structure of its items” (Borsci et al. 2009). Both Lewis and Sauro (2009) and Borsci et al (2009) identified two factors, which they termed usability (8 items) and learnability (2 items). It is in this regard that the computer system usability questionnaire (CSUQ) was chosen for this

thesis. The rationale was that the CSUQ aligns with the focus of the thesis as it is specifically for evaluating computer systems, in addition, it is the second most cited and utilized usability scale after the SUS (Lewis 2018).

**Table 2.2: Commonly cited usability scale in HCI literature (adapted from Karlin and Ford 2013).**

Scale	Items	Dimension assessed
System Usability Scale (SUS) (Brooke 1996)	10	Perceived system usability and learnability.
Computer System Usability Questionnaire (CSUQ) (Lewis 1995)	16	User satisfaction with; 1) system usefulness; 2) information quality; 3) interface quality.
Usability Metric for User Experience (UMUX) (Finstad 2010)	4	Perceived usability (efficiency, effectiveness and satisfaction).
Software Usability Measurement Inventory (SUMI) (Kirakowski and Corbett 1993)	50	1) Global usability plus perception of: 2) affect; 3) efficiency; 4) learnability. 5) helpfulness; and 6) control.

Sauro and Lewis (2016) developed a new version of the computer system usability scale (CSUQ- Version 3). The CSUQ (Version 3) is composed of sixteen statements that are scored on a seven-point Likert scale of strength of agreement with 1 indicating strongly agree and 7 representing strongly disagree. The statements cover a variety of aspects of computer system usability such as the system usefulness, information quality, and interface quality, and thus have a

high level of face validity for measuring usability of a computer system. The CSUQ instrument is generally used after the respondent has had an opportunity to use the computer system being evaluated, but before any debriefing or discussion takes place. The statements/items produce four scores- one overall score and three subscale scores. The rules for computing them are: i) overall: average responses for item 1-16 (all the items); ii) system usefulness (SysUse): average items 1-6; iii) information quality (InfoQual): average items 7-12; and iv) interface quality (IntQual): average items 13-16. The resulting scores can take values between 1 and 7 or not applicable, scores closer to 7 suggest that users strongly agree that the system is usable, while scores closer to 1 suggest that users strongly disagree that the system is usable.

Usability is a critical factor for considering the effectiveness of warnings. The CSUQ instrument has been used for a variety of evaluations. For example on the calculator (Purwaningsih et al. 2006), virtual keyboard (Monahan et al. 2009), e-government services (Bargas-Avila et al. 2010), mobile phone (Manzano-Monfort, et al. 2023), website (Morgnti et al. 2016), training game (Carrión-Toro et al. 2020), in-vehicle user-interfaces (Normark et al. 2015), and multimodal remote control (Cortellessa et al. 2018). However, the application of CSUQ for overall assessment of usability of warning cues for autonomous agricultural systems has seldom been seen.

## **2.7 Summary of the literature review and the proposed objectives**

The reviewed literature highlights the critical role of human supervision in ensuring the safe and effective operation of Autonomous Agricultural Machines (AAMs), particularly in remote settings. While AAMs offer potential for improved efficiency and reduced labour demands, their autonomy is limited by challenges in high-level reasoning and the ability to respond to unanticipated events. Consequently, the supervisor remains a vital component in field operations,

either in proximity or remotely, with several remote supervision concepts—ranging from in-field to off-site monitoring—proposed in both agricultural and non-agricultural domains.

A central component of remote supervision is the automation interface, which serves as the communication bridge between the human and the AAM. Effective interfaces must present telemetric data, spatial awareness, and system status through well-designed visual, auditory, and sometimes tactile displays. Research and interface prototypes have demonstrated the benefits of user-centered design, multiple display types (textual, symbolic, pictorial), and clear presentation of malfunction alerts to support timely human intervention and maintain situation awareness (SA).

Situation Awareness is structured into three hierarchical levels: perception (Level 1), comprehension (Level 2), and projection (Level 3). Maintaining high SA is essential for effective supervision and is influenced by how information is delivered through the interface. Various techniques—both direct (e.g., SAGAT, SART) and indirect (e.g., performance measures, verbal protocols)—have been developed to evaluate SA during task execution.

The modality of warnings—visual, auditory, or tactile—directly affects a supervisor's ability to notice, interpret, and respond to critical events. Each modality has strengths under specific environmental conditions, and research consistently supports the superiority of multimodal warnings in reducing reaction time, enhancing attention, and improving user performance, especially when primary sensory channels are overloaded. However, evidence also suggests that well-designed unimodal warnings can perform comparably to multimodal cues in certain contexts.

Lastly, usability—defined by effectiveness, efficiency, and user satisfaction—is a cornerstone of successful AAM supervision systems. While various tools exist to evaluate

usability, the Computer System Usability Questionnaire (CSUQ) is particularly well-suited for assessing the performance of automation interfaces in agricultural contexts. Despite its utility, the application of CSUQ in evaluating warning cues within AAM interfaces remains limited, pointing to a gap in current research and a direction for future studies.

In conclusion, studies in agricultural environments consistently demonstrate that operators rely heavily on sensory feedback—particularly visual, auditory, and tactile cues—to interpret machine status and maintain control. As the industry progresses toward remote supervision and fully autonomous systems, identifying and implementing the most effective warning modalities becomes critical to ensure timely and appropriate operator responses. The literature emphasizes the importance of optimizing warning design to support remote supervisors' situation awareness across all three levels—perception, comprehension, and projection—especially under dynamic field conditions. Equally important is usability, defined by effectiveness, efficiency, and user satisfaction, which serves as a cornerstone of successful AAM supervision systems. Among the tools available to assess usability, the Computer System Usability Questionnaire (CSUQ) stands out as particularly well-suited for evaluating automation interfaces in agricultural settings. However, its application to the assessment of warning cues within AAM interfaces remains limited, highlighting a key gap in the literature and presenting a valuable opportunity for future research to enhance the safety, reliability, and adoption of autonomous agricultural technologies.

## **2.8 Knowledge Gap**

While prior studies have examined the effectiveness of different warning modalities, no work has addressed their usability alongside the ability of different modalities to support all three levels of SA, particularly in the domain of remotely supervised agricultural automation.

### **3. PERCEPTION OF BIMODAL WARNING CUES DURING REMOTE SUPERVISION OF AUTONOMOUS AGRICULTURAL MACHINES**

#### **3.1 Abstract**

Agricultural machines that are fully autonomous will still need human supervisors to monitor and trouble-shoot system failures. Recognizing the emergency as soon as possible is crucial to reduce adverse effects. The ability of humans to detect visual, auditory, or tactile cues is usually enabled by warning systems. The effectiveness of different warning cues varies in terms of prompting a quick response. The study's objective was to compare the effectiveness of two bimodal warnings (i.e., visual-auditory and visual-tactile) at eliciting supervisor perception (which equates to level one situation awareness). Twenty-five participants engaged in an autonomous sprayer simulation. Two realistic remote supervision scenarios (i.e., in-field and close-to-field) were used to examine two bimodal warning cues: (i) visual-auditory and (ii) visual-tactile. The effectiveness of each bimodal warning was assessed based on two measures: (i) response time and (ii) noticeability. There was no significant difference between the bimodal warning cues in terms of response time when tractor sound was present in the experimental environment (reflecting the in-field remote supervision scenario); however, visual-tactile cues yielded shorter response times than visual-auditory cues when the experimental environment was quiet (reflecting the close-to-field remote supervision scenario). There were no statistically significant differences between visual-auditory and visual-tactile warnings concerning noticeability. Participants' subjective answers indicated they preferred the visual-tactile cues better than the visual-auditory cues. It is

concluded that visual-tactile warnings are preferred over visual-auditory warnings to enable perception during remote supervision of autonomous agricultural machines (AAMs).

### **3.2 Introduction**

In contemporary society, automation has permeated every facet of existence. Powerful new automation technologies have been launched in many sectors, such as flight management systems for pilots, navigational displays for drivers, diagnostic and surgical aids for physicians, and decision-aiding systems for air traffic controllers (Mouloua et al. 2019; Parasuraman 2000). Numerous advantages have resulted from this technological revolution. Not to be outdone, the agricultural industry uses automation technology (autosteer systems, variable rate technologies, etc.) to carry out various farm tasks. Even with the most recent developments, work is continually being done to increase these machines' operability and efficiency. Currently, the goal of agricultural machine designers is full automation, which would eliminate the need for human intervention for agricultural machines to navigate and control themselves. It is challenging to completely remove human intervention from the control loop (Schreckenghost et al. 2008), given the variable operating conditions of these autonomous machines (Adamides et al. 2014). Autonomous machines will need an interface like the one outlined by Blackmore et al. (2007) for the human supervisor to communicate with them. These interfaces should give people easily accessible and useful information for their supervisory duties (Dorais and Gawdiak 2003).

According to some research, the human's responsibilities in an autonomous system include assigning tasks, distributing resources, monitoring how tasks are being completed, and intervening through an automation interface in emergencies (Auat Cheein and Carelli 2013; Bechar and Vigneault 2016; Shi et al. 2023). Therefore, fully autonomous agricultural

machines (AAMs) must include a human supervisor to oversee the machine's operations (Alexander et al. 2009). Compared with active engagement in that same task, supervision of a task frequently results in decreased situation awareness, increased mental workload, inefficient monitoring, and a worsening capacity for manual control and intervention if automated systems malfunction (Edet and Mann 2021). To act during an emergency, the supervisor must first identify and assess the situation (Peryer et al. 2005). As a result, warning signals must be included in the automation interface to inform the supervisor of what is occurring in their surroundings at any given time. This is known as supporting the supervisor's awareness of the situation.

Situation awareness (SA) is defined as “the perception of the elements in the environment within a span of time and space, the comprehension of their meaning, and the projection of their status in the near future” (Endsley 1995). SA is essential for making decisions and taking actions that work. Regarding a specific task, information is frequently categorized as relevant or important. The self-awareness level is determined by how the individual interprets the data. When operators perceive the information required to complete the task, they reach Level 1 SA (Endsley et al. 2003). To maintain SA, different tasks call for different kinds of information. When attempting to comprehend information pertinent to the task, the operator usually combines their senses of taste, smell, touch, and hearing (Endsley and Garland 2000). When an operator reaches level 2 SA, they clearly understand the significance of perceived information for pertinent objectives (Endsley et al. 2003). To accomplish the current goals, the operator needs to process the data, combine disparate pieces of information, and develop an understanding of the information. Attaining level 3 SA entails seeing information, interpreting it based on pertinent objectives, and

forecasting how the situation will unfold (Endsley et al. 2003). To reach level 3 SA, the operator must be thoroughly aware of the existing circumstances and the system's operation. Although all three levels of situation awareness hold significance, the research presented here was limited to examining tactics for bolstering Level 1 situation awareness (or perception).

Non-agricultural devices have used various warning techniques for comparable objectives. Typically, they employ haptic, visual, or auditory modalities (Laughery and Wolgater 2006). The following situations are good candidates for visual stimuli: (i) the message is long and complex, and it is anticipated to be seen for some time or referred to later; (ii) the individual is stationary; or (iii) the surroundings are noisy. Visual stimuli can be delivered as text, images, or bursts of light (Elbert et al. 2018; Edet and Mann 2021). A vocal message, a continuous or periodic tone, or an aural symbol (natural or metaphorical) can all be used as audio warnings (Petocz et al. 2008; Sabic et al. 2017). The omnidirectional nature of auditory warnings makes them useful for drawing and focusing the user's attention on a few different situations: (i) when the receiver's position changes, (ii) when the message is brief, (iii) when the environment is visually cluttered and noisy; and (iv) when illumination or barriers obscure the user's vision (Wogalter et al. 2002; Edet and Mann 2021; Chen et al. 2022). An alternative to visual and auditory modalities is tactile (haptic) input. This is particularly useful when the user's eyesight is heavily focused on other task-related activities, the environment is noisy, or the supervisor has visual or hearing impairments (Delavarpour et al. 2019). Also, as tactile warning is less invasive, it is useful in group work environments (Smith et al. 2009).

A variety of criteria, including noticeability, response time, comprehension, recall, hazardousness, perceived urgency, risk, likelihood of injury, likelihood of compliance, and

importance, can be used to evaluate the effectiveness of each warning modality (visual, auditory, and tactile) (Wolgate et al. 2002; Edet and Mann 2021). Response time, which is the amount of time that passes between when the user receives the warning and when the user responds to the warning (through one or more modalities), is the most popular and extensively applied assessment technique (Wolgate et al. 2002; Whelan 2008). A shorter response time would suggest that the warning is more effective than a longer response time. Noticeability, or the capacity to attract attention, is another essential element of warning effectiveness. Warnings must be at least noticed for comprehension and compliance to occur (Young 2002). Saccadic reaction time was used in this study as a measure of noticeability. Rapid eye movements from one focus point to another are called saccades. Since attentional processes impact saccadic eye movements, saccadic reaction time can gauge the attentional state (Braun and Breitmeyer 1988). Compared to a longer saccadic reaction time, a shorter saccadic reaction time would suggest that the warning is more noticeable and effective. Subjective and/or objective measures can be used to measure effectiveness. Open-ended questions, oral interviews, sorting techniques, and evaluations (such as the Likert scale) are examples of subjective approaches, whereas user performance is the basis for objective measurements (Wogalter et al. 1999; Wogalter et al. 2002; Edet and Mann 2021).

Studies have demonstrated that the use of bimodal sensory modalities has advantages when compared to a single modality, particularly when one sensory modality is overloaded due to the primary task or surrounding conditions (Hancock et al. 2013; Haas and Van Erp 2014; White and Hancock 2020). Politis et al. (2014) assessed every combination of auditory, visual, and tactile driver warnings that is multi-modal (i.e., bimodal and trimodal)

in two scenarios: (i) the lead car braking and (ii) the lead car not braking. Their findings show drivers reacted to multi-modal alerts more quickly than unimodal ones. The effectiveness of warning systems (visual, auditory, and tactile, both unimodal and bimodal) in terms of their ability to alert drivers to hazardous situations when faced with various forms of interference (such as devices embedded inside a vehicle, aural noise, and vehicle vibration) was examined by Murata et al. (2013). According to their results, unimodal warnings cause slower reaction times and a lower percentage of right answers than multimodal warnings. The audio-tactile warning was discovered to be the most successful of all the unimodal and bi-modal warning cues. The efficacy of seven warning modalities (i.e., visual, auditory, tactile, visual-tactile, audio-tactile, and audio-visual-tactile) was assessed by Edet and Mann (2021) for four distinct remote location concepts: within-the-field, close-to-the-field, farm office, and outside-the-farmland. Their findings demonstrated that tactile and visual warning modalities (i.e., visual-tactile) produced the shortest response times for remote location concepts with background tractor noise (i.e., within-the-field and close-to-the-field). Compared to unimodal warning signals, the literature consistently shows that employing multiple warnings led to a faster response time. It also showed that the complexity and burden of the task affects the efficacy of bimodal warning signals, leading to higher workload circumstances and better performance when dealing with multiple tasks.

Agricultural machinery typically operates in a dynamic environment, and operators must rely on their senses (i.e., vision, hearing, and touch) to complete their tasks efficiently (Edet and Mann 2021). The most crucial sense operators employ is vision (Macadam 2003; Karimi 2008). It has been reported that the human visual system processes almost 80% of the information required for safe driving (Lee et al. 1998), implying that other senses,

including hearing and touch, provide the remaining information. Sensory cue-based signals have been used to alert the operator to potential machine malfunctions. For instance, operators have found that using tactile feedback makes them travel around the field more efficiently (Han et al. 2015; Delavarpour et al. 2019) such that, should there be lateral deviance from the intended course, the steering wheel rattles. The operator perceives this information through their palm, after which they take the appropriate steps to align the machine on the intended course (Edet & Mann 2021). An analogous visual aid is the lightbar, which conveys the machine's lateral deviations to the operator through a horizontal configuration of light-emitting diodes (LEDs) (Ima and Mann 2003). Operators use a variety of auditory input formats to make well-informed choices. One illustration would be the sound the threshing machine produces during harvesting, which varies depending on how much crop is fed into it. By listening to this sound, operators can tell when the threshing unit is overloaded. Another common source of auditory feedback is the sound produced by a vehicle's engine. Uneven engine load and performance circumstances can cause loud fluctuations in noise (Bilski 2013), and an unusual sound could be a sign of an issue with the engine that needs to be investigated.

With agricultural machinery moving closer to complete autonomy, it would be helpful to identify which bimodal warning method, visual-auditory or visual-tactile, performs best to provide the human supervisor with feedback in a remote supervision task. Therefore, the goals of this study were to (i) identify which of the bimodal warning methods, based on response time and noticeability, would be most appropriate to get the attention of an AAM's human supervisor and (ii) ascertain whether background noise has an impact on the efficacy of bimodal warning methods.

### 3.3 Materials and methods

#### 3.3.1 Experimental apparatus

The experiment used a tractor cab (Figure 3.1) in the Agricultural Ergonomics Laboratory at the University of Manitoba to control intrusion from outside noise. The experimental setup consists of two computer monitors positioned one above the other. The bottom monitor displayed the output from a simulation of an agricultural sprayer. In contrast, the top monitor was used to complete the primary internet search task, which will be described in a subsequent section.



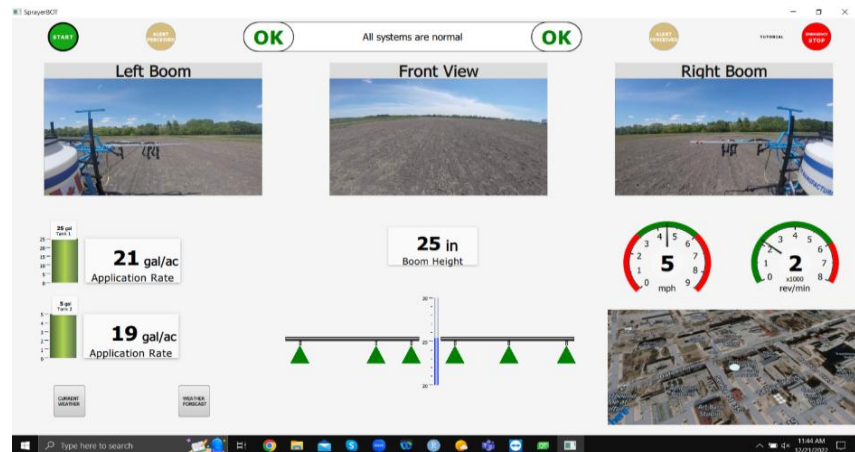
**Figure 3.1** A tractor cab was used for the experimental study. Participants used the top monitor for the internet search task, while the bottom monitor displayed the simulation of the autonomous agricultural sprayer.

An existing simulation of an autonomous agricultural sprayer, described by Edet et al. (2022), was modified to include different warning methods (i.e., visual, auditory, and tactile) and an ‘Alert Perceived’ button for acknowledging the warnings was added to the interface (Fig. 3.2). The ‘Alert Perceived’ button was positioned on both sides of the interface, considering left-handed and right-handed individuals (Fig. 3.2a). Two separate bimodal warning methods (i.e., visual-auditory or visual-tactile) were integrated with the operation of the simulated autonomous sprayer.

(a)



(b)



**Figure 3.2 Altered version of the study’s user interface. To alert the human supervisor to any irregularity, visual, auditory, and tactile warning cues were incorporated to the interface. This picture displays only the mistake acknowledgement button (Alert Perceived) and the visual warning (Alert). (a) An error-detection visual alert and error acknowledgement button, respectively. (b) A visual display that appears when everything is OK or when the supervisor clicks the Alert Perceived button to acknowledge receiving a warning.**

### 3.3.2 Experimental protocol

Screening tests, training trials, two experimental sessions, and an end-of-experiment questionnaire made up the experimental protocol. The participants were briefed on the purpose and methods before the experiment. When queries arose, the principal investigator

addressed them as clearly as possible. The participants signed a consent form certifying that they had read the terms and circumstances of their participation in the study and provided their consent voluntarily. Ethics approval was obtained from the University of Manitoba's Research Ethics Board.

The participant's visual, auditory, tactile, and comfort levels were evaluated during the screening tests. The visual screening involved showing the participants a sample of the visual warning and asking them to score how well they could see the content. Pure-tone audiometry was performed using a hearing test app (e-audiologia.pl, version 1.1.3) that was obtained from the Google Play store to assess each participant's hearing threshold ( $\leq 40$  dBHL). A tiny, coin-sized 5 VDC motor was used for the tactile assessment. It was placed inside a soft, cushioned band to reduce vibration, and the participant's wrist was wrapped in the band to provide a tactile impression. When the device was purchased, the vibration frequency was measured and found to be approximately  $180 \pm 10$  Hz. This frequency was chosen because it was the optimum frequency for vibrotactile perception (Yim et al. 2007; Edet and Mann 2021).

During the training trials, participants were allowed to become acquainted with the experimental procedures. The training trials involved presenting the warning cues to the participants while they were sitting in the tractor cab, much like in the experimental sessions. After the training, the participants were asked to rate how well they could see, hear, and feel the sensory information presented and asked to rate their comfort level in response to the various sensory cues on a post-training evaluation form to make sure they didn't feel uncomfortable in any way that would have introduced bias.

The three steps of the experiment were: (i) searching the internet for answers to specific

agronomic questions; (ii) watching the automation interface's presentation of the simulated autonomous sprayer in action; (iii) pressing the 'Alert Perceived' button on the interface screen, the bottom monitor right in front of the participant's seated position, to indicate that an error had been perceived. In a real-world situation, humans managing the autonomous sprayer might be distracted by other things. Therefore, the main goal of the internet search task was to simulate the environment that a human would encounter when monitoring the use of an autonomous sprayer. It also helped determine when participants felt that they had been induced to make an error (i.e., when they looked away from the primary task after the error had been induced). The internet search activity was selected because it accomplished three things: (i) it prevented the participant from becoming distracted from the primary screen; (ii) it had few distracting elements that would make it difficult for the participant to see the notification; and (iii) it was an ecologically valid task (i.e., it is reasonable to expect that farmers would be looking at the internet for farm-related information while remotely supervising their autonomous machines).

During the simulated spraying operation, errors were introduced at random intervals, and the participants were alerted to the faults using bimodal warning cues: visual-auditory or visual-tactile. Subsequently, the participants were required to press the 'Alert perceived' button to indicate that they had noticed the error. An eye tracking device was worn by the participants to track their eye movements (i.e., point of gaze), especially to identify when an error occurred as well as when the participant noticed the error and when clicking the 'Alert perceived' button by the participant. For additional analysis, each participant's response time and level of noticeability (i.e., their ability to identify the error) were considered. The eye tracking setup used a laptop and the SensoMotoric

Instruments (SMI) Eye Tracking Glasses 2.0 60 Hz. Previous experiments involving mobile eye tracking have used the SMI system (Caspi et al. 2018; Hoppe et al. 2018; Niehorster et al. 2020). A three-point calibration and recording were performed using the SMI iViewETG software (version 2.7.1) and a USB cable to connect the glasses to a laptop. After the eye model adaptation phase of iViewETG was finished, the calibration was initiated. The participant's task was to fixate on the centre of three distinct markers in the stimulus grid: the keyboard, the screen above the participant's seated position, and the screen below the participant's seated position. The principal investigator used the recording laptop's live view of the scene camera to select these areas during each fixation. Each eye camera recorded a video stream at 120 Hz with a  $320 \times 240$  pixels resolution. In comparison, the front-facing scene camera recorded a video stream at 24 Hz with a resolution of  $1280 \times 960$  pixels. It should be noted that the frame rate of the eye cameras does not correspond to the real camera frame rate but rather to the recorded video provided by the iView ETG.

Two sessions of experimentation were completed. No tractor noise was introduced into the tractor cab during the first session, creating a quiet environment, as might be expected for close-to-field remote supervision. It should be noted that the tractor cab was not completely soundproof; an average noise level of 44 dBA was measured. During the second session, 'tractor noise' was introduced into the environment to create the in-field remote supervision scenario. The tractor noise, measured to be 78 dBA, used in this study was previously recorded from an operating John Deere combine. The sound clip was played inside the tractor cab using a computer speaker. The average sound levels for both background noises were measured using a sound meter (Q094168, REED Instruments,

USA). The two remote supervision situations modelled for our study are described in Table 3.1.

**Table 3.1 Scenarios for remote supervision and related work environments as used in the study (adapted from Edet and Mann 2021).**

<b>Scenario</b>	<b>Background Noise</b>	<b>Primary Task</b>	<b>Monitoring Level</b>
In-field	Tractor noise	Expected to operate another machine while supervising the autonomous agricultural machine.	Intermittent
Close-to-field	Little or no tractor noise	Perform another off-field task, e.g., prepare chemical to refill the spray tank.	Intermittent

There were two trials in each experimental session, each lasting an average of 6 min. To inform the participants of the error, one of the bimodal warning cues was employed in each trial (trial 1 – visual and auditory, trial 2 – visual and tactile). The experimental sessions and trial orders within each session were counterbalanced and randomized among participants to minimize order effects. Following each trial, participants were given a trial questionnaire on which they were asked to rate and provide feedback on the warning cues used. Participants were given a 10 min break between sessions to unwind and move around. After the final session, participants were given an end-of-experiment questionnaire asking about their overall experience and any further recommendations.

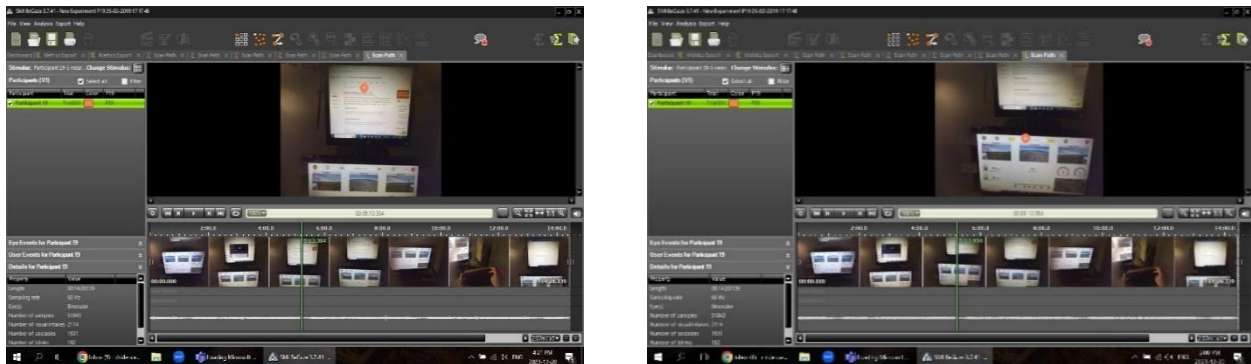
### 3.3.3 Data analysis

Participants' SA was examined in relation to their response times per trial and levels of noticeability. The time stamp specified in the sprayer simulation code computed the response time based on the difference between the error display and acknowledgement times. The level of noticeability was measured as saccadic reaction time. This was

determined as the recorded time between error display and saccade (i.e., the rapid eye movement from one gaze point to another) onset such that short saccadic reaction time denotes a high level of noticeability and vice versa. The BeGaze™ Analysis Software (version 3.7.41) estimated the saccadic reaction time. The saccade onset was interpreted as the quick eye movement of the participant from the primary task screen above the participant’s seated position to the top centre of the screen below the participant’s seated position. The entire top centre of the screen below the participant’s seated position was classified as the region of interest as it contains the visual warning indicator, which continuously displays when each of the bimodal warnings (i.e., visual-auditory or visual-tactile) occurs together with the accompanying warning message drawing the attention of the participant to that specific region (Fig. 3.3). Figure 3.4 shows examples of gaze fixation points relevant to this study.



**Figure 3.3** The region of interest associated with perception of the warning cues.



**Figure 3.4** Display of gaze fixation points following saccade onset. Gaze cursor on primary task screen prior to error display (left) and gaze cursor on region of interest at saccade onset (right).

Data analysis was performed to determine the effectiveness and efficiency of the two bimodal warning modalities tested in the two environments (i.e., noisy and quiet). Outlier responses were evaluated using the  $2 \times SD$  criteria for the average number of responses. Statistically significant differences were accepted at the 95% confidence level ( $p < 0.05$ ) for the repeated measures analysis of variance (ANOVA) conducted. To find the most effective bimodal warning technique, the participants' saccadic reaction and response times to the warnings were compared with each other and with two different background noise levels (tractor sound and quiet). The participants' subjective evaluations and comments from the end-of-experiment questionnaire were also considered during the data analysis.

### **3.4 Results and Discussion**

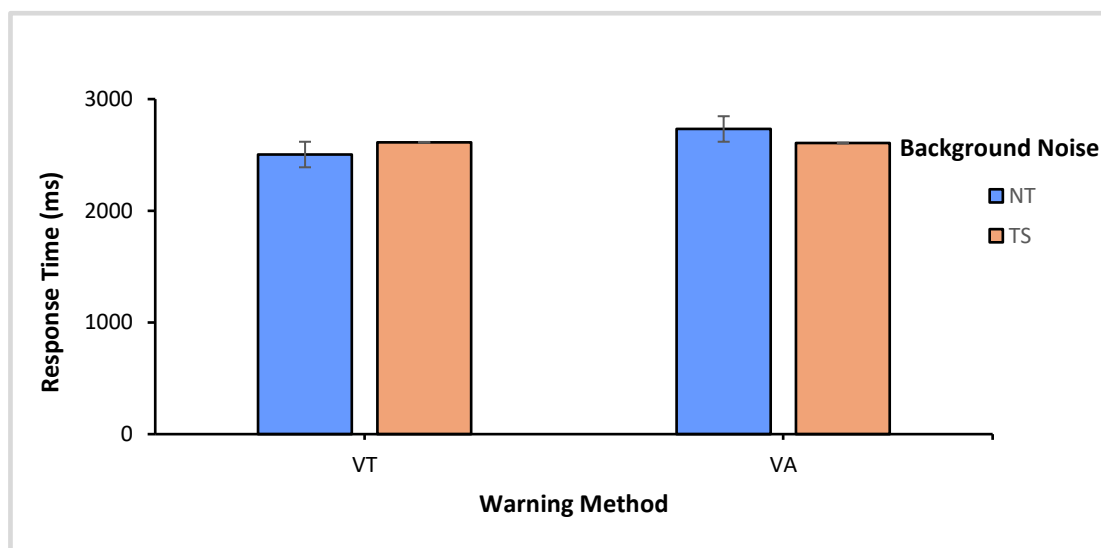
#### **3.4.1 Participant demographics**

A total of 25 participants between the ages of 18 and 35 ( $29 \pm 4.9$ ) participated in the study (11 male, 14 female, 2 left-handed). Fourteen participants had farming experience and ten out of the fourteen self-reported having experience driving a tractor or operating an agricultural sprayer. Each participant completed an informed consent form, and they received an honorarium for their time. During the visual screening, all participants were able to see the visual cues that were provided to them. In addition, the findings of the pure-tone audiometry hearing tests showed that none of the participants had any hearing impairments that would influence the study's conclusions (i.e., they were able to discern between various background noises and the auditory warning).

#### **3.4.2 Response time**

Figure 3.5 presents the mean response times for each background condition for the two types of trials. Both bimodal warning cues (i.e., visual-auditory and visual-tactile) were

able to draw the attention of participants, however, the visual-tactile warning cue had a lower response time for both the quiet ( $2464 \pm 393.5$ ) and tractor noise ( $2452 \pm 445.8$ ) conditions making it the more effective warning cue. The response times were entered into a 2 (Trial type)  $\times$  2 (Background condition) ANOVA, which showed that there was a significant main effect of Trial type,  $F(1, 24) = 5.36, p < 0.05$ , and no significant effect of background condition,  $F(1, 24) = 0.03, p > 0.05$  with an interaction between them,  $F(1, 24) = 6.03, p < 0.05$ .



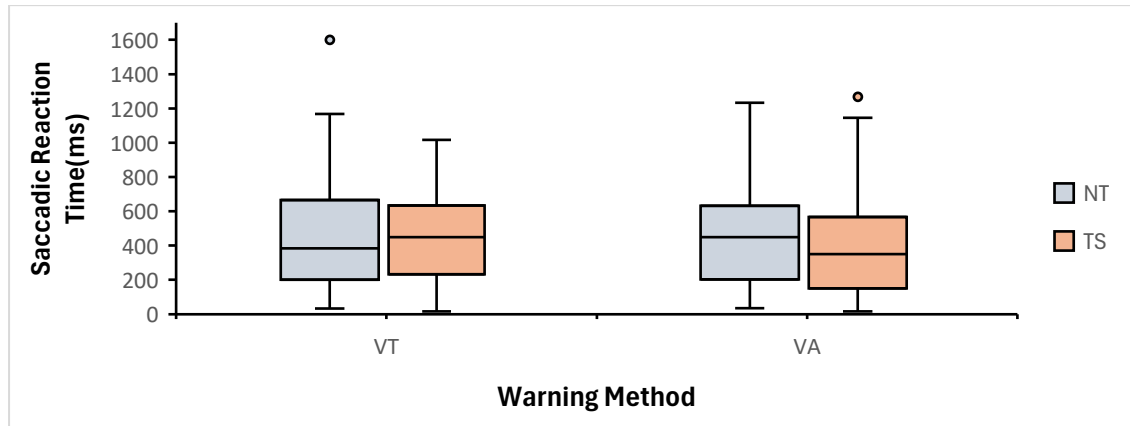
**Figure 3.5 Comparison of participants' response times in relation to background noise. VA–visual-auditory; VT- visual-tactile; NT- no tractor sound; TS- tractor sound; error bars represent standard error.**

The participants' visual and auditory sensory overload may be the cause of these findings (Lee 2015). The majority of the participants' time during the tractor sound session was spent using their visual and auditory senses to complete an internet search task and listen to the sound of the tractor. As a result, it is possible that individuals took longer to understand the warning when they were informed of an issue utilizing visual and auditory stimuli. When participants shifted their focus from the online search to the sprayer simulation screen, the visual load remained rather consistent, which is why this effect was stronger for the visual-auditory stimuli. Nonetheless, the

participants were subjected to tractor noise all during the session because there was a visual-auditory warning cue for when the tractor sound was introduced into the background. Therefore, the auditory burden was further enhanced by the audio warning from the visual-auditory warning cue, which might have made the visual-auditory cue less effective. The results displayed in Fig. 3.5 are also in line with findings from other studies, which indicated that visual-tactile stimuli were more effective than visual-auditory stimuli (Burke et al. 2006; Whang et al. 2007). Hence, visual-tactile warning cues seem to work best for close-to-field remote supervision, when background noise might not be present.

### **3.4.3 Noticeability**

Out of the 25 participants who participated in the study, nine were excluded from the eye-tracking data analysis because of various problems with the eye movement recording device. Figure 6 reveals the mean saccadic reaction times for each background condition for the two types of trials (trial 1– visual-auditory; trial 2– visual-tactile). Notably, visual-auditory warning when background noise was present had the shortest saccadic reaction time ( $379 \pm 185.1$ ), which denotes the highest level of noticeability. The reaction times were entered into a  $2$  (Trial type)  $\times$   $2$  (Background) ANOVA, which showed that there was no significant main effects of Trial type,  $F(1, 15) = 0.53, p > 0.05$ , and background condition,  $F(1, 15) = 2.18, p > 0.05$  with no interaction between them,  $F(1, 15) = 0.01, p > 0.05$ .



**Figure 3.6. Comparison of participants’ saccadic reaction times in relation to background noise; VA– visual-auditory; VT – visual-tactile; NT – no tractor sound; TS – tractor sound; error bars represent standard error.**

This outcome is in agreement with the findings by Corneil and Munoz (1996), that an irrelevant auditory cue influenced gaze shifts to visual targets differently than an irrelevant visual cue influenced gaze shifts to auditory targets in a complex environment. This is consistent with the notion that peripheral or surrounding auditory stimuli are powerful in capturing visual attention when notified by visual-auditory cues (Mazza et al. 2007). Conversely, visual-tactile warning when there was no tractor sound in the background had the lowest level of noticeability as it had the longest saccadic reaction time ( $469 \pm 237.8$ ).

### 3.4.4 Subjective responses

Participants were able to recognize the bimodal warning cues and felt at ease receiving error notifications with either the visual-tactile or the visual-auditory bimodal warning cues, according to an analysis of the end-of-experiment questionnaire. The participants also reported that both bimodal warning cues were successful in getting their attention. However, there were differences in the participants’ efficiency levels (i.e., slightly or highly effective) as well as in terms of background noise (quiet scenario and tractor sound).

In general, 24% of participants preferred employing visual-auditory cues, whereas 76%

suggested using visual-tactile cues. It was not suggested by any participant to use both bimodal warning cues simultaneously. When asked why they made their suggestions, the participants said that they found it harder to distinguish between the visual-auditory cues and the background noise, therefore the visual-tactile cues were less distracting when it came to recognizing the warning messages. Six participants also stated that the visual-auditory cues were less annoying than the visual-tactile cues and easily allowed them to think. They stated that the visual-auditory cues seemed more like an alert to them. On average, however, visual-auditory warning cues did not yield the fastest response times for both quiet ( $2498 \pm 617.1$ ) and tractor noise ( $2488 \pm 597.8$ ) conditions (Fig. 3.5). The subjects' increased mental workload and decreased SA may have contributed to this heterogeneity. According to this, when tractor noise was introduced into the background, for the visual-tactile the participants had to perceive and process only one auditory stimulus- the background noise- while for the visual-auditory the participants had to perceive and process two auditory stimuli- the background noise and the auditory warning cue- during the visual-tactile warning cue. This resulted in a higher mental workload and a longer response time before participants were able to correct the error. Table 3.2 shows the summary of findings as discussed above.

**Table 3.2 Summary of Findings**

<b>Scenario</b>	<b>Warning Method</b>	<b>Response Time</b>	<b>Noticeability</b>	<b>Subjective Response</b>
In-Field (Noisy)	Visual-Auditory	NS	NS	Preferred
	Visual-Tactile	NS	NS	
Close-to-Field (Quiet)	Visual-Auditory	NS	NS	Preferred
	Visual-Tactile	SS	NS	

*NS- Not statistically significant, SS- Statistically significant.*

### 3.5 Conclusion

The purpose of this study was to identify the most appropriate bimodal warning cue to alert an AAM's human supervisor. Specifically, this study assessed the supervisor's response based on what is known as Level 1 SA or perception. The perception of two different bimodal warning signals, with and without background tractor noise, was assessed by measuring response time and level of noticeability in four conditions. Visual-tactile and visual-auditory warning cues had the shortest and longest response times, respectively. In terms of noticeability, there were no statistically significant differences observed between visual-auditory and visual-tactile although noticeability improved with the presence of background tractor noise. A greater percentage of the participants indicated that they preferred the visual-tactile warning method compared to the visual-auditory warning method. This suggests that the most appropriate warning cue is visual-tactile in remote supervision situations when humans might not be exposed to tractor noise. Both bimodal warning methods are suitable for remote supervision scenarios that expose humans to tractor noise as there was no significant effect between the bimodal warnings when tractor sound was present. That said, the most consistent, and preferred bimodal warning modality, as indicated by participants, was the visual-tactile. This result will help designers select the best modality when designing warning systems for remotely supervised autonomous agricultural machines; minimizing hazards experienced by farmers during spraying operations and enhancing the efficiency of the farmers.

This chapter established the critical role of perception in remote supervision of autonomous agricultural machines (AAMs), particularly emphasizing how bimodal warning cues—such as visual-auditory and visual-tactile combinations—affect a supervisor's ability to quickly detect and respond to system alerts. This initial stage of situation awareness (Level 1 SA) forms the cognitive foundation upon which higher-order processes like comprehension and projection are built. The

findings highlighted that the effectiveness of bimodal warnings is influenced by both environmental context and sensory integration, setting the stage for understanding how warning modality not only captures attention but also contributes to the broader cognitive framework required for decision-making in autonomous agricultural operations.

### 3.6 Preamble to Chapter 4

Perceiving warning cues is only the initial layer of effective remote supervision of autonomous agricultural machines; to maintain robust situation awareness (SA), supervisors must go beyond detection (Level 1 SA) and engage in deeper cognitive processes such as interpreting the meaning of alerts (Level 2 SA – Comprehension) and anticipating future system behavior (Level 3 SA – Projection). These higher-order levels of SA are crucial for timely and appropriate decision-making during unexpected system events, and they are strongly influenced by the cognitive clarity, intuitiveness, and compatibility of the warning modality with the operator’s mental model and workload. Chapter 3 of this thesis addressed the perceptual component by comparing two bimodal warning configurations—visual-auditory and visual-tactile—and found that while both improved initial detection, visual-tactile cues were generally more effective in quieter environments. However, this evaluation was focused exclusively on how well these combinations supported perception and response time, without considering how each sensory channel contributes to the comprehension or prediction of system states.

Chapter 4 builds on these findings by deliberately shifting the research focus from bimodal to unimodal warning modalities to investigate how each sensory channel—visual, auditory, or tactile—supports the operator’s ability to understand the nature of system anomalies and forecast their consequences. This transition reflects both a methodological and a practical necessity. From a methodological standpoint, assessing modalities in isolation provides greater experimental control and allows the study to disentangle the unique cognitive contributions of each channel. Bimodal cues, while effective at capturing attention, introduce overlapping or synergistic effects that make it difficult to identify which modality is primarily responsible for comprehension accuracy or successful projection. For instance, a quick response to a visual-auditory cue may be

due to the auditory component's urgency or the visual component's clarity, but without isolating the inputs, their individual impacts remain ambiguous. Evaluating unimodal cues, therefore, enables a more precise understanding of how specific sensory pathways affect different stages of SA.

From a practical perspective, agricultural environments are highly dynamic, and certain modalities may be impaired or less effective depending on the context. Visual cues may be missed due to attention diversion or screen clutter; auditory cues may be masked by tractor or environmental noise; tactile cues may go unnoticed if not grounded in familiar patterns. Understanding how each modality performs on its own equips interface designers with the knowledge to develop more resilient and adaptable human-machine interfaces (HMIs), especially in conditions where reliance on a particular sensory modality is necessary. This level of insight is essential for promoting cognitive ergonomics in remote supervisory roles, where the operator is physically detached from the machine and must depend entirely on mediated cues to maintain awareness.

Thus, Chapter 4 represents a critical advancement in the overall research trajectory: it moves beyond perception to evaluate comprehension and projection, and it does so in a way that allows for a more nuanced and context-sensitive evaluation of warning design. The results obtained from this unimodal investigation not only complement the perceptual data from Chapter 3 but also provide foundational knowledge for the subsequent usability assessments explored in Chapter 5. Ultimately, this progression ensures that warning systems can be designed not just for perceptual salience, but for cognitive effectiveness across all three levels of situation awareness—enabling remote supervisors to detect, interpret, and respond to system anomalies with greater confidence and accuracy.

# **4. MODALITY-SPECIFIC SUPPORT FOR COMPREHENSION AND PROJECTION OF SYSTEM STATUS DURING REMOTE SUPERVISION OF AUTONOMOUS AGRICULTURAL MACHINES**

## **4.1 Abstract**

The integration of autonomous agricultural machines (AAMs) has introduced significant efficiencies in modern farming, but these systems still require effective human supervision to ensure safety and performance, particularly because typical field conditions require operator monitoring and regular system intervention. Human-machine interfaces (HMIs) must therefore support operators in maintaining situation awareness (SA), especially comprehension (Level 2 SA) and projection (Level 3 SA) of system status. Unimodal warning cues—visual, auditory, or tactile—are commonly used to convey critical information, yet their effectiveness varies depending on sensory modality, user interpretation, and environmental conditions. This study investigates the relative effectiveness of unimodal warning modalities in supporting Level 2 and Level 3 SA in the context of a remotely supervised autonomous agricultural sprayer. Across two controlled experiments, we evaluate how visual, auditory, and tactile warnings influence operators' response accuracy, perceived urgency, and response time under typical field conditions requiring operator monitoring and intervention. Subjective evaluations were also collected to assess user preference. Findings indicate that visual warnings were consistently rated highest in both comprehension accuracy and urgency projection, with the shortest response times and strongest user preference (84%). Auditory cues yielded moderate performance, while tactile cues were the least effective across both objective and subjective measures. These results align with existing SA theory and underscore the importance

of aligning warning modality with task demands. The study contributes to the development of user-centered HMIs in agricultural automation and highlights the potential for SA-aligned modality design to improve operator performance, especially under time-sensitive supervisory conditions.

## **4.2 Introduction**

The rapid advancement of automation and artificial intelligence has transformed modern agriculture, enabling the development of autonomous agricultural machines (AAMs) capable of performing key operations such as planting, spraying, harvesting, and soil preparation with minimal human input (Sanchez and Duncan, 2009; Parasuraman, 2000). These technologies are increasingly deployed to improve efficiency, productivity, and sustainability. However, due to the unpredictable nature and complexity of agricultural environments, human oversight remains essential to ensure safe and effective operation (Adamides et al., 2014; Schrenghost et al., 2008).

Remote supervision of AAMs typically involves human operators interacting with machines via automation interfaces (Blackmore et al., 2007; Duckett et al., 2018; Opiyo et al., 2021). These interfaces must provide timely and comprehensible information to support supervisory functions such as task setting, resource allocation, progress monitoring, and emergency intervention (Dorais and Gawdiak, 2003; Jin et al., 2021; Rakhra et al., 2020). In emergency scenarios, the operator's ability to recognize, interpret, and respond to warnings is critical. To support these functions, automation interfaces must present warning signals that maintain the operator's awareness of the system and environment—a concept referred to as situation awareness (SA) (Endsley, 2017; Peryer et al., 2005).

Situation awareness, particularly in supervisory control settings, is central to effective decision-making. According to Endsley's (1995) widely adopted framework, SA comprises three

hierarchical levels: Level 1 (perception of elements in the environment), Level 2 (comprehension of their meaning), and Level 3 (projection of future states). These levels are sequential but interdependent; accurate comprehension and prediction rely on initial perception. In dynamic environments, operators must interpret incoming data quickly and accurately to maintain SA. Deficits in SA—whether due to incomplete perception or misinterpretation—can impair decision-making and jeopardize system safety (Endsley, 1995; Endsley et al., 2003).

Recent studies have examined SA in the subject of explainable automation. For instance, Avetisyan et al. (2022) proposed an SA-based explanation framework, aligning information presentation with the three SA levels. Their findings indicated that modality and information load significantly influenced users' comprehension, cognitive workload, and trust in automated systems. Specifically, visual-only explanations were preferred for lower SA levels, that require detection. When a future-state projection was required (i.e., Level 3 SA), then a combination of visual and auditory explanations was favored.

Despite progress in supervisory interface design, achieving and sustaining all three levels of SA in remote supervision remains challenging. Higher levels of automation can reduce operator involvement, leading to diminished SA and increased risk of complacency (Bye et al., 1999; Endsley, 2017). As a result, the implementation of effective feedback systems—particularly warning modalities—is essential to maintain operator awareness and performance.

Unimodal warning cues, which use a single sensory channel (visual, auditory, or tactile), are commonly used in automation interfaces. Each modality has distinct strengths and limitations depending on task demands and environmental conditions. Auditory warning signals are often effective in rapidly capturing attention, that said, auditory signals may be masked in noisy settings or contribute to cognitive overload when excessive (McNeill et al., 2010). Visual warnings, such as

color-coded alerts or dynamic icons, are well-suited for spatial interpretation but require the operator's visual focus (Lee, 2007). Tactile cues, including vibration-based feedback, offer hands-free signaling and are useful in visually or auditorily constrained environments, although they often lack semantic clarity and require proper calibration (Ho and Spence, 2013; Lee et al., 2024).

The effectiveness of warning modalities can be evaluated using a variety of metrics, including response time, comprehension, perceived urgency, risk perception, and likelihood of compliance (Wogalter et al. 2002; Edet and Mann 2021). Objective performance indicators such as response accuracy and time are often used to quantify warning performance, while subjective methods—including rating scales, interviews, and preference rankings—provide insights into user perception (Wogalter et al., 1999). Notably, several studies have linked these effectiveness criteria to the levels of situation awareness. For instance, Chiou and Lee (2021) and Salmon et al. (2006) have demonstrated that measures such as accuracy and response latency can reflect operator performance at different SA levels. Neuroergonomic research by Ayaz et al. (2023) further supports the association between SA development and task-related physiological or behavioral indicators. Their findings support the notion that fluctuations in cognitive workload, attentional allocation, and environmental comprehension can be meaningfully captured through combined physiological and behavioral measures.

Prior studies have investigated the role of unimodal cues in SA-related settings. For example, Whang et al. (2007) found tactile warnings to be most effective in regaining attention during figure-matching tasks, while Scott and Gray (2008) reported superior redirection of driver attention with tactile feedback. However, the effectiveness of a given modality can vary depending on the complexity and semantics of the task. In visually complex environments, for instance, Tuch et al.

(2009) observed reduced recognition rates. Additionally, response time to warning stimuli has been shown to vary by modality, with tactile stimuli producing the fastest responses (Kosinski, 2008).

Edet and Mann (2022) conducted a foundational study evaluating seven warning modalities in an agricultural supervision context. While their findings contributed to understanding attentional capture across various remote supervision locations, the study did not directly address the cognitive mechanisms underlying SA—particularly comprehension and projection in dynamic emergencies.

To address this gap, the present study evaluates the effectiveness of unimodal warning modalities (visual, auditory, tactile) in supporting Level 2 SA (comprehension) and Level 3 SA (projection) during typical field conditions requiring operator monitoring and intervention for a remotely supervised autonomous agricultural sprayer. Two experiments were conducted to assess: (1) which modality most effectively supports comprehension based on response accuracy, and (2) which modality most effectively supports future-state projection based on accuracy and response time. By aligning warning evaluation with Endsley's SA model, this research contributes to a more nuanced understanding of how unimodal cues influence critical cognitive processes in agricultural automation.

## **4.3 Materials and methods**

### **4.3.1 Participants and Ethics**

Participants were recruited from the University of Manitoba community and provided written informed consent preceding participation. All procedures were approved by the University of Manitoba Research Ethics Board (REB 2). Participants completed a screening process to evaluate visual, auditory, and tactile sensitivity, ensuring suitability for the experimental tasks.

Participants completed relevant sensory screen tests before completing the experimental protocol. Visual clarity was assessed using warning cue samples. Auditory sensitivity was tested with a pure-tone audiometry app (e-audiologia.pl, ver. 1.1.3), using a threshold of  $\leq 40$  dB HL as an inclusion criterion. Tactile perception was evaluated using a 5V DC vibrating motor embedded in a cushioned wristband; the selected vibration frequency ( $\sim 180 \pm 10$  Hz) corresponded with optimal tactile sensitivity for human skin mechanoreceptors. This frequency range has been shown to maximize the detectability and discriminability of tactile stimuli, thereby enhancing the likelihood that users will perceive and respond to vibrotactile warnings effectively in dynamic task environments (Yim et al., 2007; Edet and Mann, 2021).

#### **4.3.2 Apparatus and Experimental Setup**

Both experiments were conducted in a sound-controlled tractor cab located in the Agricultural Ergonomics Laboratory at the University of Manitoba (see Figure 4.1). The setup included two vertically arranged monitors: the lower screen displayed a simulation of an autonomous agricultural sprayer, while the upper monitor was used for a concurrent internet search task. The sprayer simulation, adapted from Ezeagba et al. (2025), incorporated unimodal warning cues—visual, auditory, and tactile—to signal operational conditions.



**Fig. 4.1. Tractor cab used for the experimental study. Participants used the upper monitor for the internet search task while the lower monitor displayed the simulation of the autonomous agricultural sprayer.**

### **4.3.3 Warning Cue Design**

Each modality was configured to reflect either system status (Experiment I) or urgency levels (Experiment II). Warning designs were linked to three components of the sprayer: nozzle (N), boom (B), and tank (T). Visual warnings used colored letters (green and red letters N, B, T for comprehension evaluation; yellow, orange and red letters N, B, T for urgency projection evaluation) as these colors result in a prompt user reaction (Yun and Yang 2020), while different frequencies of the auditory and tactile warnings (recommended optimal aural and vibrotactile frequencies) were employed using the Morse code—short and long signals called dots and dashes to represent letters, to denote the different components and integrated into the simulation of the autonomous sprayer (Tan et al. 1997; Thepvilojanapong et al. 2014; Wang et al. 2024) (Table 4.1).

**Table 5.1: Warning Design Considerations**

<b>Modality</b>	<b>Design Features (Exp. I)</b>	<b>Design Features (Exp. II)</b>
Visual	Green (Normal), Red (Abnormal) letters (N, B, T)	Yellow (Low), Orange (Medium), Red (High) letters (N, B, T)
Auditory	500 Hz, 1000 Hz frequencies (Chi et al. (2017) at seat locations	500 Hz, 1000 Hz, 2000 Hz frequencies (Casali, 1999)
Tactile	40 kHz, 50 kHz wrist-mounted vibrations	100 Hz, 140 Hz, 200 Hz (Bao et al., 2019)

#### **4.3.4 Experimental Procedure**

##### ***4.3.4.1 Training and Familiarization***

Participants underwent training trials to familiarize themselves with the interface, warning modalities, and tasks. A perception checklist was administered post-training to document their ability to perceive each cue as well as to rate the comfort.

##### ***4.3.4.2 Experiment I: Effect of Warning Modality on Comprehension***

During the experimental procedure, participants engaged in three tasks. The primary task was to monitor the autonomous sprayer simulation; this involved responding to warning cues by selecting the appropriate machine condition from a list of options provided (Table 2). To ensure a realistic test environment, participants were asked to conduct an internet search task designed to simulate real-world cognitive demands.

**Table 5.2: Possible conditions from which selections were made (comprehension evaluation).**

S/N	Machine Condition
1.	Nozzle is normal [Clear]
2.	Nozzle is abnormal [Blocked]
3.	Boom height is normal [Correct Position]
4.	Boom height is abnormal [Too High/Low]
5.	Tank level is normal [Adequate]
6.	Tank level is abnormal [Low]

The experimental procedure consisted of three trial types (i.e., visual, auditory, tactile) with six warnings per trial. Each of the three trials lasted approximately 7 minutes and were randomized across participants. Trials were followed by a short break and a modality-specific evaluation questionnaire. Warning cues indicated system status (normal or abnormal), and participants' accuracy in identifying these conditions served as the primary performance measure.

#### **4.3.5 Comprehension Analysis**

To assess the effectiveness of each modality in supporting Level 2 SA, response accuracy was calculated as the proportion of correct selections per condition. A chi-square test of independence was used to compare the distribution of correct versus incorrect responses across modalities ( $p < .05$ ). Qualitative feedback from post-trial and end-of-experiment questionnaires was analyzed to supplement quantitative findings.

#### **4.3.6 Experiment II: Effect of Warning Modality on Urgency Projection**

Procedures were identical to Experiment I, with the addition of graded urgency cues (i.e., low, medium, high). Participants selected the most appropriate response from a list of escalating

intervention scenarios (see Table 4.3). Each participant completed three trials (one per modality) with nine warnings per trial, randomized and counterbalanced.

**Table 4.3: Possible conditions from which selections were made (projection evaluation).**

S/N	Machine Condition
1.	A small reduction in flow through the nozzle has been detected; check for nozzle obstructions the next time the sprayer is stopped for refilling.
2.	Flow through nozzle is no longer symmetric; stop machine at the end of the current pass to unplug nozzle.
3.	Nozzle is completely plugged; stop machine immediately to unplug nozzle.
4.	A slight change in wind conditions has been detected; check that spray is hitting intended target the next time the sprayer is stopped for refilling and adjust boom height if necessary.
5.	It is likely that some spray is missing intended target; adjust boom height to optimum level within the next few minutes.
6.	The spray is missing the intended target; adjust boom height to optimum level immediately.
7.	Tank levels have dropped to 25%; plan to stop for refilling when most convenient within the next 30 minutes.
8.	Tank levels are very low; stop at the end of the current pass for refilling.
9.	The tank is completely empty; stop spraying immediately and take action to refill to avoid leaving portions of the field untreated.

#### 4.3.7 Projection Analysis

Effectiveness (accuracy) and efficiency (response time) were assessed for each warning modality's support of Level 3 SA. A one-way repeated measures ANOVA was conducted to evaluate differences in mean response times. Chi-square tests were used to assess response accuracy. Outlier response times were identified individually as response times exceeding  $\pm 2$  SD from each

participant's mean. Descriptive and inferential statistics were computed, and qualitative feedback was reviewed to provide insights into cue clarity, urgency perception, and participant preferences.

## **4.4 Results and Discussion**

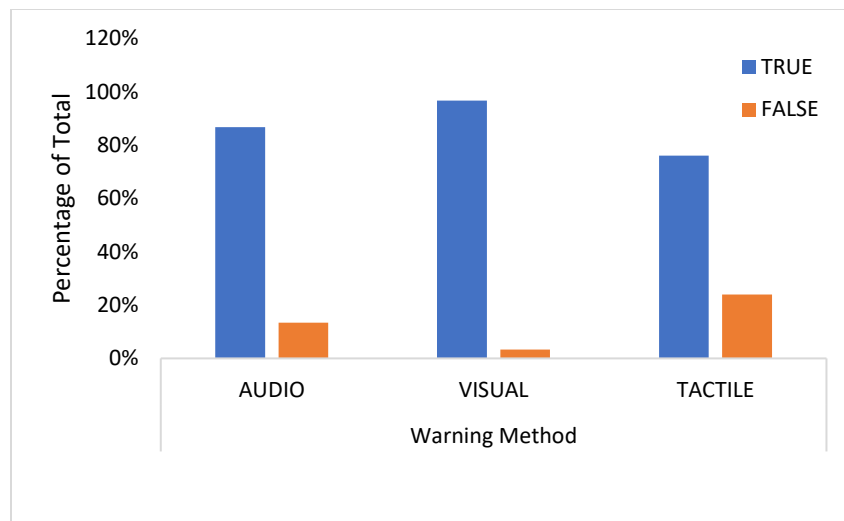
### **4.4.1 Experiment I: Effect of Warning Modality on Comprehension**

#### ***4.4.1.1 Participant demographics***

A total of 25 individuals ( $26 \pm 4.8$ ), ranging in age from 18 to 35 years, participated in the study. The sample consisted of 9 males and 16 females. Of the 25 participants, 11 reported having prior farming experience, and 8 of these individuals had experience operating either a tractor or an agricultural sprayer. Notably, this was an entirely new cohort of participants, distinct from those recruited for the Chapter 3 study. All participants provided informed consent following the University of Manitoba Research Ethics Board guidelines and received an honorarium for their time. To ensure sensory capabilities did not confound the results, participants completed visual, auditory, and vibrotactile screening procedures before the experimental tasks. All participants were able to perceive the visual cues presented during screening. Pure-tone audiometry assessments were conducted using a validated hearing test application, and results confirmed that none of the participants exhibited hearing impairments that could interfere with their ability to perceive auditory warnings. Also, the tactile screening assessment confirmed that participants were able to comfortably detect the tactile stimulation, indicating that the selected vibration frequency was within a readily perceivable and non-intrusive range for all individuals. These screenings helped ensure that any differences in response to sensory cues were not attributable to individual perceptual limitations.

#### 4.4.1.2 Comprehension Accuracy

A chi-square test of independence was conducted to examine the relationship between warning modality (audio, tactile, visual) and response accuracy (correct vs. incorrect). The distribution of correct and incorrect responses varied significantly across the three modalities,  $\chi^2 (2, N = 450) = 27.35, p < .001$ . Visual warnings produced the highest proportion of correct responses (145/150 correct), with very few incorrect responses observed (Fig. 5). Auditory warnings showed a moderate number of errors (20/150 incorrect), while tactile warnings had the highest rate of incorrect responses (36/150 incorrect), indicating lower comprehension effectiveness. These findings suggest that the type of warning modality significantly influences participants' ability to correctly interpret system status.



**Figure 4.2 Percentage of correct (True) and incorrect (False) responses by warning modality (Comprehension- Level 2 SA).**

The results of the chi-square analysis revealed a significant association between warning modality and participants' response accuracy, suggesting that the modality through which a warning is delivered substantially impacts user comprehension in remote supervisory tasks. Specifically, visual warnings produced the highest accuracy rates (145 out of 150), while tactile cues resulted in

the lowest (114 out of 150), indicating that visual cues were more effective in conveying system status information to operators. This finding aligns with prior research indicating the superior performance of visual modalities in tasks requiring rapid situational comprehension. According to Wickens and Hollands (2000), visual cues are generally more effective when information must be processed with high precision or spatial interpretation, which may explain their dominance in this context. Endsley (1995) emphasizes that effective support for Level 2 Situation Awareness—comprehension of the current system state—requires timely, easily interpretable cues. The clarity and immediacy of visual cues likely contributed to participants' improved performance in accurately assessing system status. Auditory warnings, which produced moderate error rates (130 correct, 20 incorrect), may have been less effective due to the transient nature of sound. Although previous studies (e.g., Ho and Spence, 2005) have shown that auditory warnings are advantageous in time-sensitive or attention-divided scenarios, they are also susceptible to masking and cognitive overload, especially when background noise or mental workload is high, both of which can occur in agricultural environments. Tactile warnings, despite their utility in hands-free or visually overloaded settings (Van Erp and Van Veen, 2004), were the least effective in this study. Participants may have found the haptic feedback less intuitive or harder to map onto meaningful system states, consistent with findings from Spence and Gallace (2007), who noted that tactile cues are more effective when designed with spatial congruency and trained associations. The high error rate (36 incorrect responses) suggests that the tactile modality, as implemented here, lacked the immediate interpretability needed for accurate comprehension in time-sensitive situations. These results have practical implications for the design of human-machine interfaces in autonomous agricultural systems. Given the complexity and risk associated with remote supervision of machinery, especially during typical field conditions requiring operator monitoring and intervention, the choice of warning

modality can significantly influence operator performance and safety. Visual cues, when used as the primary modality or in multimodal combinations, may offer the most reliable path for supporting comprehension and reducing operational error.

#### **4.4.1.3 Subjective Responses**

Participants' subjective evaluations provided further insight into their experiences with each warning modality. As summarized in Table 5, 84% of participants indicated a preference for visual warnings, citing their clarity and ease of interpretation. In contrast, auditory warnings were preferred by only 12%, and tactile warnings by just 4%. Participant comments reinforced these trends. One user described the visual cues as, "*natural—I could understand what was happening without second-guessing,*" while, in reference to the tactile modality, another noted, "*I wasn't always sure what the vibration was trying to tell me,*". Thematic analysis revealed that visual warnings were consistently associated with intuitive mapping and immediate comprehension. Auditory warnings were acknowledged for their utility when visual attention was diverted, but they were sometimes lost in background noise. Tactile cues were generally described as vague or delayed, undermining their effectiveness in this context. The findings of this study demonstrate a clear relationship between warning modality and the effectiveness of information delivery in remotely supervised autonomous systems. Specifically, visual warnings significantly outperformed auditory and tactile cues in both objective accuracy and subjective user preference. These results provide strong evidence for the primacy of visual modalities in supporting operator comprehension (Level 2 Situation Awareness) in supervisory control environments, particularly under time-constrained and emergency conditions. These findings align closely with Endsley's (1995) model of situation awareness, which defines Level 2 SA as the operator's ability to synthesize and understand the significance of perceived information. Visual warnings appear to facilitate this cognitive integration

more effectively than other modalities, likely due to their inherent capacity to deliver spatially rich, temporally stable information (Wickens and Hollands, 2000). Participants' qualitative feedback supports this interpretation, with several noting that visual cues required less cognitive effort and were more immediately understandable than their auditory or tactile counterparts. From a human-machine interface (HMI) design perspective, these results also reinforce the modality appropriateness principle (Wickens 2002), which suggests that the effectiveness of a sensory modality depends on its alignment with the task demands. In this case, comprehension of system status during remote operation benefited most from visual cues, which are best suited for spatial and status-related information. Although auditory warnings have been found useful in attention-shifting or time-critical environments (Ho and Spence 2005), their effectiveness in this context was likely constrained by the complexity of interpreting status-related information through sound alone. Tactile warnings, while promising in situations where visual or auditory channels are overloaded (Van Erp and Van Veen, 2004), were the least effective in this study. This suggests a mismatch between the tactile modality and the cognitive demands of the task. Moreover, the lack of prior training or situational association with the tactile signals may have further reduced their interpretability—an issue also observed by Spence and Gallace (2007), who emphasized the importance of spatial and semantic compatibility in vibrotactile displays.

**Table 4.4: Participant Feedback by Warning Modality for Comprehension**

Modality	Participant Preference (%)	Primary Positive Themes	Primary Negative Themes	Representative Quotes
Visual	84	Clear and immediate; easy to interpret; intuitive mapping	May be missed if screen is not in view	“The visual warnings felt natural—I could understand what was happening without second-guessing.”
Auditory	12	Useful when not looking at screen; helps in divided attention	Prone to being masked by background noise; less noticeable	“The sound helped when I wasn’t looking at the screen, but sometimes it blended into the background noise.”
Tactile	4	Hands-free modality; potential in noisy or visually overloaded environments	Ambiguous meaning; often delayed or too subtle	“I wasn’t always sure what the vibration was trying to tell me.”

#### 4.4.2 Experiment II: Effect of Warning Modality on Urgency Projection

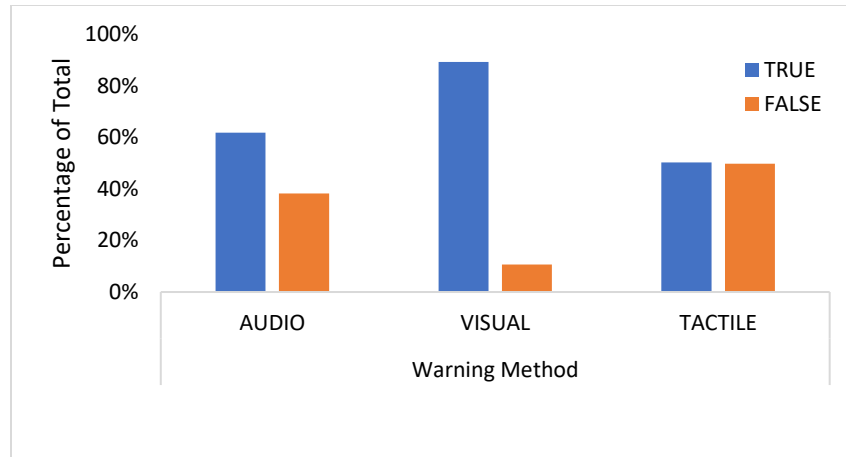
##### 4.4.2.1 Participant demographics

The study involved 25 participants ( $25 \pm 3.5$ ), all between the ages of 18 and 35 years old. The sample included 8 males and 17 females. Among these, 9 participants reported prior experience in farming, and 7 of them indicated they had operated agricultural equipment such as tractors or sprayers. Importantly, this was an entirely new cohort of participants, distinct from those recruited for the chapter 3 study and Experiment I. Under the University of Manitoba Research Ethics Board protocols, all participants provided informed consent and received an honorarium for their participation. Each participant completed preliminary visual, auditory, and vibrotactile screening.

All participants demonstrated adequate visual perception of the warning cues during screening. Additionally, auditory capabilities were assessed using a validated pure-tone audiometry application, which confirmed that no participants had hearing impairments that could affect their ability to perceive auditory signals. Furthermore, results from the tactile screening confirmed that participants reliably and comfortably detected the stimulation, indicating that the selected vibration frequency was both perceptually salient and non-disruptive. These screening measures ensured that participants could detect each of the warning cues.

#### ***4.4.2.2 Projection Accuracy***

A chi-square test of independence was conducted to assess the relationship between warning modality (visual, audio, tactile) and the accuracy of responses (correct vs. incorrect) based on perceived urgency of the machine system state. The results indicated a statistically significant association,  $\chi^2(2, N = 675) = 82.32, p < .001$ , suggesting that the warning modality significantly influenced participants' ability to perceive and respond appropriately to urgent system changes. Visual warnings were most effective in communicating urgency, with 201 out of 225 responses (89.3%) correctly reflecting the urgency level of the system. Auditory warnings led to 139 correct urgency-related responses (61.8%), indicating moderate effectiveness. Tactile warnings performed least effectively, with only 113 responses (50.2%) aligning with the intended urgency level and 112 incorrectly interpreted, reflecting difficulty in distinguishing urgency through tactile feedback alone (Fig. 4.3). These results suggest that visual cues are more intuitively perceived as urgent and are more likely to prompt accurate projection of system state, while tactile cues may lack the resolution or clarity needed to convey urgency in remote supervision scenarios. The auditory modality, while better than tactile, showed limitations that may relate to transient signal characteristics or competing cognitive demands during task performance.



**Figure 4.3 Percentage of correct and incorrect responses by warning modality (Projection-Level 3 SA).**

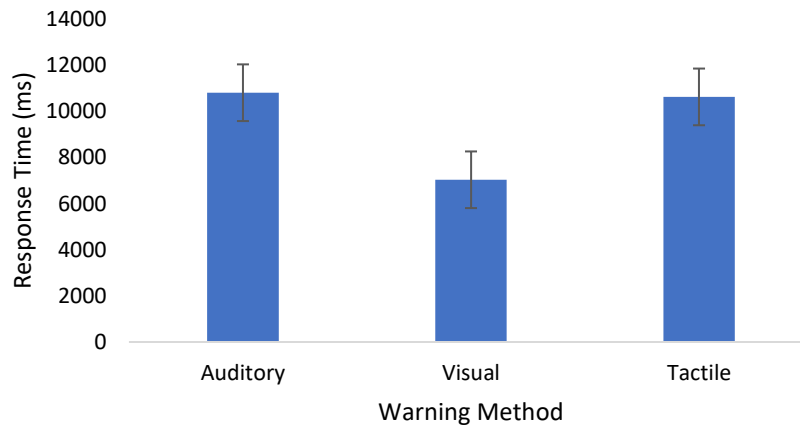
The results of the current study demonstrate a clear and statistically significant relationship between warning modality and participants' ability to interpret the urgency of a machine system's state accurately, a key aspect of Level 3 Situation Awareness (projection). Visual warnings, which produced the highest projection accuracy (89.3%), appear to support urgency perception most effectively. This aligns with prior research showing that visual cues offer greater temporal and spatial resolution, allowing users to better anticipate system trajectories (Wickens and Hollands, 2000). Participants' ability to project future states using visual cues may also reflect stronger intuitiveness and lower cognitive load associated with visually encoded urgency indicators, such as color or motion dynamics (Endsley, 1995; Sarter, 2006). In contrast, auditory cues—while superior to vibrotactile cues—were associated with moderate projection accuracy (61.8%). This finding is consistent with the transient and less persistent nature of auditory signals, which may be more susceptible to interference, particularly in multitasking environments (Ho and Spence, 2005).

Moreover, the effectiveness of auditory urgency may depend heavily on sound design factors such as pitch, tempo, and repetition, which were not explicitly varied in the current study, but merit further investigation. Tactile warning signals, which produced the lowest accuracy

(50.2%), were largely ineffective in conveying urgency. These findings are in line with existing literature that notes challenges in using haptic feedback to communicate nuanced or dynamic system states without extensive user training (Van Erp and Van Veen, 2004). The poor performance of tactile cues in this context may also be attributed to their limited bandwidth and lack of intuitive mapping to urgency—a problem exacerbated in remote or low-attention environments. Taken together, these findings suggest that warning systems in autonomous or semi-autonomous machinery should prioritize visual channels for urgency-related alerts, especially in remote supervision scenarios. Where visual channels are overloaded or unavailable, auditory cues may serve as a secondary modality, provided that their design is optimized for salience and interpretability. Tactile cues, while promising for alerting in noisy and visually restricted situations, may require multimodal pairing or training interventions to be effective for urgency projection.

#### ***4.4.2.3 Projection Response Time***

A one-way repeated measures ANOVA was conducted to examine the effect of warning modality (visual, auditory, tactile) on participants' response time in projecting future system status. The results revealed a significant main effect of warning modality on response time,  $F(2, 48) = 7.32, p < .002, \eta^2 = .23$ , indicating that the type of sensory modality significantly influenced how quickly participants responded. Post hoc pairwise comparisons with Bonferroni correction indicated that response times were significantly shorter for visual warning ( $M = 7,039$  ms,  $SD = 2107.7$ ) compared to both auditory ( $M = 10,815$  ms) and tactile warning ( $M = 10,634$  ms). No significant difference was observed between the auditory and tactile warnings. These results suggest that visual cues enable faster processing and action compared to other unimodal warning types (Fig. 4.4).



**Figure 4.4 Mean response time (ms) by modality. Visual warning resulted in significantly faster response times compared to auditory and tactile modalities. Error bars represent standard errors.**

The results of the one-way repeated measures ANOVA provide compelling evidence that warning modality significantly influences response time in tasks requiring projection of future system status, a key component of level 3 situation awareness (Endsley, 1995). Participants responded significantly faster to visual warnings ( $M = 7,039$  ms,  $SD = 2,107.7$ ) than to auditory ( $M = 10,815$  ms) or tactile ( $M = 10,634$  ms) cues. The absence of a statistically significant difference between auditory and tactile warnings further emphasizes the relative processing advantage of visual cues in this scenario. These findings are consistent with cognitive processing theory, which suggests that visual information is often more efficient for tasks requiring precise spatial and temporal interpretation (Wickens and Hollands, 2000). Visual cues may provide more immediate and sustained information, enabling users to construct more accurate mental models and act more quickly. In contrast, auditory and tactile cues are typically transient and may require additional cognitive effort to decode, particularly when system urgency or temporal forecasting is involved. Furthermore, the comparable response times between auditory and tactile modalities may reflect overlapping limitations in their salience and the user's ability to rapidly associate these cues with predictive meanings. This result supports prior research indicating that while auditory and tactile

feedback can be effective in alerting users, their utility in supporting projection may depend heavily on cue design, context, and prior training (Sarter, 2006; Van Erp and Van Veen, 2004). From an applied perspective, these findings suggest that visual feedback should be prioritized in interface designs for remote supervision of autonomous systems, especially in scenarios where rapid response to projected machine behavior is critical. Designers should also consider the cognitive load associated with each modality and explore the integration of multimodal cues only where they complement rather than compete with visual information.

#### 4.4.2.4 Subjective Responses

Participants’ subjective evaluations of warning modality effectiveness in conveying urgency—an essential aspect of projecting future machine system status (level 3 situation awareness)—were collected through end-of-experiment questionnaires. The majority of participants (84%) reported that visual warnings were most effective in helping them perceive system urgency. A smaller proportion preferred tactile cues (12%), while only 4% indicated a preference for auditory warnings, as shown in Table 4.5.

**Table 4.5: Urgency Projection Performance by Warning Modality.**

Warning Modality	Objective Accuracy (%)	Subjective Preference (%)	Key Strengths	Key Limitations
Visual	89.3%	84%	Clear urgency mapping; rapid response; spatially and temporally precise	May be missed if user is visually disengaged
Auditory	61.8%	4%	Helpful when vision is occupied; quick delivery of alerts	Easily masked by noise; less intuitive mapping to urgency
Tactile	50.2%	12%	Hands-free; viable in loud or dark environments	Often vague or delayed; difficult to interpret urgency without prior training

These results suggest that visual cues were perceived as the most intuitive and effective modality for recognizing urgent conditions and anticipating future system behavior. This subjective trend aligns with the objective findings, which demonstrated higher accuracy and faster response times in the visual modality, further supporting its suitability for urgency-related tasks in remote supervision scenarios. The subjective evaluations of warning modality effectiveness in conveying urgency offer valuable insight into user experience and confirm patterns observed in the objective performance data. A strong majority of participants (84%) identified visual warnings as the most effective for perceiving urgency—an essential component of Level 3 Situation Awareness (Endsley, 1995). Only 12% and 4% preferred tactile and auditory modalities, respectively. These preferences suggest that visual cues are not only easier to interpret but also more naturally associated with the perception of threat or change, enabling faster mental projection of future system states. This subjective trend strongly aligns with the study's objective findings, where visual cues led to the highest accuracy and the fastest response times. From a cognitive perspective, this alignment reflects the modality appropriateness hypothesis (Wickens, 2002), which holds that the effectiveness of a sensory modality depends on its compatibility with task demands. Visual information, by offering high spatial resolution and persistent representation, likely supports more robust and timely internal models of system trajectory (Wickens and Hollands, 2000). In contrast, auditory and tactile signals are inherently transient and may lack the salience or semantic clarity needed to support urgency perception without significant related training (Sarter, 2006; Van Erp and Van Veen, 2004). From a design standpoint, these findings reinforce the need to prioritize visual feedback in warning systems for autonomous or semi-autonomous operations, especially under conditions requiring rapid anticipation and action. While auditory and tactile cues may play a supportive role in multimodal interfaces—particularly in high-load or visually constrained

environments—this study underscores that their standalone use for urgency projection may be insufficient unless supplemented with enhanced cue salience or interpretive aids.

#### **4.5 Conclusion**

This study examined the effectiveness and efficiency of unimodal warning modalities—visual, auditory, and tactile—in supporting operator comprehension and projection of system status during remote supervision of autonomous agricultural machinery. Across all measures (i.e., comprehension accuracy, perceived urgency, and response time), visual warnings consistently outperformed both auditory and tactile cues, offering compelling evidence for their primacy in supervisory human-machine interface (HMI) design. Visual cues resulted in the highest comprehension and projection accuracy, as well as the fastest response times, highlighting their cognitive efficiency and intuitive interpretability. Participants also overwhelmingly preferred visual warning signals, citing clarity, immediacy, and ease of understanding. These results align with established cognitive theories and situation awareness models, particularly Endsley’s (1995) framework, which emphasizes the role of perceptually accessible and timely information in supporting situational understanding and predictive decision-making. Auditory cues, while moderately effective in conveying urgency and supporting performance, were limited by their transient nature and vulnerability to distraction or environmental masking. Tactile cues, though theoretically promising in scenarios with visual or auditory overload, proved least effective in this study. Their reduced performance likely reflects a mismatch between tactile signal characteristics and the interpretive demands of supervisory control tasks, especially without adequate training or related reinforcement. Collectively, these findings underscore the importance of modality-task alignment in HMI design. Designers of remote supervision systems should prioritize visual feedback for conveying both system status and urgency, particularly in time-sensitive or emergency

conditions. Auditory cues may serve as secondary or supplementary channels when visual input is unavailable, while tactile cues should be reserved for specialized conditions and employed cautiously, ideally as part of multimodal systems designed with careful attention to salience, spatial mapping, and training. Future research should explore how multimodal combinations can optimize situation awareness under varying workload conditions and investigate how adaptive interface systems might tailor feedback delivery based on user factors and performance. Ensuring that sensory cues align with both cognitive demands and user expectations will be critical to advancing safe and effective interaction in the evolving domain of autonomous system oversight.

## 4.6 Preamble to Chapter 5

Having examined how individual (unimodal) warning modalities—visual, auditory, and tactile—support comprehension and projection in remote supervision tasks, the research now turns to a crucial next step: evaluating the practical usability of these warning systems in more realistic, cognitively demanding settings. Understanding how a modality performs in isolation provides foundational insight into its cognitive affordances; however, real-world agricultural supervision rarely relies on a single sensory channel. In operational contexts where environmental noise, visual overload, or task-switching are common, operators are often exposed to combined sensory cues rather than isolated ones. As such, it becomes essential to assess not only which modalities are cognitively effective on their own, but also how they function when integrated as bimodal warnings and, importantly, how these combined cues are perceived, trusted, and acted upon by users in practice.

This shift in research focus from unimodal to bimodal assessment is grounded in both ecological validity and user-centered design priorities. While unimodal experiments in Chapter 4 allowed for controlled comparisons across modalities in terms of supporting Level 2 and Level 3 Situation Awareness, such tests do not capture the full complexity of human interaction with multimodal interfaces. In real supervisory environments, usability factors—such as intuitiveness, learnability, perceived urgency, user satisfaction, and trust—become decisive in determining whether a warning system will be effective outside the lab. Bimodal cues, by offering redundant or complementary information through multiple channels, have the potential to enhance usability by reinforcing signal clarity, reducing misinterpretation, and accommodating diverse user preferences or sensory limitations. However, these benefits must be validated empirically.

Therefore, Chapter 5 moves beyond performance metrics and isolated modality analysis to conduct a comprehensive usability evaluation of bimodal warning cues within the context of a prototype human-machine interface. This chapter assesses how real users experience, interpret, and respond to combined cues under simulated field conditions, using both subjective measures (e.g., Computer System Usability Questionnaire responses, user feedback) and objective performance data. By doing so, the research ensures that the proposed warning systems are not only cognitively effective, but also operationally viable, accessible, and aligned with the practical demands of remote supervision in agriculture. This integrative approach closes the loop between theoretical effectiveness and real-world applicability, ensuring that the final design recommendations are grounded in both science and user experience.

# 5. USABILITY EVALUATION OF WARNING CUES FOR REMOTELY SUPERVISED AUTONOMOUS AGRICULTURAL MACHINES

## 5.1 Abstract

As autonomous agricultural machines (AAMs) become more prevalent, effective communication through warning systems is essential for safe and efficient remote supervision. This study evaluated the usability and cue effectiveness of two bimodal warning modalities (visual–auditory, VA and visual–tactile, VT) during a simulated remote supervision task. Usability was assessed from the supervisor’s perspective using the Computer System Usability Questionnaire (CSUQ). Cue effectiveness was examined through objective performance-based measures aligned with three situation awareness levels: i) noticeability and response time as measures of perception, ii) accuracy and comprehension time as measures of comprehension, and iii) accuracy and projection time as measures of projection. Thirty participants (5 with farming experience and 25 without farming experience) interacted with a simulated human-machine interface (HMI). Both modalities received high usability ratings, although the visual-tactile was rated more favorably by farming participants. Projection accuracy was significantly lower for farming participants using visual-auditory cues (86.7%),  $\chi^2(3, N = 540) = 5.37, p = .147$ . Although comprehension accuracy differed slightly across modalities—particularly among farming participants—these differences were minimal and not statistically significant. In contrast, non-farming participants exhibited significantly faster saccadic and manual response times to visual-auditory warnings,  $t(24) = 3.56, p = .004$ , and  $t(24) = 3.56, p = .002$ , respectively. Comprehension and projection times did not differ significantly by modality. Subjective preferences aligned with

performance trends; non-farming participants favored visual-auditory cues, while farming participants preferred visual-tactile cues. Correlation analyses indicated that faster comprehension strongly predicted higher usability, and task accuracy was perfectly correlated with usability ratings. These findings underscore the influence of user experience on multimodal warning efficacy and support the need for adaptive, user-informed interface designs in AAM supervision.

## **5.2 Introduction**

The design of an interface that enables humans to communicate with the machine and perform supervisory tasks should be part of the development of an autonomous agricultural machine (AAM) (Mann et al., 2021; Edet and Mann, 2022). Studies on remote supervision have observed that task assignment, resource allocation, task execution monitoring, and emergency intervention are all part of the human supervisor's function in an autonomous system (Berenstein et al. 2012; Edet and Mann 2022). However, the human supervisor must first identify and assess the emergency before intervening (Peryer et al. 2005). Hence, a well-designed warning system incorporated into the automation interface is perhaps of even greater importance when the human supervisor is expected to fulfill these supervisory functions. For the human supervisor to respond promptly, such warnings should specify the urgency and provide clear, comprehensible information (Laughery and Wolgater, 2006). Furthermore, the warning should not cause irritation or impede cognitive function, preventing humans from ignoring emergencies or turning off warning signals before taking action to resolve them (Peryer et al., 2005).

In summary, human factors principles need to be considered in the design of these warning systems. Stated in more general terms, the design of warnings should always consider the abilities and limitations of the human supervisor. Human-centered design will ensure both optimal system efficiency and the well-being and comfort of the human supervisor. Although the design of human

machine interfaces (HMIs) for AAMs has been pursued for several decades, most of the research in this area has focused on identification and presentation of relevant telemetric data that would warn the supervisor of upcoming problems (Blackmore et al. 2002; Johnson et al. 2009; Moorehead et al. 2012; Edet et al. 2018; Edet et al. 2022). Very little attention has been paid to the usability of the warning system from the supervisor's point of view.

### **5.2.1 Usability and its Assessment**

The International Organization for Standardization defined usability as the 'extent to which a product or system can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use' (ISO 2018). Additional work has defined several characteristics of usability within the above definition. Although variations abound, a common definition of usability includes five key characteristics: effectiveness, efficiency, error tolerance, ease of use, and engagement (Quesenbery 2001). Effectiveness, efficiency, and error tolerance all refer to the users' ability to complete tasks with the system or interface. Effectiveness refers to overall ability to accomplish the task, efficiency refers to the speed and accuracy of completion, and error tolerance refers to the ability to minimize errors.

The characteristics are typically measured objectively via usability studies in which subjects complete a task and metrics related to overall performance (effectiveness), time to completion (efficiency), and number of errors (error tolerance) are evaluated (Lewis 1995). Ease of use refers to the ability of a user to learn and use a system or interface; it is sometimes broken into sub-characteristics of learnability and memorability (Nielsen 1993). Engagement refers to whether a system or interface is pleasing and satisfying to use. As both ease of use and engagement are inherently subjective, self-report is the primary form of data collection for these characteristics. These two variables have been determined to be particularly important in predicting the degree to

which people accept and use particular information technologies (Davis 1989). People are likely to discontinue using an autonomous machine if its usefulness is questioned, particularly the usefulness of the warning system.

Usability evaluation of warnings allows analysis and evaluation of the impact of the warning system design on the supervisory experience of the human supervisor during remote supervision of these autonomous systems. A number of survey instruments have been developed to evaluate the usability of a system or interface (Table 5.1), assessing a number of characteristics related to usability, including perceived efficiency, learnability, and satisfaction.

**Table 5.1: Commonly cited usability scale in HCI literature (adapted from Karlin and Ford 2013).**

Scale	Items	Dimension assessed
System Usability Scale (SUS) (Brooke 1996)	10	Perceived system usability and learnability.
Computer System Usability Questionnaire (CSUQ) (Lewis 1995)	16	User satisfaction with; 1) system usefulness; 2) information quality; 3) interface quality.
Usability Metric for User Experience (UMUX) (Finstad 2010)	4	Perceived usability (efficiency, effectiveness and satisfaction).
Software Usability Measurement Inventory (SUMI) (Kirakowski and Corbett 1993)	50	1) Global usability plus perception of: 2) affect; 3) efficiency; 4) learnability. 5) helpfulness; and 6) control.

Among them, the System Usability Scale (SUS) is by far the most commonly cited and utilized scale in the human-computer interaction (HCI) literature (Bangor et al. 2008; Lewis and Sauro 2009). The SUS is a 10-item, 5-point Likert scale widely used for evaluating overall system usability due to its ease of use, cost-effectiveness, and reliability at small sample sizes, though it has faced criticism for lacking feature-specific assessment and showing inconsistent factorial structure, with later studies identifying separate usability and learnability dimensions (Bangor et

al. 2008; Lewis and Sauro 2009; Borsci et al. 2009). The CSUQ was chosen for the current study due to its focus on evaluating computer systems and its ability to assess specific system features (Lewis, 2018).

The CSUQ (Version 3) consists of 16 statements rated on a 7-point Likert scale, where 1 indicates strong agreement and 7 strong disagreement. It assesses system usability across three dimensions: system usefulness, information quality, and interface quality, offering strong face validity. Administered after system use but before debriefing, the CSUQ yields four scores: overall (items 1–16), system usefulness (1–6), information quality (7–12), and interface quality (13–16). Scores range from 1 to 7 (or N/A), with higher scores indicating greater perceived usability. The CSUQ has been widely applied in evaluating various technologies, including calculators, virtual keyboards, e-government services, mobile phones, websites, training games, in-vehicle interfaces, and multimodal remote controls (Monahan et al. 2009; Bargas-Avila et al. 2010; Manzano-Monfort et al. 2023; Tullis and Stetson, 2004; Carrión-Toro et al. 2020; Cortellessa et al. 2018; Ilyas et al. 2022).

### **5.2.2 Cue Effectiveness and its Assessment**

When appropriate warning information is communicated to the supervisor using effective means, the usability of the warning system is likely to improve. The concept of “situation awareness” can be used to determine whether the correct warning information is communicated. Endsley (1995) defined situation awareness (SA) as “the perception of the elements in the environment within a span of time and space, the comprehension of their meaning, and the projection of their status in the near future”. Using a tractor-machine system as an example, “level 1” situation awareness is achieved when the supervisor perceives a change in the tractor-machine system. If the supervisor also understands what the perceived change means, “Level 2” situation

awareness has been achieved. Achieving the final level of situation awareness (i.e., “Level 3”), the supervisor must be able to anticipate the consequences of the perceived change in the near future. While situation awareness (SA) can enhance operational effectiveness, poor SA—such as being incomplete or inaccurate—can negatively impact performance. A lack of complete SA may indicate failures in detecting critical information or interpreting its significance, potentially resulting in inefficiency or even dangerous conditions (Endsley, 1995). Endsley (1996) described several catastrophic airline crashes which were directly or indirectly related to poor situation awareness of the operators of the automated flight system. A common reason for poor situation awareness relates to the presence of automation in the system. Automation may shift the role of the operator from “active participant” to “passive user or supervisor” (Bryne and Parasuraman 1996). In partially automated driving scenarios, adequate situation awareness is essential for the safety of the driver. During partially automated driving scenarios, human drivers are expected to take control of the situation whenever the situation demands attention (i.e., due to technology failure or technology limitation). This can be problematic as the driver has not likely been actively involved in decision-making leading up to the point of technology failure, and therefore, lacks complete understanding of the situation. It is for such reasons that it is critical to design a user interface that adequately supports the situation awareness of the user. Taylor et al. (2010) developed and evaluated three interfaces for regenerative life support systems using the “ecological interface design” which considers a user-centered approach to better support the overall situation awareness of the operators. Results of the study have indicated that the interfaces which presented “situation-rich” information helped in better decision making.

Jiang et al. (2024) investigated SA using a virtual driving task, operationalizing SA across its three levels (i.e., perception, comprehension, and projection) through eye-tracking-based

metrics. Their study demonstrated that objective SA scores, aligned with these levels, significantly predicted driving performance. By quantifying attentional allocation and decision quality in real time, they provided empirical validation of the SA framework in a dynamic context. The results highlighted the utility of multimodal data in capturing SA development and its relationship to operator performance, offering practical implications for designing systems that foster robust user awareness.

Despite advances in such decision-support frameworks, achieving and maintaining complete SA remains challenging in remote supervision contexts. Studies have shown that increasing levels of automation may inadvertently lead to user complacency, especially when systems fail to provide sufficient or context-sensitive feedback, thereby reducing operator engagement and diminishing SA (Endsley, 2017; Bye et al., 1999). Consequently, it is essential to incorporate multimodal warning systems (e.g., bimodal warning cues) into interface designs that align with user expertise and cognitive processing requirements, ensuring that all SA levels are adequately supported.

A range of non-agricultural systems have incorporated various sensory modalities, including visual, auditory, and tactile signals, to improve situation awareness and prompt timely user responses. Visual warnings are particularly effective in scenarios where the message is lengthy or complex, the user is stationary, or when later reference is anticipated (Chen et al., 2022). These cues may include text, symbols, or flashing lights, but can become less effective in cluttered or visually demanding environments. In contrast, auditory alerts, including spoken commands, beeps, or symbolic sounds, are well-suited for dynamic conditions where the user is mobile or when the visual field is overloaded (Wang et al., 2023). Their omnidirectional nature allows them to quickly capture attention, particularly when visual access is limited or obstructed. Tactile

feedback offers a compelling alternative, especially in noisy environments or when users are visually or auditorily engaged elsewhere. Studies have shown that tactile alerts can outperform visual signals and match or exceed auditory ones in terms of response time and attention capture (Spence and Ho, 2008; Mohebbi et al., 2009). This makes them particularly advantageous in safety-critical systems where visual or auditory channels are compromised. Additionally, because of their non-intrusive nature, tactile cues are preferred in collaborative settings to avoid disrupting others' attention (Zhu et al., 2025).

The effectiveness of warning modalities can be assessed across several performance dimensions including detectability, response speed, comprehension, memory retention, perceived urgency and risk, likelihood of compliance, and overall importance (Zhu et al., 2025; Edet and Mann, 2021). Among these, response time—defined as the interval between warning onset and initiation of a reaction—is widely accepted as a primary objective metric, with shorter latencies indicating greater warning effectiveness (Zhu et al., 2025). Noticeability, or the ability of a warning to attract attention, is another critical factor in determining the effectiveness of warnings. Without first capturing attention, warnings cannot achieve comprehension or user compliance. Recent studies emphasize the importance of early attentional engagement in determining response effectiveness (Kowler et al., 1995).

Saccadic reaction time (SRT)—the latency between warning stimulus onset and the initiation of a saccadic eye movement—can be used as an objective measure of noticeability. Saccades, which are rapid eye movements between fixation points, are tightly linked to attentional processes. Because attention must be directed before a saccade is initiated, SRT serves as a reliable indicator of attentional allocation (Kowler et al., 1995; Deubel and Schneider, 1996). A shorter SRT suggests that the visual stimulus is more salient and effective in capturing attention, thus

increasing the likelihood of a warning being noticed and acted upon. Research also emphasizes the value of subjective measures such as interviews, sorting tasks, and Likert scales alongside objective performance data to evaluate modality performance (Edet and Mann, 2021; Wogalter et al., 2002).

Importantly, many of these effectiveness attributes are interlinked with SA. Initial conceptualizations by Endsley (1995) outlined three SA levels (i.e., perception, comprehension, and projection), each positively influencing operator performance and decision-making. Recent empirical work has directly connected task accuracy and timing outcomes to specific SA levels in dynamic systems (Gutzwiller and Clegg, 2013). Furthermore, HCI research by Smith et al. (2025) demonstrated that physiological and behavioral task performance align closely with the progression of SA, reinforcing the integral role SA plays in evaluating modality effectiveness.

Studies have shown that bimodal warning systems are more effective than unimodal systems, especially under conditions where one sensory modality may be overloaded or impaired due to environmental or task-related factors (Zhu et al., 2025; Haas and Van Erp, 2014). For instance, auditory–tactile warnings have been found to significantly reduce response times compared to auditory-only or tactile-only signals in complex driving environments (Zhu et al., 2025). Similarly, Haas and Van Erp (2014) argue that multimodal signals offer redundancy, ensuring the message is received even if one channel is compromised. Meta-analyses and empirical studies further confirm that multimodal alerts, including combinations of auditory, visual, and tactile cues, enhance hazard detection and decision-making speed in high-stakes situations (Zhu et al., 2025; Geitner et al., 2019). Edet and Mann (2021) evaluated seven warning modalities—visual, auditory, tactile, visual–tactile, audio–tactile, and audio–visual–tactile—across four remote-site scenarios (i.e., within-the-field, close-to-the-field, farm office, and off-farm environments). Their

results showed that the audio–tactile combination was the most effective overall. In environments with significant tractor noise, tactile and visual–tactile cues yielded the shortest response times. Based on their study outcome and more recent studies by Ezeagba et al. (2025), the current study chose to evaluate two bimodal warning modalities: visual-tactile and visual-auditory as these two options gave the overall best performance.

Usability is a critical factor for considering the effectiveness of warnings. The objectives of this study were to: 1) evaluate usability of visual–tactile (VT) and visual–auditory (VA) warning systems using the Computer System Usability Questionnaire (CSUQ), and 2) assess cue effectiveness by determining how these bimodal warnings support SA levels (i.e., perception, comprehension, and projection) during a remote supervision task. Cue effectiveness was examined through objective measures aligned with three situation awareness levels: i) noticeability and response time as measures of perception, ii) accuracy and comprehension time as measures of comprehension, and iii) accuracy and projection time as measures of projection.

### **5.3 Materials and Methods**

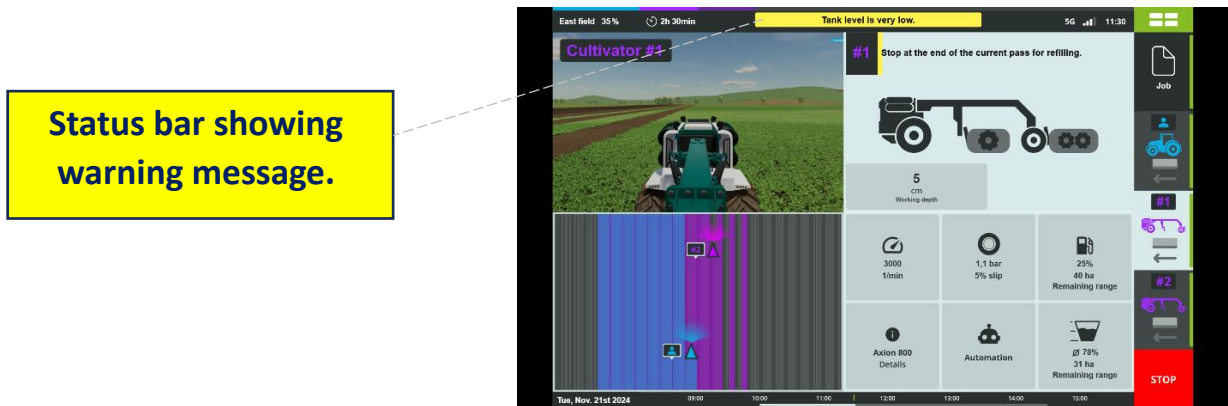
The experiment was conducted inside a tractor cab (Fig. 5.1) in the Agricultural Ergonomics Laboratory at the University of Manitoba to control interference from outside noise. The experimental configuration included two computer monitors arranged vertically. The lower monitor displayed the output from a simulation of agricultural machines in operation, whereas the upper monitor facilitated the completion of the primary internet search task, which will be detailed in a subsequent section.



**Figure 5.1. Tractor cab used for the experimental study. Participants used the upper monitor for the internet search task while the lower monitor displayed the simulation of the AAMs.**

A prototype human-machine interface (HMI) originally developed by researchers at the University of Technology (TU) Dresden, Germany, for controlling multiple autonomous agricultural machines (AAMs)—specifically two cultivators and a planter—was used in the present study (Bobbe et al., 2024). The HMI was modified to include two separate bimodal warning methods (i.e., VA and VT) and a status bar/button displaying the warning message positioned at the top center of the interface for warning acknowledgement (Fig. 5.2). Three states of the bimodal warning methods, which signify different operational conditions of the AAMs (i.e., “normal” and “abnormal”), as well as the various levels of urgency (visual: green, yellow, and red colors; auditory: low, medium, and high level frequencies (500 Hz, 1000 Hz and 2000 Hz) indicated to be most preferred fundamental frequencies for auditory perception by Harrell (2002); and tactile: low, medium and high level intensities (28 Hz, 42 Hz and 64 Hz) specified to be acceptable range of vibration frequency for vibrotactile perception) (Mori et al. 2012) respectively. The different states of the warning methods were related to three parts each machine (i.e., cultivators: working depth (D), engine speed (S), and fuel tank (T); and planter: hopper (H), furrow opener/seed spacing (O)

and fuel tank (T)) used for comprehension and urgency projection evaluations. The visual warning used in this study was presented using colored messages (green, yellow and red texts) while the auditory and tactile stimuli levels were established using morse code which applies short and long signals called dots and dashes to represent letters (specifically the machine part letters in parentheses were used for this study), and integrated into the simulation of the prototype HMI (Tan et al. 1997; Walker and Reed 2018; Haas et al. 2021) (Table 5.2).



**Figure 5.2. Augmented version of the prototype HMI used for the study. Visual, auditory, and tactile warning cues were incorporated into the interface to alert the human supervisor to irregularity; this picture displays only the status bar (acknowledgement button) showing the visual warning text/message**

**Table 5.2: Warning Design Considerations**

Modality	Design Factors	Features
Visual	Location	Simulation Screen Top Centre
	Image	Green, Yellow, and Red Texts/Messages.
Auditory	Location	operator's seat bottom, back
	Frequency	500Hz, 1000Hz, 2000Hz
Tactile	Location	operator's waist
	Frequency	28Hz, 42Hz, 64Hz

### 5.3.1 Experimental procedure

The experimental procedure included screening tests, training trials, an experimental session, and an end-of-experiment questionnaire after the experiment. Prior to the experiment, the participants received a briefing on the purpose and procedures. The principal investigator answered questions as clearly as feasible. By signing a consent form, the participants attested to having read the terms and conditions of their involvement in the study and gave their free and informed consent. The University of Manitoba's Research Ethics Board granted ethics approval.

The participant's visual, auditory, tactile, and comfort levels were assessed during the screening procedures. Participants in the visual screening were shown a sample of the visual warning and asked to rate the clarity and legibility of the content. Auditory screening was conducted using pure-tone audiometry via the hearing test application (*e-audiologia.pl* ver. 1.1.3) available on the Google Play Store, to assess each participant's hearing threshold. Participants with thresholds  $\leq 40$  dB) were deemed to have sufficient hearing sensitivity for the auditory warnings. The tactile assessment was accomplished using a Woojer Strap 3 wearable vibration system (WJRS3-101BN, Woojer, Inc., China). The participant's waist was then wrapped with the device strap to provide a tactile impression. The optimum haptic frequency range for the Woojer Strap 3 is 1–250 Hz, with especially strong performance in sub-bass to bass frequencies (typically below 250 Hz), where it delivers maximum tactile impact (Woojer, 2025).

During the training trials, participants were allowed to familiarize themselves with the experimental protocols. Participants were shown the warning cues while seated in the tractor cab. To ensure they were not uncomfortable in any way that would have introduced bias, the participants were asked to rate their comfort level in response to the various sensory cues and how well they could see, hear, and feel the sensory information presented on a post-training evaluation form.

The experimental sessions included two tasks: (1) searching the internet for answers to specific agronomic questions; (2) watching the HMI’s presentation of the simulated AAMs in action. During the simulation the participant was required to tap the status bar on the interface screen to indicate that a warning had been perceived; select the right choice of condition based on perceived warning from a list of possible conditions to acknowledge comprehension (Table 5.3); and finally, to select the right choice of condition based on perceived warning from a list of possible conditions to acknowledge the level of perceived urgency (Table 5.4).

In a real-world situation, humans monitoring the AAM could be preoccupied with other tasks. Therefore, the primary purpose of the internet search task was to simulate the surroundings a human would encounter when monitoring the deployment of an AAM. It also helped determine when participants felt that they had been induced to make an error (i.e., when they looked away from the primary task after the error had been induced; see Ezeagba et al. 2025).

**Table 5.3: List of possible conditions from which selections were made (Level 2 SA-comprehension evaluation)**

S/N	Operating Conditions (Cultivator)	Operating Conditions (Planter)
1.	Engine speed for Cultivator #1/#2 is normal [Stable].	Hopper level is normal [Sufficient].
2.	Engine speed for Cultivator #1/#2 is abnormal [Too High/Low].	Hopper level is abnormal [Low].
3.	Working depth for Cultivator #1/#2 is normal [Correct Position].	Seed spacing is normal [Consistent].
4.	Working depth for Cultivator #1/#2 is abnormal [Too High/Low].	Seed spacing is abnormal [Inconsistent].
5.	Tank level for Cultivator #1/#2 is normal [Adequate].	Tank level is normal [Adequate].
6.	Tank level for Cultivator #1/#2 is abnormal [Low].	Tank level is abnormal [Low].

**Table 5.4: List of possible conditions from which selections were made (Level 3 SA- urgency projection evaluation)**

S/N	Operating Conditions (Cultivator)	Operating Conditions (Planter)
1.	The engine speed of Cultivator #1/#2 is normal; the tachometer is in check so keep on with operation.	Hopper is full and the seeds are sufficient to resume current activity; proceed with operation.
2.	Engine speed of Cultivator #1/#2 is slightly low check the tachometer at the end of the current pass and regulate speed to the optimal range (sweet spot).	The seeds in the hopper have dropped to 25%; stop at the end of the current pass for refilling.
3.	Engine speed of Cultivator #1/#2 is too high; stop the machine immediately and check the tachometer to avoid excessive fuel consumption.	Hopper is empty; stop the machine immediately and take action to refill to avoid leaving portions of the field unattended.
4.	The working depth of Cultivator #1/#2 is within the optimal level; the depth adjuster is in check so proceed with operation.	The seeds are properly spaced and aligned into the opened furrows; continue with operation.
5.	A slight deviation from optimum depth in Cultivator #1/#2 due to uneven terrain; regulate working depth to optimal level within next few minutes.	A slight change in soil conditions has been detected; check that the seed dropping is in the intended furrow openings the next time the planter is stopped for refilling.
6.	Cultivator #1/#2's working depth is below the optimum, resulting in shallow soil penetration; adjust working depth to optimal level immediately.	It is likely that some seeds are missing intended opening; adjust the furrow opener immediately.
7.	Tank level of Cultivator #1/#2 is full and fuel is adequate for the current activity; proceed with the operation.	Tank level is full and fuel is adequate for the current activity; proceed with the operation.
8.	Cultivator #1/#2's tank level is very low; stop at the end of the current pass for refilling.	Tank level is very low; stop at the end of current pass for refilling.
9.	Tank level of Cultivator #1/#2 is empty; take action to refill immediately to minimize operation downtime.	Tank level is empty; take action to refill immediately to minimize operation downtime.

Operational conditions of the agricultural machines were introduced at random intervals during the simulation. Participants were informed about the conditions using different states of the bimodal warning methods: visual-auditory (VA) or visual-tactile (VT). Subsequently, participants were expected to: i) tap the status bar to indicate they had noticed the warnings within each trial; ii) select the correct choice of condition from the lists of possible conditions based on their level of

comprehension and perceived urgency of the warnings. Responses were recorded and compared with the correct answers for subsequent analysis.

Participants wore an eye-tracking device to monitor their gaze behavior (SensoMotoric Instruments (SMI) Eye Tracking Glasses 2.0, 60 Hz), specifically to determine when the participant detected the warning. For further analysis, both the participants' manual response times and their warning detection capability (i.e., noticeability) were also considered. Calibration and data collection were conducted using a three-point method via the SMI iViewETG software (version 2.7.1), with the glasses linked to the laptop using a USB connection (Niehorster et al., 2020; Caspi et al., 2018; Hoppe et al., 2018).

Following the completion of the eye model adaptation phase in iViewETG, the calibration process commenced. Participants were instructed to fixate on the center of three specific markers positioned within the stimulus grid: one on the top center of the simulation screen, one on the middle-right of the simulation screen, and one on the middle-left of the simulation screen. The principal investigator used the live scene camera feed displayed on the recording laptop to identify and mark these fixation points during the calibration. Each eye camera captured video at 120 Hz with a resolution of  $320 \times 240$  pixels, while the front-facing scene camera recorded at 24 Hz with a resolution of  $1280 \times 960$  pixels. It is important to clarify that the stated frame rate of the eye cameras reflects the recording output from iViewETG software, not the physical frame rate of the hardware.

The experimental session had two trials with an average length of 7 minutes and nine warnings per trial, with tractor noise introduced into the tractor cab for the entire session to create the in-field remote supervision scenario as it gave the best performance for both bimodal warning systems in a previous study (Ezeagba et al. 2025). The tractor noise, measured to be 78 dB, used in

this study was previously recorded from an operating John Deere combine. The sound clip was played through a portable Bluetooth speaker (BC-AU-BS-226, Bytech NY Inc., China). The average sound level was measured using a sound meter (Q094168, REED Instruments, USA). Each trial used the various states of each warning system for all three parts of the AAMs to notify the participants about the conditions (i.e., trial 1: visual and auditory; trial 2: visual and tactile). The order of the trials within the session was randomized and counterbalanced across participants to reduce order effects. At the end of each trial, participants were given the computer system usability questionnaire (CSUQ) to rate their user satisfaction level with the warning system presented during that trial. A 10-minute break was included between trials to allow participants to relax and move around. After the session was completed, an end-of-experiment questionnaire was given to participants to inquire about their experience throughout the experiment and to provide any additional suggestions beneficial to the study.

### **5.3.2 Data Analysis**

For the usability evaluation, the average CSUQ ratings for both bimodal warning methods (i.e.,  $(\text{SUM (System Usefulness)} + \text{SUM (Information Quality)} + \text{SUM (Interface Quality)})/16$ ) were calculated to obtain usability scores on a percentage scale, by converting to a 0–100-point scale using the formula:  $\text{Converted Score} = 100 - ((\text{Average CSUQ Score} - 1) \times 100 / 6)$ . After converting CSUQ scores to the 0–100 scale, they can be interpreted using the Sauro–Lewis curved grading scale: 85-100 is Excellent, 70-84 is Good, 50-69 is OK, Below 50 is Poor. Therefore, a converted CSUQ score of 70% or higher is considered a "good" usability rating (Lewis 2018). It is important to note that the original CSUQ scores range from 1 (strongly agree) to 7 (strongly disagree), with lower scores indicating better usability. For example, an average CSUQ score of 2.5 would convert to approximately 75% on the 0–100 scale, falling into the "good" category.

CSUQ responses were analyzed using parametric statistical tests. Although the CSUQ is composed of Likert-type items, composite scores derived from aggregating responses across items (e.g., overall usability, system usefulness, information quality, and interface quality) were treated as interval-level data. This approach is supported by psychometric literature indicating that aggregated Likert scales approximate continuous distributions, particularly when assumptions of normality are satisfied and internal consistency is high (Carifio and Perla, 2008; Norman, 2010; Sullivan and Artino, 2013). Prior to analysis, the composite scores were tested for normality and found to meet the assumptions necessary for parametric testing. Parametric methods, including the two-sample independent t-test, were employed to assess usability differences between the warning modality conditions, offering increased statistical power and interpretability over non-parametric alternatives (Salman and Aleem, 2024). Cue effectiveness was assessed based on the accuracy of participants' selected responses. A Chi-square test of independence was used to compare the distribution of correct versus incorrect responses across conditions, while efficiency was evaluated through the various performance time measurements: level of noticeability (saccadic reaction time), response time, decision time 1 (comprehension time), and decision time 2 (projection time). The time stamp specified in the HMI simulation code computed the response time based on the difference between the warning display and acknowledgement times, the comprehension time based on the difference between the first pop-up page display time and time of submission of selected responses, the projection time based on the difference between the second pop-up page display time and the time of submission of selected responses. The level of noticeability was measured as saccadic reaction time. This was determined as the recorded time between warning display and saccade (i.e., the rapid eye movement from one gaze point to another) onset, such that short saccadic reaction time denotes a high level of noticeability and vice versa. The BeGaze™

Analysis Software (version 3.7.41) estimated the saccadic reaction time. The saccade onset was interpreted as the first quick eye movement of the participant from the primary task screen (upper monitor) to the top centre of the simulation screen (lower monitor) (Fig. 5.1). The entire top centre of the lower monitor was classified as the region of interest, as it contains the visual warning indicator, which continuously displays when each of the bimodal warnings (i.e., visual-auditory or visual-tactile) occurs together with the accompanying warning message, drawing the attention of the participant to that specific region. Outliers in the time measurement data by the participants were identified, using the criteria of (+or-) 2 standard deviations from their mean, and were excluded from subsequent analyses. Descriptive statistics were computed for each modality, and inferential statistics were used to test significant differences across warning conditions.

A paired-samples t-test was used to examine differences in the mean time measurement data between the two modalities. Statistical significance was determined at the 95% confidence level ( $p < 0.05$ ). In addition to the quantitative measures, participants' subjective evaluations and comments, collected via end-of-experiment questionnaires, were analyzed to provide qualitative insights into perceived clarity, urgency, and overall preference for each warning modality. These subjective responses were used to understand and complement the quantitative findings in assessing the users' satisfaction level and suitability of each bimodal cue for supporting overall SA in remote supervision scenarios.

## **5.4 RESULTS AND DISCUSSION**

### **5.4.1 Participant demographics**

Two groups of individuals participated in the study. The non-farming experience (NF) group included 25 participants (  $28 \pm 6.19$  years-old). The farming experience (F) group consisted of 5 participants (  $40 \pm 14.30$  years-old), all of whom were actively engaged in farming. The NF group

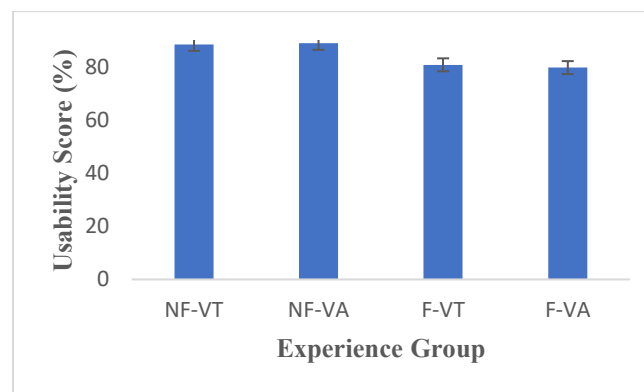
comprised 11 males and 14 females, whereas the F group included only males ( $n = 5$ ). It should be noted that this cohort of participants was entirely new and did not overlap with those recruited for the chapter 4 study. The small sample size of the farming group was attributable to the limited ability of most farmers to travel to the study location during the timeframe for data collection. While prior usability literature suggests that small samples (e.g., 5 participants) can be sufficient to identify prominent interface issues in formative evaluations (Nielsen, 2000; Bailey, 2006), the current study involved inferential statistical comparisons, and thus, the small farming group size represents a significant limitation. Accordingly, statistical findings involving the F group should be interpreted with caution and regarded as preliminary trends rather than conclusive evidence. Future studies with larger, more representative farming cohorts are needed to validate these early insights.

In accordance with the guidelines of the University of Manitoba Research Ethics Board, all participants provided informed consent and received an honorarium for their participation. Prior to beginning the experimental tasks, participants underwent visual and auditory screening to control for potential sensory confounds. All individuals successfully detected the visual stimuli during the screening. Auditory capabilities were assessed using a validated pure-tone audiometry application, and no participants demonstrated hearing impairments that would hinder their perception of auditory signals. These screening procedures ensured that the individuals could perceive the sensory cues.

#### **5.4.2 Usability Evaluation**

Independent two-sample t-tests were conducted to compare usability scores between NF and F participants for each warning method: Visual-Tactile (VT) and Visual-Auditory (VA). For the VT condition, the usability scores were higher for the NF group ( $M = 88.54$ ,  $SD = 9.88$ ) than for the F group ( $M = 80.83$ ,  $SD = 6.32$ ). This difference approached statistical significance,  $t(4.91)$

= 2.24,  $p = .054$ . For the VA condition, usability scores were slightly higher for the NF group ( $M = 88.92$ ,  $SD = 10.16$ ) compared to the F group ( $M = 79.79$ ,  $SD = 14.26$ ), but this difference was not statistically significant,  $t(5.19) = 1.36$ ,  $p = .233$ . As illustrated in Fig. 5.3, both groups rated the usability of VT and VA warning methods highly, with error bars representing the standard error of the mean. While statistical differences were not confirmed, the trend suggests a possible experience-related influence on usability perceptions for VT warnings.



**Figure 5.3. Mean usability scores (in percentage) by experience group (non-farming [NF] vs. farming [F]) and warning method (Visual-Tactile [VT] vs. Visual-Auditory [VA]). Error bars represent the standard error. Although not statistically significant, VT usability ratings were descriptively higher for farming participants than for non-farming participants.**

Nevertheless, the small sample size in the farming group ( $n = 5$ ) limits the generalizability of these findings. The observed variability in usability ratings and the descriptive preference for VT warnings among farming participants should be considered exploratory. Although some trends align with theoretical expectations and prior literature on domain-specific modality preferences (e.g., Ho and Spence, 2005; Wickens, 2008), the current inferential analyses are underpowered to support robust conclusions within this subgroup. A post-hoc power analysis is recommended for future work to determine the minimum sample sizes necessary to detect modality-related usability effects in experience-stratified populations.

These preliminary observations may reflect deeper cognitive or perceptual differences rooted in participants' prior exposure to multimodal interfaces or operational environments. For example, Ho and Spence (2005) noted that user familiarity with tactile or auditory cues can significantly influence usability perceptions. Similarly, Wickens (2008) emphasized how interface effectiveness depends on congruence between modality type, user experience, and task complexity. The relatively consistent usability ratings for VA warnings across both groups in this study may suggest auditory warnings are perceived as more universally applicable, whereas tactile feedback may demand more domain-specific familiarity.

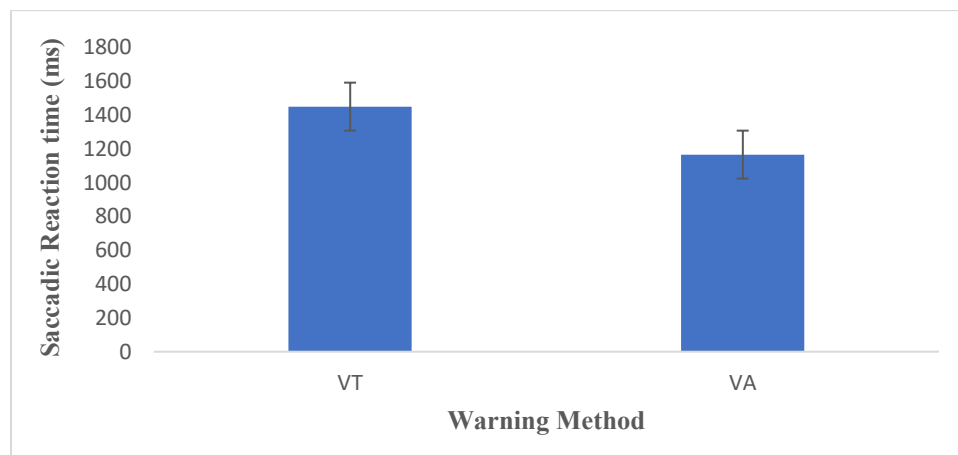
Importantly, the current findings align with expectations grounded in previous work by Ezeagba et al. (2025), which demonstrated the general efficacy of both VT and VA warnings in agricultural contexts. That study, like the present one, advocated for the integration of multiple sensory channels to support diverse operator needs. Together, these results highlight the value of multimodal design while cautioning against overgeneralization from small or imbalanced samples.

Looking forward, future research should pursue broader and more diverse participant pools, particularly expanding the representation of farming-experienced users. Studies should also incorporate ecologically valid environments—either through field testing or high-fidelity simulation—to better capture how usability perceptions and modality preferences unfold under realistic cognitive and physical demands. Finally, adaptive multimodal systems that dynamically adjust feedback based on user state and environmental context (e.g., fatigue, workload) may offer a promising path toward more inclusive and effective interface design.

### 5.4.3 Cue Effectiveness Evaluation for Perception

#### 5.4.3.1 Noticeability

A paired-samples t-test was conducted to examine whether the level of noticeability as a function of saccadic reaction time differed between the VT and VA warning methods and the experience groups. The farming group ( $N = 5$ ) was excluded from the eye-tracking data analysis because only three participants had normal vision without corrective eyewear. Since corrective eyewear interferes with data capture using SMI eye-tracking glasses, the resulting sample size was insufficient to produce conclusive findings. The analysis of the NF group revealed a significant difference in reaction times between the two warning conditions,  $t(24) = 3.16$ ,  $p = .004$ . Participants responded significantly faster (high level of noticeability) under the VA condition ( $M = 1166$  ms,  $SD = 784$ ) compared to the VT condition ( $M = 1450$  ms,  $SD = 976$ ). These results are depicted in Figure 5.4, where mean saccadic reaction times are plotted for each warning method, with error bars indicating the standard error of the mean.



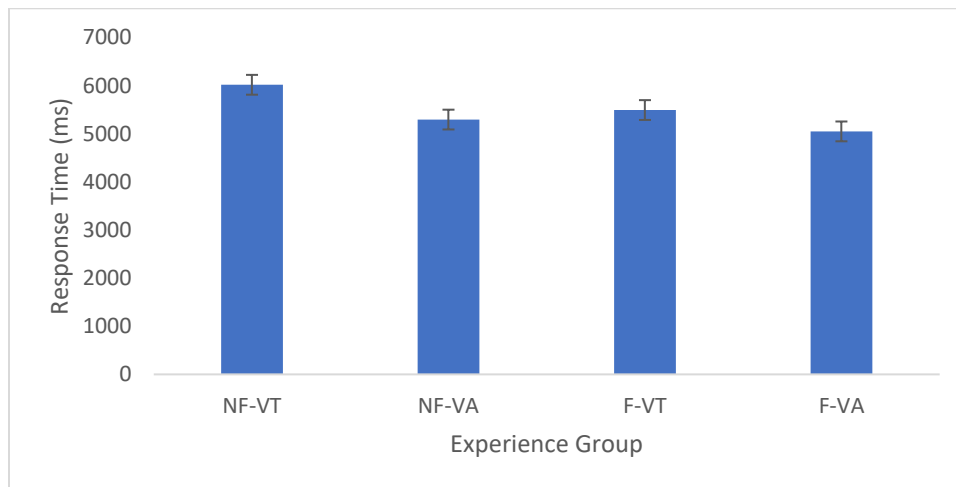
**Figure 5.4. Mean saccadic reaction times (in milliseconds) for Visual–Tactile (VT) and Visual–Auditory (VA) warning methods of the non-farming group (NF). Error bars represent standard error.**

The findings demonstrate that participants responded significantly faster to VA warnings compared to VT warnings in terms of saccadic reaction time which means high level of noticeability with the VA compared to the VT warning conditions. The observed reduction in saccadic latency under the VA condition is consistent with the temporal advantage of auditory processing, as auditory cues are processed more rapidly than tactile inputs in the brain's subcortical pathways (Spence and Driver, 2004). The result also supports previous evidence that auditory stimuli facilitate faster alerting and orienting responses compared to tactile stimuli, particularly in tasks requiring rapid oculomotor responses (Colonius and Diederich, 2011; Kim et al., 2023).

For example, recent research on multisensory alerts in driver assistance systems and safety-critical environments has emphasized the superior performance of auditory and audiovisual warnings in capturing attention quickly and supporting faster gaze shifts (Zhou et al., 2024). The current data extend this literature by confirming that even bimodal VA cues outperform VT cues in initiating saccades, a proxy for visual attention redirection, under time-sensitive conditions. This result suggests that auditory cues may be more effective in prompting immediate attentional engagement, making them highly suitable for urgent warnings in real-time systems such as agriculture, aviation, or driving contexts. However, these findings should be interpreted within the study's controlled environment, which lacks competing sensory inputs or distractions. Under more ecologically valid conditions, tactile cues may provide benefits in high-noise or visually overloaded scenarios (Banani Ardecani et al., 2024). Future research should investigate how multimodal warning combinations, environmental noise levels, and individual differences in sensory processing (e.g., experience, sensory impairments, or age) interact with modality to affect performance.

### 5.4.3.2 Response Time

To examine whether response time differed between warning methods (VT vs. VA), paired-samples t-test were conducted separately for NF and F participants. For the NF group, there was a significant difference in response times between the two warning conditions,  $t(24) = 3.56, p = .002$ . Participants responded significantly faster to VA warnings ( $M = 5295.56$  ms,  $SD = 2072$ ) than to VT warnings ( $M = 6019.44$  ms,  $SD = 2635$ ). For the F group, there was no statistically significant difference in response times between the two warning conditions,  $t(4) = 0.65, p = .550$ . Response times were similar between VA ( $M = 5049.80$  ms,  $SD = 1223$ ) and VT warnings ( $M = 5493.60$  ms,  $SD = 1530$ ). As shown in Fig. 5.5, the NF group exhibited a clear response time advantage for VA warnings, while no such pattern was observed in the F group. Error bars represent the standard error of the mean.



**Figure 5.5. Mean response times (in milliseconds) by experience group (Non-Farming [NF] vs. Farming [F]) and warning method (Visual-Tactile [VT] vs. Visual-Auditory [VA]). Error bars represent standard error.**

The results suggest that the effectiveness of warning modality in influencing response time may be moderated by user experience. The separate paired-samples t-test for each experience group revealed differing patterns. In the NF group, participants responded significantly faster to

VA warnings than to VT warnings, indicating a clear modality effect. In contrast, no significant difference in response time between the two warning types was observed in the F group, suggesting that experienced users may not be as sensitive to modality differences. It is important to note that a statistically non-significant result (e.g.,  $p > 0.05$ ) does not imply that the treatments or groups being compared are equivalent. A lack of statistical significance simply means that, based on the available data, there is insufficient evidence to conclude that a difference exists. However, this should not be interpreted as confirmation that no meaningful difference exists. Demonstrating equivalence requires a distinct statistical approach, typically an equivalence test such as the Two One-Sided Tests (TOST) procedure, with pre-specified margins that define what constitutes a negligible difference. Without applying such methods, the conclusion of equivalence cannot be supported solely by non-significant  $p$ -values. Therefore, when interpreting the findings of this study, particularly in cases where non-significant results are observed, caution is warranted in assuming practical similarity or interchangeability between treatments or systems without formal testing of equivalence.

These findings align with prior literature suggesting that auditory warnings are processed more rapidly and capture attention more effectively than tactile cues, especially in unfamiliar or visually demanding environments (Ho and Spence, 2005; Wickens, 2008). For users without domain-specific experience, auditory cues may benefit from the superior temporal resolution and lower cognitive load associated with the auditory channel (Castro-Alonso and Sweller, 2020; Mayer et al., 2017). Conversely, the absence of a significant modality effect in the F group may reflect the influence of experience and context familiarity on perceptual processing. Users with extensive exposure to mechanized or tactile interfaces may interpret tactile warnings more efficiently (Prewett et al., 2012), reducing the relative advantage of auditory alerts. This suggests

that user expertise modulates modality effectiveness, consistent with findings that training and environmental exposure shape multisensory cue integration (Ernst and Bühlhoff, 2024; Shams and Seitz, 2008).

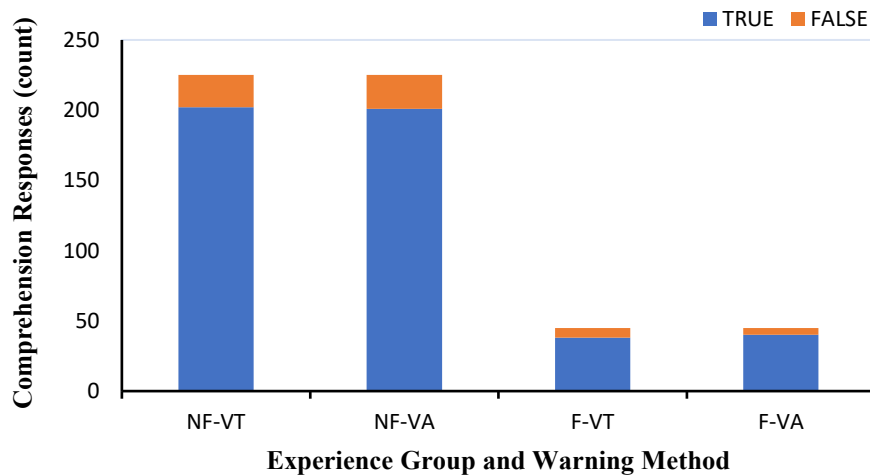
Multimodal warnings have frequently been shown to outperform unimodal ones in attentionally demanding tasks, due to redundancy benefits and increased perceptual reliability (Wogalter et al., 2012; Kallioniemi et al., 2021). However, mismatched or poorly timed combinations can also increase cognitive load, emphasizing the need for adaptive and user-specific warning systems. Recent studies advocate for context-aware multimodal design, in which the modality, timing, and intensity of alerts are tailored to the user's task load and environment (Zhu et al., 2025; Hu et al., 2025). The experimental task was conducted under controlled conditions, which may not reflect real-world stressors such as environmental noise, multitasking, or fatigue. Future work should explore warning system performance under more ecologically valid scenarios and across a broader range of expertise levels.

#### **5.4.4 Cue Effectiveness Evaluation for Comprehension**

##### ***5.4.4.1 Comprehension Accuracy***

A chi-square test of independence was conducted to examine the relationship between participant experience group (NF vs. F), warning method (VT vs. VA), and response accuracy (TRUE vs. FALSE) during a simulated hazard perception task. The analysis did not reveal a statistically significant association among these variables,  $\chi^2(3, N = 540) = 1.12, p = .772$ , suggesting that the combined influence of experience and warning modality did not significantly affect participants' ability to comprehend system warnings. NF participants demonstrated relatively high comprehension across both warning methods, with 202 out of 225 responses (89.8%) correct in the VT condition and 201 out of 225 responses (89.3%) correct in the VA

condition. F participants also showed high comprehension, though with more noticeable differences between modalities. In the VT condition, 38 out of 45 responses (84.4%) were correct, while the VA condition yielded 40 out of 45 correct responses (88.9%) (Fig. 5.6). While these patterns indicate marginal differences in comprehension across modalities—particularly among farming participants—the variation was minimal and not statistically significant.



**Figure 5.6. Percentage of correct (TRUE) and incorrect (FALSE) comprehension responses for each warning modality (Visual-Tactile [VT] and Visual-Auditory [VA]) across non-farming (NF) and farming (F) groups.**

These findings align with contemporary human–factors literature demonstrating robust comprehension rates for both tactile and auditory alerts. For instance, recent research comparing tactile and auditory warnings in noisy environments has shown that tactile cues can enhance hazard detection without compromising understanding (Murata et al., 2013). Meanwhile, in contexts involving in-vehicle systems, auditory or combined auditory–visual alerts typically match tactile warnings in terms of comprehension, even if tactile cues sometimes promote faster responses (Geitner et al., 2019).

Although some studies have highlighted tactile warnings' superiority under high noise loads—especially for reaction speed or urgency—these advantages tend to appear in latency measures, rather than basic recognition accuracy (Cooper et al., 2018; Chan and Ng, 2012). Our results reinforce this pattern: comprehension accuracy remained high (84.4–89.8%) across all modalities and experience groups, with no significant effect of modality, echoing findings by Geitner et al. (2019).

Although farming participants showed a marginal trend toward better accuracy in the VA condition (88.9% vs. 84.4% in VT), this difference was minimal and non-significant. One possible explanation is that farming professionals may exhibit slight sensitivity to auditory warnings based on occupational exposure—although comprehension does not differ enough to reach statistical significance. A recent VR-based agricultural training study reported differences in hazard prediction accuracy based on experience, indicating context-dependent effects of modality (Breese, 2025). However, our findings suggest that basic comprehension of warning signals is resilient to both modality type and user experience.

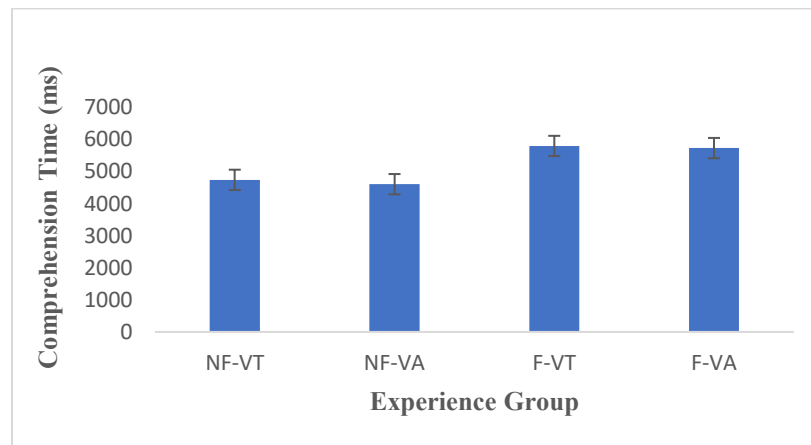
These results carry meaningful implications for design and deployment: both VT and VA systems can be confidently implemented without concern for differences in comprehension, irrespective of user background. For applications such as agricultural machinery or vehicles, where environmental noise may challenge auditory warnings, VT offers a comparably reliable alternative (Murata et al., 2013).

Future work should target real-world performance variables—for example, reaction time, recall durability, or cognitive workload—to investigate whether tactile or auditory systems hold advantages under stress, distraction, or multitasking. Such research could clarify whether modality

benefits manifest beyond comprehension, as suggested by prior work (Geitner et al., 2019; Cooper et al., 2018).

#### 5.4.4.2 Comprehension Time

A paired-samples t-test was conducted to examine the effect of warning method (i.e., VT vs. VA) on comprehension time across participants with different levels of experience. The results showed no statistically significant difference,  $t(29) = 0.68, p = .505$ , indicating that comprehension times did not differ reliably between VT and VA conditions. Descriptively, NF participants showed similar mean comprehension times for VT ( $M = 4740.24$  ms,  $SD = 1022$ ) and VA warnings ( $M = 4605.04$  ms,  $SD = 1039$ ). F participants also demonstrated closely matched mean times between VT ( $M = 5796.8$  ms,  $SD = 2417$ ) and VA ( $M = 5730.4$  ms,  $SD = 2223$ ). As shown in Fig. 5.7, mean comprehension times were numerically higher in the F group than the NF group, regardless of warning method. However, no statistically significant interaction or main effect was observed.



**Figure 5.7. Mean comprehension times (in milliseconds) by experience group (non-farming [NF] vs. farming [F]) and warning method (Visual-Tactile [VT] vs. Visual-Auditory [VA]). Error bars represent standard error.**

Based on this pattern of results, regardless of participants' experience (NF vs. F), comprehension of warning cues required similar processing time whether the modality was tactile or auditory. These findings are consistent with recent research indicating equivalent efficacy of unimodal tactile and auditory warnings for comprehension, particularly when cognitive demands are moderate. For instance, Politis et al. (2017) found that adding tactile feedback to auditory warnings did not shorten comprehension time significantly, although response accuracy improved—suggesting modality changes may affect detection rather than processing (Zhu et al., 2025). Similarly, Geitner et al. (2019) reported that tactile warnings did not slow comprehension compared to auditory methods, although auditory-tactile combinations showed advantages for detection (Geitner et al., 2019).

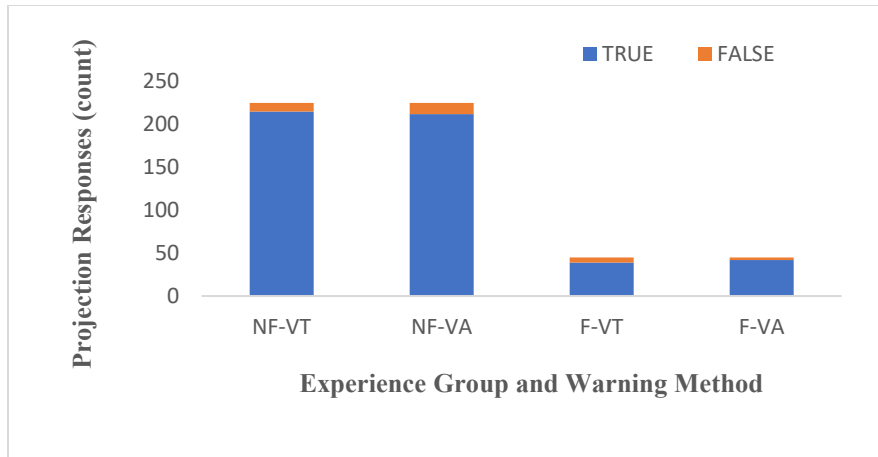
In practical contexts, such as in-vehicle systems or agricultural machinery, comprehension—not just detection—is critical for informed decision-making. Our results imply that either modality supports comprehension equivalently, enabling designers to prioritize modality based on constraints such as environmental noise or physical workload. Recent studies of augmented reality in work zones further suggest that modality effectiveness depends on task demands rather than comprehension time per se (Sabeti et al., 2024). The present experimental comprehension task was completed under controlled conditions. In real-world scenarios—where distractions, noise, and stress vary—modality effects on comprehension may differ. For example, studies show that modality efficacy can change under high cognitive load or when concurrent tasks compete for sensory resources (e.g., Wickens, 2008; Sabeti et al., 2024). Future research should examine how modality choice and warning combinations affect comprehension under realistic, high-load environmental conditions. Investigations could include adaptive warning systems where modalities shift in real time according to cognitive or situational demands (Politis et al., 2017).

Such systems may balance efficiency and user experience by dynamically optimizing modality use for comprehension and response effectiveness.

## **5.4.5 Cue Effectiveness Evaluation for Projection**

### ***5.4.5.1 Projection Accuracy***

A chi-square test of independence was conducted to examine the relationship between participant experience group (NF vs. F), warning method (VT vs. VA), and projection accuracy (TRUE vs. FALSE) during a simulated hazard perception task. The analysis did not reveal a statistically significant association among these variables,  $\chi^2(3, N = 540) = 5.37, p = .147$ , suggesting that the combination of experience and warning modality did not meaningfully affect participants' ability to accurately project urgency level. NF participants demonstrated consistently high accuracy across both warning methods, with 215 out of 225 responses (95.6%) correct in the VT condition and 212 out of 225 responses (94.2%) correct in the VA condition. In contrast, F participants showed a lower rate of accuracy, particularly in the VA condition. While 42 out of 45 responses (93.3%) in the VT condition were correct, only 39 out of 45 responses (86.7%) in the VA condition were accurate (Fig. 5.8). This discrepancy suggests that auditory cues posed a greater challenge for participants with farming experience. However, the variation was minimal and did not reach statistical significance.



**Figure 5.8. Percentage of correct (TRUE) and incorrect (FALSE) projection responses for each warning modality (Visual-Tactile [VT] and Visual-Auditory [VA]) across non-farming (NF) and farming (F) groups.**

The results revealed no statistically significant interaction between participant experience group and warning modality,  $p = .147$ . This suggests that the joint influence of farming background and warning delivery mode did not meaningfully shape participants’ ability to accurately interpret projected hazard information. However, descriptive trends—particularly the modest decline in projection accuracy among farming participants in the VA condition (86.7% vs. 93.3% in VT)—invite a nuanced interpretation of user-background influences.

These patterns underscore the potential impact of occupational familiarity and contextual exposure on system comprehension. Non-farming participants maintained high accuracy across both modalities, possibly reflecting routine interaction with audio-enabled digital devices—common in modern work and leisure environments (Norman, 1999; Yamamoto and Mori, 2021; Luo, 2024). In contrast, farming participants exhibited slightly lower performance under VA conditions, which may be linked to lower baseline exposure to auditory-centric alerts in agricultural settings—where sensors and indicators tend to rely more on tactile or visual feedback (Li et al., 2024; Mandil et al., 2023).

The diminished accuracy in VA conditions for farming participants may point to modality-driven cognitive constraints. Auditory alerts can be transient, competing with ongoing cognitive load and requiring higher short-term retention (Van der Heiden et al. 2022). Tactile cues, by contrast, offer spatial and persistent signals that are less likely to be masked by environmental noise—a critical advantage in farm environments characterized by engine sounds and machinery (Spence and Ho 2008; Zhao et al. 2024).

From a design perspective, these trends encourage more adaptive, user-centered warning systems that align with users' occupational experience and sensory expectations. Rather than assume uniform efficacy across modalities, designers should consider incorporating profiling mechanisms or training modules that calibrate warning formats to user characteristics and environmental contexts (Riener et al., 2017; Tang et al., 2023).

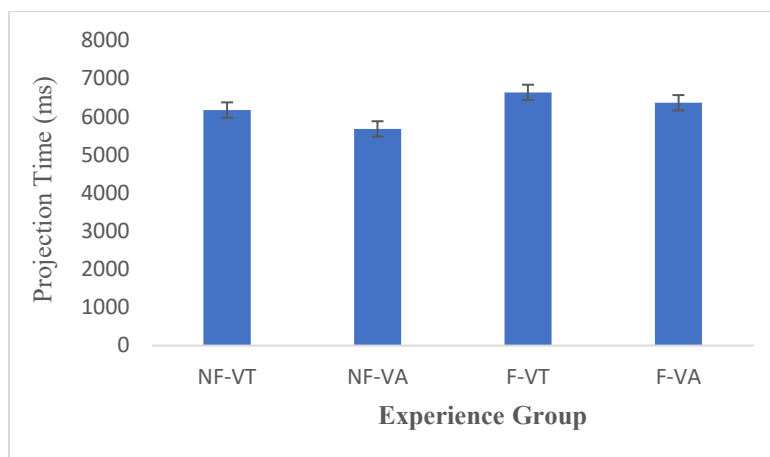
For high-risk industries like agriculture—where digitalization is rapidly expanding—these results highlight the need for careful attention to interface intuitiveness and perceptual alignment. While overall comprehension remained high, even small decrements in auditory warning effectiveness could impact safety-critical decisions in real-world conditions.

Future research should test whether targeted training or prolonged exposure can enhance auditory warning interpretation among farmers. Longitudinal studies examining the development of multimodal familiarity and its effect on projection accuracy in operational scenarios would provide valuable insight.

#### ***5.4.5.2 Projection Time***

A paired-samples t-test was conducted to examine whether projection time differed between VT and VA warning methods. The results showed no statistically significant difference,

$t(29) = 1.00, p = .325$ , indicating that participants' projection times did not reliably differ between conditions. Descriptive statistics showed that NF participants exhibited longer mean projection times for VT warnings ( $M = 6175.16$  ms,  $SD = 2319$ ) than for VA warnings ( $M = 5680.28$  ms,  $SD = 2499$ ). Similarly, F participants also had slightly higher projection times for VT warnings ( $M = 6638.00$  ms,  $SD = 2431$ ) compared to VA warnings ( $M = 6366.80$  ms,  $SD = 1207$ ). However, these differences did not reach statistical significance. These patterns are visualized in Fig. 5.9, with error bars representing the standard error of the mean.



**Figure 5.9. Mean projection times (in milliseconds) by experience group (non-farming [NF] vs. farming [F]) and warning method (Visual-Tactile [VT] vs. Visual-Auditory [VA]). Error bars represent standard error.**

Despite the absence of statistical significance, descriptive data showed that VA warnings yielded marginally faster projection times than VT for both NF and F participants. These trends align with existing research suggesting minimal performance disparities between auditory and tactile modalities in time-sensitive tasks (Zhu et al., 2025; Lee and Edworthy, 2024). While auditory cues often benefit from faster temporal resolution, tactile cues are generally more resistant to interference from environmental stimuli, contributing to their relative parity under controlled conditions.

However, while the simulated tractor cab environment used in this study offered high experimental control and minimized extraneous distractions, it failed to replicate several critical dimensions of real-world agricultural autonomous machinery (AAM) supervision. Actual farming scenarios introduce a host of additional stressors—including extended task durations, physical fatigue, ambient noise, lighting variability, dust, and multitasking demands—that can significantly modulate the effectiveness of different warning modalities. For instance, high ambient noise may mask auditory warnings, while fatigue or vibration exposure may diminish tactile sensitivity, potentially delaying response times.

Moreover, the study's setting did not include social dynamics or concurrent machinery oversight, both of which are common in active farming operations. This absence limits the ecological validity of the findings. Although the current results suggest modality differences may be functionally equivalent in low-complexity, moderate-demand environments, this equivalence may not hold under more stressful or unpredictable field conditions.

Previous multimodal research highlights the role of user familiarity, situational context, and adaptive interface design in optimizing modality effectiveness (Ekandem, 2017; Spence and Ho, 2008). Adaptive systems that respond dynamically to operator fatigue, environmental load, or sensory impairment may offer enhanced performance in real-world applications. Consequently, future work should transition beyond tightly controlled simulations to field-based or hybrid environments. This would better capture how modality performance interacts with the dynamic, high-load conditions characteristic of active agricultural settings. Such research is essential for developing inclusive, robust, and context-aware AAM warning systems.

#### **5.4.6 End-of-Experiment Subjective Responses**

The warning modality preferences diverged by experience group. NF participants preferred the VA modality, with 60% selecting it over VT (40%). Conversely, F participants favored the VT modality (60%) over VA (40%). This descriptive pattern offers insight into modality-specific comfort and usability across occupational contexts.

These results suggest that prior experience with specific types of sensory interaction may influence subjective preferences for system feedback. NF participants' preference for VA warnings is consistent with literature on digital familiarity, where auditory alerts—such as those used in emails, smartphones, and smart devices—are a routine part of human–computer interaction (Norman, 1999; Zhang and Wang, 2024). These users may perceive auditory signals as efficient and contextually appropriate, particularly in multitasking environments where visual attention is divided. In contrast, F participants demonstrated a marked preference for tactile feedback. This may reflect their greater familiarity with physical machinery and environments where haptic signals, such as vibrations from engines or tools, are commonly used to indicate mechanical changes or hazards. Tactile warnings may also be perceived as more reliable in high-noise outdoor settings, where auditory signals risk being masked by environmental noise (Wersényi, 2022; Gao et al., 2025). These patterns highlight the importance of aligning interface design with user experience. While both VA and VT warnings were capable of supporting accurate performance in previous tasks, participants' subjective preferences suggest that the feedback modality plays a critical role in how information is perceived and acted upon. Designers of multimodal safety systems should consider the sensory channels most familiar and reliable to target user groups.

These findings support recommendations for adaptive interface design, where users are offered the ability to select their preferred modality or where the system dynamically adjusts based on user profile or environmental conditions (Spence and Ho, 2008; Tang et al., 2023). The

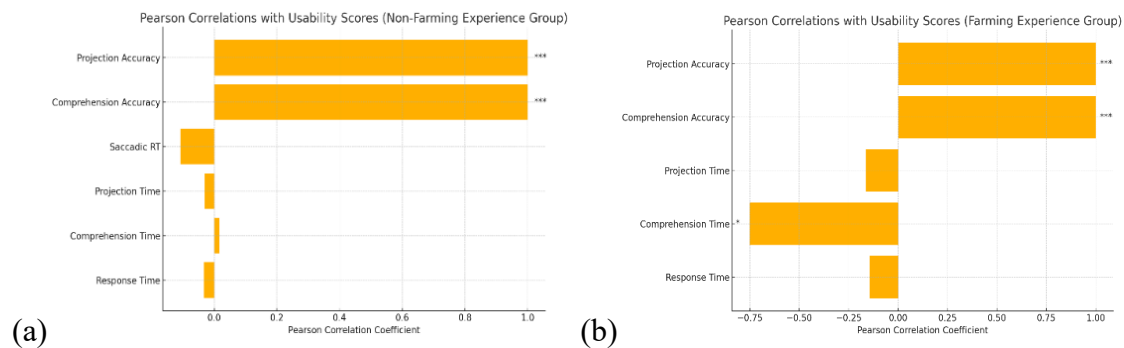
variability observed between experience groups also reinforces the need for inclusive design strategies that accommodate diverse work contexts. Future research should explore whether these preferences persist across repeated interactions, and whether they translate into behavioral advantages in long-term use. Studies involving larger samples and controlled modality testing can further clarify how subjective preference interacts with actual system performance.

#### 5.4.7 Correlation Analysis

The relationship between objective performance metrics and perceived usability scores was assessed using Pearson correlation coefficients, calculated separately for F and NF participants. For the NF group, a significant negative correlation emerged between comprehension time and usability scores,  $r(23) = -.75$ ,  $p = .012$ , indicating that participants who processed information more quickly rated the system as more usable. This finding underscores the importance of cognitive efficiency in shaping usability perceptions among non-expert users. A moderate negative correlation was also observed between noticeability (saccadic reaction time) and usability,  $r(23) = -.41$ , though this relationship did not reach statistical significance ( $p = .239$ ). These results suggest that visual attention efficiency may play a role in usability perceptions, albeit not strongly. Strikingly, comprehension accuracy exhibited a perfect positive correlation with usability scores,  $r(23) = 1.00$ ,  $p < .001$ . A similarly perfect correlation was found for projection accuracy. While these results suggest a robust relationship between task success and perceived system usability, such perfect correlations are rare and may indicate redundancy in measurement or scoring ceiling effects. Notably, other objective measures, including response time ( $r = -.14$ ,  $p = .692$ ) and projection time ( $r = -.16$ ,  $p = .655$ ), showed negligible associations with usability in this group.

In the F group, a comparable pattern was observed for comprehension-related measures (Fig. 5.10b). Specifically, comprehension time showed a significant negative correlation with

usability scores,  $r(9) = -.75$ ,  $p = .012$ , indicating that even among experienced users, faster understanding of the interface correlated with higher usability ratings. Saccadic reaction time also showed a moderate negative relationship with usability,  $r(9) = -.41$ ,  $p = .239$ , consistent with the NF group, though again not statistically significant. As with the NF group, comprehension accuracy and projection accuracy both demonstrated perfect positive correlations with usability ( $r = 1.00$ ,  $p < .001$ ), reinforcing their apparent influence on perceived usability (Fig. 5.10a). However, this again raises concerns about potential measurement overlap. Response time ( $r = -.14$ ,  $p = .692$ ) and projection time ( $r = -.16$ ,  $p = .655$ ) remained weakly related to usability in this group, suggesting that for experienced users, rapid task execution may be less influential on usability perceptions.



**Figure 5.10.** Pearson correlation coefficients between objective performance metrics and usability scores (a) for the non-farming experience (NF) group (b) for the farming experience (F) group (Note the significant negative correlation between comprehension time and usability). Asterisks indicate significance levels ( $p < .05$ ,  $*p < .01$ ,  $**p < .001$ ).

These findings reinforce the importance of cognitive efficiency—particularly comprehension speed—as a strong predictor of perceived usability across diverse user profiles. Such results align with prior studies emphasizing cognitive processing speed in usability judgments, especially for novice users (Tuch et al., 2012; Norman, 2013). The moderate relationship between noticeability (saccadic reaction time) and usability supports the idea that

efficient visual search may aid usability, but may not independently drive evaluations unless paired with other cognitive factors (Poole and Ball, 2006; Thayer et al., 2022).

The perfect correlations observed for comprehension and projection accuracy require careful interpretation. While it is plausible that users who perform well perceive the interface as more usable,  $r = 1.00$  values are statistically rare. They may result from methodological artifacts, such as usability rating scales that heavily weight performance outcomes. This echoes concerns in the literature about construct redundancy and ceiling effects in usability evaluation frameworks (Wu et al., 2022). Future studies should consider disaggregating accuracy from perceived usability to avoid inflating such associations.

Although speed metrics such as response time and projection time showed limited correlation with usability, particularly for experienced users, this suggests a nuanced view of interface evaluation. For domain-expert users, usability may depend more on system predictability, logical flow, and alignment with task goals than on raw task completion speed. This supports theories proposing that domain knowledge can buffer users from the effects of minor interface inefficiencies (Mahmud et al., 2025).

Despite this study focused on interface usability and perceptual responses to warning modalities, the implications extend to broader concerns in agricultural safety and operator well-being. In high-risk farming environments, delayed or missed warnings—particularly under multitasking, fatigue, or sensory overload—can result in serious injuries or equipment failures. The superior noticeability and faster reaction times observed for auditory warnings suggest they may help reduce oversight-related errors in time-sensitive scenarios. Conversely, tactile warnings may offer a more reliable alternative in outdoor or high-noise settings where auditory cues can be masked by machinery.

Designing adaptive human–machine interfaces that respond to cognitive load, fatigue, and environmental factors could help prevent safety incidents and promote long-term health outcomes for agricultural workers. These insights are especially relevant as autonomous and semi-autonomous technologies become more common in agricultural settings. Multimodal warning systems integrated into these platforms—capable of adjusting cues based on sensory context and operator state—can improve real-time hazard communication and situation awareness.

These findings also have implications for policy and regulation. Agencies such as Cal/OSHA and national agricultural safety authorities can use this evidence to guide standards for acceptable warning system designs in autonomous equipment. Regulations should ensure that user interfaces account for operator state and prioritize intuitive, effective communication, especially in dynamic or high-risk field environments.

Finally, future research should conduct field-based trials that incorporate real-world variables such as weather exposure, fatigue, and multitasking to validate the effectiveness of different warning modalities. Additionally, the development of alternative usability frameworks—which clearly separate performance metrics from subjective perceptions—will be critical in refining our understanding of how humans interact with increasingly automated agricultural systems (Mahmud et al., 2025; Zhao et al., 2022).

## **5.5 Conclusion**

This study examined how individuals with and without farming experience interact with multimodal warning systems, comparing their performance, preferences, and usability perceptions across visual–tactile (VT) and visual–auditory (VA) modalities. Both groups rated VT and VA warnings as usable and demonstrated high comprehension and projection accuracy. However, non-

farming (NF) participants responded more quickly and accurately—especially under VA conditions—while farming-experienced (F) participants preferred VT cues and performed less effectively with auditory warnings, likely due to lower exposure to audio-based systems in high-noise agricultural environments.

Saccadic reaction times indicated higher noticeability for VA cues in NF users, though eye-tracking data for F users were limited due to vision-related constraints. While comprehension and projection times showed no significant differences across modalities, VA conditions resulted in slightly faster processing for NF users. Correlation analyses showed that comprehension time was a significant predictor of usability in both groups ( $r = -.75$ ,  $p = .012$ ), with moderate, non-significant correlations for saccadic reaction time ( $r = -.41$ ,  $p = .239$ ). Comprehension and projection accuracy showed perfect correlations with usability ( $r = 1.00$ ,  $p < .001$ ), suggesting a strong link between task success and perceived usability—though likely influenced by ceiling effects or construct overlap.

Subjective feedback supported these findings: NF participants favored auditory cues, while F participants preferred tactile ones, reinforcing the role of perceptual familiarity and occupational context. However, the small, all-male F sample ( $n = 5$ ) and the controlled lab setting limit generalizability and ecological validity. These limitations call for field-based studies with more diverse samples and real-world environmental complexity.

The results highlight the value of adaptive multimodal interfaces that allow users to adjust warning modalities based on task, context, or experience. Systems that incorporate real-time user profiling, dynamic feedback adjustment, and targeted training—especially for users unfamiliar with certain modalities—can improve safety, inclusivity, and performance. These findings also inform the design of autonomous agricultural equipment and support the development of

regulatory standards by agencies like Cal/OSHA to ensure effective hazard communication tailored to operator states.

Future research should test these systems under real-world conditions, considering factors such as fatigue, noise, and multitasking. Longitudinal studies should assess how modality preferences evolve with training, and new usability models should distinguish between performance and perception to avoid misleading statistical artifacts.

To conclude, usability is not a universal construct but one shaped by experience, sensory modality, and context. Centering diverse user needs—particularly among underrepresented groups like farmers—can guide the development of more intuitive, adaptive, and safe multimodal systems for high-risk environments.

## 6. RESEARCH SUMMARY

### 6.1 General Conclusion

This thesis explored the design, effectiveness, and usability of unimodal and bimodal warning modalities for enhancing operator performance in the remote supervision of autonomous agricultural machinery (AAMs). Through a series of experimental studies, it systematically investigated how sensory modalities—visual, auditory, and tactile—individually and in combination, influence key aspects of situation awareness (SA), specifically Level 1 SA (perception), Level 2 (comprehension), and Level 3 (projection).

The findings consistently affirmed the superiority of visual cues across multiple dimensions of performance, including response time, comprehension accuracy, and user preference. Visual-tactile (VT) combinations emerged as the most effective bimodal configuration, particularly in scenarios without background noise, offering a balance of noticeability and interpretability. In contrast, visual-auditory (VA) cues were more context-sensitive—effective in noisy environments but less preferred overall. Unimodal tactile cues, while theoretically promising in conditions of sensory overload, proved less effective in this research, highlighting the need for more targeted applications and user training.

Additionally, this research addressed the usability of these warning systems by evaluating how participants with and without farming experience interacted with VT and VA cues. The results underscored the importance of user experience, occupational background, and environmental context in shaping modality effectiveness and usability perceptions. Participants without farming backgrounds often performed better and showed stronger preference for auditory cues, while those with farming experience preferred tactile warnings—suggesting that one-size-fits-all designs may fall short in real-world agricultural applications.

Together, these findings provide critical guidance for the development of user-centered, multimodal human-machine interfaces for AAM supervision. Designers are encouraged to prioritize visual feedback as the primary modality, supplementing it with auditory or tactile cues in a context-responsive manner. Importantly, multimodal systems should be adaptive, allowing for user profiling and real-time adjustments based on experience level, environmental conditions, and task demands. Future research should focus on developing adaptive feedback systems, expanding to broader user populations, and testing under ecologically valid conditions. Longitudinal studies could also help illuminate how sustained exposure and training influence modality preference and performance. Taken together, the results of this research highlight the central role of perception and usability in multimodal warning design. The findings reinforce the need for interfaces that are not only effective but also intuitive, inclusive, and aligned with the real-world needs of diverse users in agriculture and beyond.

## **6.2 Contributions**

During the course of this research, several key contributions were made toward the development of effective and user-centered warning systems for the remote supervision of autonomous agricultural machinery (AAMs). These contributions are as follows:

- Established empirical evidence on the effectiveness of sensory modalities—visual, auditory, and tactile—in supporting the three levels of situation awareness (SA): perception (Level 1), comprehension (Level 2), and projection (Level 3), in remote supervision tasks.
- Confirmed the superiority of visual warning cues across all performance metrics, including response time, comprehension accuracy, and user preference, reinforcing their role as the primary modality in supervisory interface design.

- Identified the visual–tactile (VT) bimodal combination as the most effective warning modality for non-noisy environments, offering an optimal balance between noticeability and interpretability.
- Determined that visual–auditory (VA) cues are more suitable in noisy operational contexts, although they were generally less preferred by users.
- Demonstrated that unimodal tactile warnings are less effective overall, highlighting the importance of selective use and proper training when implementing tactile alerts in supervisory systems.
- Provided insights into how user experience and background influence usability and modality preference, revealing that participants with farming experience preferred tactile cues, while those without farming backgrounds performed better with auditory feedback.
- Highlighted the need for adaptive, user-centered interface designs that account for environmental context, operator expertise, and individual sensory preferences.
- Offered design guidelines for integrating multimodal warning cues into human–machine interfaces in a way that enhances performance, supports user intuition, and accommodates diverse agricultural work environments.

### **6.3 Limitations**

Despite the valuable insights gained from this research, several limitations should be acknowledged:

- The small sample size, particularly in the farming group in the last study, limited statistical power and generalizability, restricting conclusions about individual differences.
- The simulated environment lacked the complexity and situational pressures of real-world supervision, potentially limiting the ecological validity of the findings.
- The study focused only on unimodal and bimodal cues; future research should explore trimodal combinations, as cross-modality congruence and sensory integration may affect usability and effectiveness.
- The study measured immediate responses but not how preferences or performance evolve with sustained use; longitudinal research is needed to assess the effects of familiarity and training.

### **6.4 Future Directions**

The findings of this research provide important insights into the effectiveness, usability, and user preferences for bimodal warning cues in the context of remote supervision of autonomous agricultural machinery. However, several critical avenues remain for future investigation to extend the generalizability and practical applicability of these results.

- **Testing Under Real-World Conditions:** The experiments in this study were conducted under controlled laboratory conditions. Real-world supervision of autonomous agricultural systems involves environmental complexities such as background noise, vibration, shifting

weather, and operator multitasking. Future studies should aim to replicate these ecologically valid conditions to determine how environmental stressors influence the effectiveness of visual-auditory (VA) and visual-tactile (VT) warning cues in practice (Kallioniemi et al., 2021).

- **Expanding Participant Diversity and Sample Size:** The current sample included a relatively small number of farming-experienced participants, limiting statistical power and generalizability to that population. Future research should include a larger and more demographically diverse participant pool, especially among farmers and operators with domain-specific expertise, to better understand how age, gender, sensory impairments, and digital literacy affect modality preferences and performance outcomes.
- **Adaptive and Personalized Multimodal Systems:** Results showed differences in modality effectiveness and preference based on user experience—non-farmers preferred VA cues while farmers leaned toward VT cues. This highlights the potential for adaptive interfaces that dynamically adjust modality configurations based on user profiles, sensory load, or environmental context. Future work should explore the feasibility of adaptive warning systems that tailor the modality (or combinations of modalities) to user characteristics, real-time workload, or situational demands (Dritsas et al., 2025).
- **Incorporating Trimodal or Multimodal Feedback:** While this study focused on bimodal combinations, evidence suggests that trimodal cues (visual-auditory-tactile) may enhance situation awareness and response reliability through sensory redundancy. Further research should investigate how additional modalities might be integrated effectively—without overwhelming users or introducing sensory or cognitive overload—and under what conditions such combinations are most beneficial (Zhu et al., 2025).

- Longitudinal Studies on Learning and Familiarization: Although usability scores were high, particularly among those who responded quickly or accurately, these ratings may shift with continued exposure. Future longitudinal studies are necessary to examine how familiarity, training, and sustained use influence modality effectiveness, subjective preference, and perceived usability over time. This could inform training protocols and user onboarding strategies for automated farming technologies.
- Investigating Cognitive Load and Task Switching: The correlation between faster comprehension time and higher usability ratings—especially among non-farming participants—indicates that cognitive efficiency is a key determinant of user satisfaction. Future studies should assess how multimodal cues perform under high cognitive load, when users are multitasking or switching between supervision and other farm tasks. Eye-tracking and neurophysiological methods could offer deeper insights into attention allocation and processing effort in such contexts.
- Evaluating Alert Hierarchies and Urgency Differentiation: While visual warnings were most effective in conveying urgency, future work should explore how modality selection affects alert prioritization. For instance, can tactile cues be optimized for low-level alerts while auditory cues are reserved for high-urgency events? Understanding how to design multimodal hierarchies will help in delivering the right information through the most appropriate sensory modality at the right time.
- Enhancing Tactile and Auditory Cue Design: Tactile warnings underperformed in comprehension and urgency projection, possibly due to inadequate spatial or semantic mapping. Future studies should investigate how haptic cue characteristics (e.g., vibration intensity, location, rhythm) and auditory signal properties (e.g., pitch, tempo, repetition)

influence interpretability and task performance, particularly in outdoor, noisy agricultural settings.

- Usability Model Refinement and Measurement Validity: The perfect correlations observed between comprehension/projection accuracy and usability suggest potential overlap or ceiling effects in measurement tools. Future work should refine usability measurement frameworks to disaggregate performance from perception and prevent score inflation. This may include multi-dimensional usability models that account for cognitive effort, trust, satisfaction, and adaptability.

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## 8. APPENDIX A: Chapter 3 STUDY MATERIALS

### A1: Perception Study- Consent Form

Assessment of Warning Modalities for Remotely Supervised Autonomous Agricultural

Machines: Experiment I.

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**This consent form, a copy of which will be left with you for your records and reference, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. Please take the time to read this carefully and to understand any accompanying information. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask.**

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**RESEARCH OBJECTIVE:** The purpose of this study is to determine which warning modality would be most suitable for attracting attention of the supervisor of an autonomous agricultural machine during emergencies. The study should take no longer than one hour to complete.

**RESEARCH PROCEDURE:** Before you begin the experiment, your visual, hearing and tactile comfort levels will be assessed. You will then be asked to record daily farm tasks (visible on a computer monitor) and monitor the operation of a simulated autonomous sprayer (information presented on another computer monitor). You are expected to focus on the farm recording task until your attention is drawn to the other screen through a combine effect of either visual and sound or visual and tactile stimulation (an SMI eye tracking device will be worn to monitor your head/eye movement). Once you perceive any of the bimodal warning modalities (i.e., visual and sound or visual and tactile), you are expected to click on the “Alert Perceived” button located on the top left corner of the interface screen to acknowledge awareness.

The experiment comprised of 6 trials which are divided equally into two sessions. There are also three training trials to enable you to become familiar with the experiment. The first session will take place in a quiet environment while the second session will take place at different noise level. Each trial will adopt multiple modalities to alert you. At the end of each trial, you will be asked to share your experience by completing a trial questionnaire. After you have finished the last session (session 2), you will be given an “end-of-experiment questionnaire” to comment on your overall experience.

The questions presented in this study are **NOT** intended to test your intellectual competence. They are only meant to gather your opinion with regards to the experiment.

**RISKS:** You will be exposed to physical stimuli such as; flashing light, loud sounds, and tactile stimulations. But the quantity and duration of exposure to these conditions during the experiment are below the allowable maximum recommended limits. However, there are scheduled breaks within sessions to minimize such discomfort. Nevertheless, if you indicate fatigue and/or discomfort during the experiment, you can either request for an unscheduled break or discontinue the experiment if it persists. Prior to the training session, you will be asked as part of the recruitment process while filling the Participant's Information form if you have underlying conditions that will predispose to sensitivity/reactions to: flashing light, loud sounds, or tactile indication (buzzing). If yes, you undertake the experiment at your own risk.

**COSTS:** Your participation in this study does **NOT** require any financial commitment on your part.

**COMPENSATION:** You will be offered a twenty-five-dollar UM bookstore gift card as honorarium upon receipt of your consent as compensation for your time.

**CONFIDENTIALITY:** Your personal information will be strictly confidential. It will not be cited nor used directly during analysis, publications or any presentation. In all cases, only group average or summary will be presented to protect your identity. To further ensure the safety of your information, only the principal investigator, Ms. Anita Eze will have access to your identifiable data while her supervisors, Dr. Danny Mann and Dr. Cheryl Glazebrook will have access to both your identifiable & coded/de-identifiable data. A password protected laptop will be used to access and analyze your information. All documents containing identifiable information will be store in a locked drawer of a secured filing cabinet while all de-identifiable information will be store in a second locked drawer of the same filing cabinet.

By December 2030, hard copies of this consent form, and other documents containing your personal information will be deleted or destroyed to protect your identity.

**DEBRIEFING:** A formal feedback will not be provided immediately after the experiment. However, the principal investigator will be willing to answer any questions that may arise. A summary of the study will be made available upon completion by June, 2023 to participants who will indicate interest by providing their email and mailing addresses at the end of this consent form.

**DISSEMINATION:** Results from this study will appear in a PhD thesis of the Department of Biosystems Engineering at the University of Manitoba as well as articles published through MSpace, in peer-reviewed scientific journals and conferences. The results will also be included in oral presentations that are open to the public. Some data and information from this study may be sent outside of the University of Manitoba to other researchers, organizations, or made publicly available. This is for further analysis, testing, as part of the research study, or a requirement by a granting agency or journal. Any information sent out of the University of Manitoba will not show your name or address, or any other identifiable personal information about you. However, despite efforts to keep your personal information confidential, absolute confidentiality cannot be guaranteed. Your personal information may be disclosed if required by law.

**WITHDRAWING:** Your participation in this study is voluntary. You are free to withdraw anytime you wish by notifying the principal investigator, and there are no consequences for withdrawing from the study. If you decide to withdraw from the study while in progress, the Principal Investigator, Ms. Anita Eze will delete all your data collected including those from the data collection computer and any back-ups on hard drives. Once the study process is complete, it would not be possible to remove your data which is approximately by December, 2023 (withdrawal deadline).

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Your signature on this form indicates that you have understood to your satisfaction, the conditions regarding your participation in this study and have given your consent. In no way does this waive your legal rights nor release the researchers, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time, and /or refrain from answering any questions you prefer to omit, without prejudice or consequence. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation.

The University of Manitoba may look at our research records to see that the research is being done in a safe and proper way.

**This research has been approved by the Research Ethics Board at the University of Manitoba, Fort Garry Campus. If you have any concerns or complaints about this project, you may contact any of the above-named persons or the Human Ethics Coordinator at 204-474-7122, [humanethics@umanitoba.ca](mailto:humanethics@umanitoba.ca).**

A copy of this consent form has been given to you to keep for your records and reference.

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-----  
Participant Name: \_\_\_\_\_

Participant Signature: \_\_\_\_\_ Date: \_\_\_\_\_

Researcher Signature: \_\_\_\_\_ Date: \_\_\_\_\_

Please, check the box and provide your email and/or postal address if you are interested to receive a summary of the findings of this research.

Email address: \_\_\_\_\_

Postal Address: \_\_\_\_\_

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## A2: Perception Study– Participant’s Information Form

Name: \_\_\_\_\_

Subject ID: \_\_\_\_\_

Participant’s Information

Instruction: Please answer the questions below as honestly and accurately as possible. Circle the answer that best describes you. For questions with a blank, open responses are encouraged.

Participant's information:

1. Age?

18 - 24          25 - 30          31 - 35

2. Location of residence (Province/City)?

\_\_\_\_\_ / \_\_\_\_\_

3. Did you previously live on a farm?

Yes                  No

If yes, please indicate the number of years: \_\_\_\_\_

4. Have you ever operated an agricultural sprayer?

Yes                  No

If yes, please indicate the number of years of experience: \_\_\_\_\_

5. Have you ever driven an agricultural tractor?

Yes                  No

If yes, please indicate the number of years of experience: \_\_\_\_\_

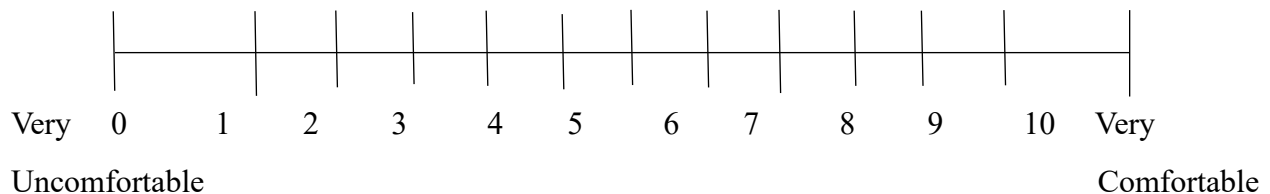
### A3: Perception Study– Trial Questionnaire

Trial Number: \_\_\_\_\_

Subject ID: \_\_\_\_\_

**Instruction:** Please circle the answer that best matches your opinion. Multiple responses are ONLY allowed in question 2.

1. How comfortable or uncomfortable did you feel during the trial?

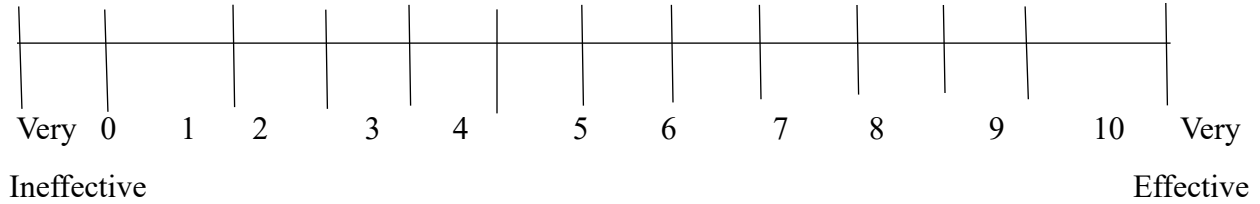


2. Overall, which warning cue(s) best informed you of the error?

a. Combination of Flashing Alert and Beep (Visual and Auditory)

- b. Combination of Flashing Alert and Vibration (Visual and Tactile)
- c. Unconscious turning of the head/eye
- d. None

3. How effective was that warning cue(s)?



4. Would you recommend this type of warning cue(s)?  
                   Yes                  No

5. Why?

Additional comments (if any):

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**A4: Perception Study– End-of-Experiment Questionnaire**

Subject ID: \_\_\_\_\_

**Instruction:** Please answer the questions below as honestly and accurately as possible. Circle the answer that best describes your experience. For questions with blank spaces, written responses are encouraged.

1. Which bimodal warning cue would you recommend for remote supervision of an autonomous sprayer?
  - a. Combination of flashing alert and beep (Visual and Auditory)
  - b. Combination of flashing alert and vibration (Visual and Tactile)
  
2. Why would you recommend this bimodal warning cue?

3. Do you have any suggestions that might be beneficial to this study?

**A5: Perception Study– Post-training Assessment Form**

Subject ID: \_\_\_\_\_

Post-Training Assessment

- Please select the response that best describes the flashing “Alert!!!” that was used during the experiment:

It was barely visible                      It was clearly visible

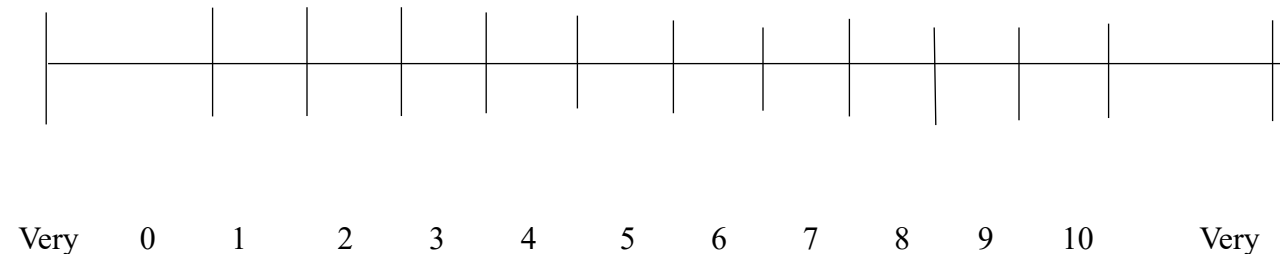
- How comfortable or uncomfortable were you when presented with the flashing “Alert !!!”?



- Please select the response that best describes the auditory “beep” sound that was used during the experiment:

I could barely detect it I could easily detect it

- How comfortable or uncomfortable were you when presented with the auditory “beep sound”?



Uncomfortable

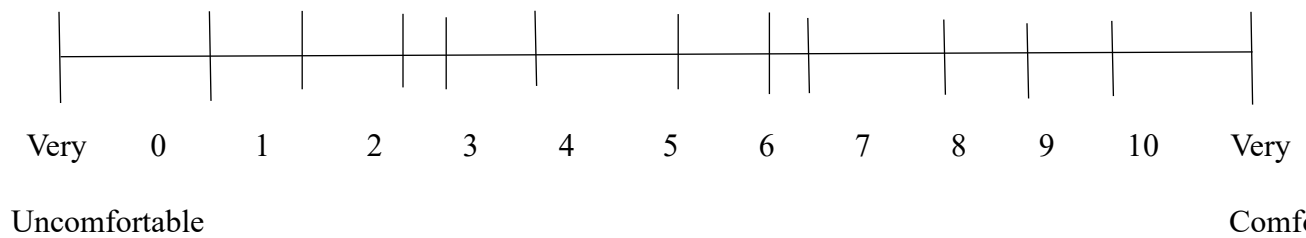
Comfortable

Please select the response that best describes the tactile vibration that was used during the experiment:

I could barely detect it

I could easily detect it

- How comfortable or uncomfortable were you when you felt the vibration?

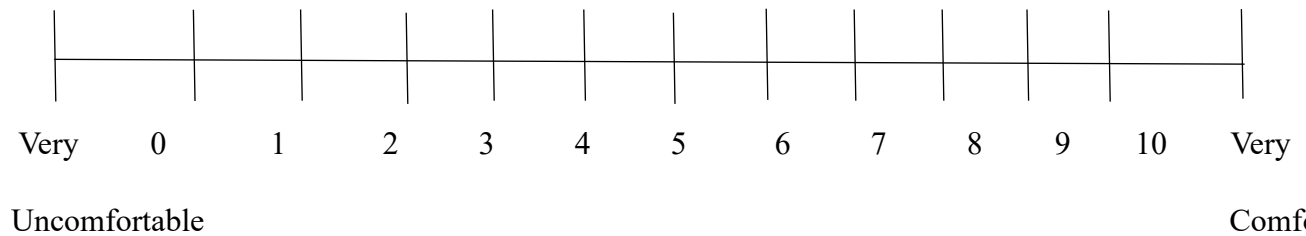


- Please select the response that best describes the tractor sound that was used during the experiment:

I could barely detect it

I could easily detect it

- How comfortable or uncomfortable did you feel hearing the tractor sound?



## A6: Perception Study- Recruitment Poster



# PARTICIPANTS NEEDED



### Purpose of study:

You are invited to participate in a study that will be carried out in a Lab. to determine which medium would be suitable to attract the attention of the supervisor of an autonomous agricultural machine during emergencies. The study should take no longer than one hour to complete.

### Role of participants:

You will be asked to do the following; (1). Record daily farm management tasks (on a screen) and monitor the operation of a simulated autonomous sprayer (on another screen). (2). Click on a button to acknowledge that you have perceived a warning notification. (3). You will be presented a trial questionnaire and an end-of-experiment questionnaire to rank each warning mode(s) and give your personal experience during the entire experiment respectively.

### Inclusion/exclusion criteria:

Potential participants must be willing to submit to auditory, visual and tactile screening should have either three (3) years of farming experience specifically with the knowledge of spraying of fertilizer and herbicides or tractor driving experience and also should be in the age bracket of 18-35 years old. Participants who do not have either farming experience or tractor driving experience and less than 18 years old or more than 35 years old would not be eligible. Also, participants with impaired vision and hearing would be ineligible.

### Contact information:

Interested participants can email Anita (Principal Investigator): [ezeagbaa@myumanitoba.ca](mailto:ezeagbaa@myumanitoba.ca), Phone: [REDACTED] or Dr. Danny Mann (Advisor): [danny.mann@umanitoba.ca](mailto:danny.mann@umanitoba.ca) for more information.

*This study has been approved by the Research Ethics Board at the University of Manitoba, Fort Garry Campus. If you have any concerns or complaints about this project, you may contact any of the above-named persons or the Human Ethics Coordinator at 204-474-7122.*

A \$25 UM bookstore gift card will be provided as honorarium.



ibility: Investigate

## 9. APPENDIX B: Chapter 4 STUDY MATERIALS

### B1: Modality-Specific Support for Comprehension and Projection Study (Part 1)- Consent Form

Assessment of Warning Modalities for Remotely Supervised Autonomous Agricultural Machines: Experiment II.

***Principal investigator:***

**Anita Eze**  
Ph.D. student  
Dept. of Biosystems Engineering  
University of Manitoba  
Phone: 204-474-7966  
Email: ezeagbaa@myumanitoba.ca.

***Advisor:***

**Danny Mann, Ph.D., P.Eng.**  
Professor and Head  
Dept. of Biosystems Engineering  
University of Manitoba  
Phone: 204-474-7149  
Email: Danny.Mann@umanitoba.ca.

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**This consent form, a copy of which will be left with you for your records and reference, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. Please take the time to read this carefully and to understand any accompanying information. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask.**

---

**RESEARCH OBJECTIVE:** The purpose of this study is to determine which warning modality would be most suitable to proffer comprehension to the supervisor of an autonomous agricultural machine during emergencies. The study should take no longer than one hour to complete.

**RESEARCH PROCEDURE:** Before you begin the experiment, your visual, hearing and tactile abilities and comfort levels respectively, will be assessed. You will then be asked to conduct an internet search to answer specific agronomic questions (visible on a computer monitor) and then move focus to another computer monitor (where you will be informed about the statutory information of a simulated autonomous sprayer using different stimuli levels of various warning methods- visual, auditory and tactile) once you hear a notification sound. An SMI eye tracking device will be worn to monitor your head/eye movement. During the experiment, you are expected to select the right choice of condition based on perceived warning from a list of possible conditions to acknowledge comprehension.

The experiment comprised of 3 trials which will be completed in one session. There are also three training trials to enable you to become familiar with the experiment. Each trial will adopt the warning modalities (visual, auditory and tactile) at the different stimuli levels to alert you and you are expected to select the right choice of condition based on perceived warning from a list of possible conditions to acknowledge comprehension. At the end of each trial, you will be asked to share your experience by completing a trial questionnaire. After you have finished the session, you will be given an “end-of-experiment questionnaire” to comment on your overall experience.

The questions presented in this study are **NOT** intended to test your intellectual competence. They are only meant to gather your opinion with regards to the experiment.

**RISKS:** You will be exposed to physical stimuli such as; flashing light, loud sounds, and tactile stimulations. But the quantity and duration of exposure to these conditions during the experiment are below the allowable maximum recommended limits. However, there are scheduled breaks within sessions to minimize such discomfort. Nevertheless, if you indicate fatigue and/or discomfort during the experiment, you can either request for an unscheduled break or discontinue the experiment if it persists. Prior to the training session, you will be asked as part of the recruitment process while filling the Participant's Information form if you have underlying conditions that will predispose to sensitivity/reactions to: flashing light, loud sounds, or tactile indication (buzzing). If yes, you undertake the experiment at your own risk.

**COSTS:** Your participation in this study does **NOT** require any financial commitment on your part.

**COMPENSATION:** You will be offered a twenty-five-dollar UM bookstore gift card as honorarium upon receipt of your consent as compensation for your time.

**CONFIDENTIALITY:** Your personal information will be strictly confidential. It will not be cited nor used directly during analysis, publications or any presentation. In all cases, only group average or summary will be presented to protect your identity. To further ensure the safety of your information, only the principal investigator, Ms. Anita Eze will have access to your identifiable data while her supervisors, Dr. Danny Mann and Dr. Cheryl Glazebrook will have access to both your identifiable & coded/de-identifiable data. A password protected laptop will be used to access and analyze your information. All documents containing identifiable information will be store in a locked drawer of a secured filing cabinet while all de-identifiable information will be store in a second locked drawer of the same filing cabinet.

By December 2030, hard copies of this consent form, and other documents containing your personal information will be deleted or destroyed to protect your identity.

**DEBRIEFING:** A formal feedback will not be provided immediately after the experiment. However, the principal investigator will be willing to answer any questions that may arise. A summary of the study will be made available upon completion by December, 2023 to participants who will indicate interest by providing their email and mailing addresses at the end of this consent form.

**DISSEMINATION:** Results from this study will appear in a PhD thesis of the Department of Biosystems Engineering at the University of Manitoba as well as articles published through MSpace, in peer-reviewed scientific journals and conferences. The results will also be included in oral presentations that are open to the public. Some data and information from this study may be sent outside of the University of Manitoba to other researchers, organizations, or made publicly available. This is for further analysis, testing, as part of the research study, or a requirement by a granting agency or journal. Any information sent out of the University of Manitoba will not show your name or address, or any other identifiable personal information about you. However, despite efforts to keep your personal information confidential, absolute confidentiality cannot be guaranteed. Your personal information may be disclosed if required by law.

**WITHDRAWING:** Your participation in this study is voluntary. You are free to withdraw anytime you wish by notifying the principal investigator, and there are no consequences for withdrawing from the study. If you decide to withdraw from the study while in progress, the Principal Investigator, Ms. Anita Eze will delete all your data collected including those from the data collection computer and any back-ups on hard drives. Once the study process is complete, it would not be possible to remove your data which is approximately by December, 2023 (withdrawal deadline).

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Your signature on this form indicates that you have understood to your satisfaction, the conditions regarding your participation in this study and have given your consent. In no way does this waive your legal rights nor release the researchers, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time, and /or refrain from answering any questions you prefer to omit, without prejudice or consequence. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation.

The University of Manitoba may look at our research records to see that the research is being done in a safe and proper way.

**This research has been approved by the Research Ethics Board at the University of Manitoba, Fort Garry Campus. If you have any concerns or complaints about this project, you may contact any of the above-named persons or the Human Ethics Coordinator at 204-474-7122, [humanethics@umanitoba.ca](mailto:humanethics@umanitoba.ca).**

A copy of this consent form has been given to you to keep for your records and reference.

-----  
-----  
Participant Name: \_\_\_\_\_

Participant Signature: \_\_\_\_\_ Date: \_\_\_\_\_

Researcher Signature: \_\_\_\_\_ Date: \_\_\_\_\_

Please, check the box and provide your email and/or postal address if you are interested to receive a summary of the findings of this research.

Email address: \_\_\_\_\_

Postal Address: \_\_\_\_\_

---

**B2: Modality-Specific Support for Comprehension and Projection Study (Part 1)-  
Participant's Information Form**

Name: \_\_\_\_\_

Subject ID: \_\_\_\_\_

Participant's Information

**Instruction:** Please answer the questions below as honestly and accurately as possible. Circle the answer that best describes you. For questions with a blank, open responses are encouraged.

**Participant's information:**

1. Age?

18 - 24

25 - 30

31 - 35

2. Location of residence (Province/City)?

\_\_\_\_\_ / \_\_\_\_\_

3. Did you previously live on a farm?

Yes

No

If yes, please indicate the number of years: \_\_\_\_\_

4. Have you ever operated an agricultural sprayer?

Yes

No

If yes, please indicate the number of years of experience: \_\_\_\_\_

5. Have you ever driven an agricultural tractor?

Yes

No

If yes, please indicate the number of years of experience: \_\_\_\_\_

6. Do you have any underlying condition that will predispose you to sensitivity/reactions to:  
flashing light, loud sounds, or tactile indication (buzzing)?

Yes

No

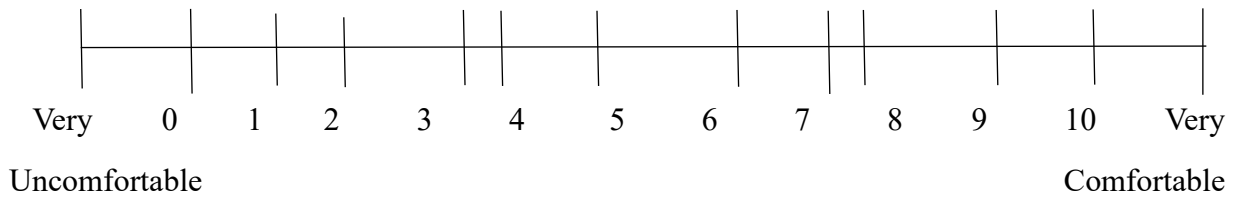
**B3: Modality-Specific Support for Comprehension and Projection Study (Part 1)- Trial Questionnaire**

Trial Number: \_\_\_\_\_

Subject ID: \_\_\_\_\_

**Instruction:** Please circle the answer that best matches your opinion. Multiple responses are ONLY allowed in question 2.

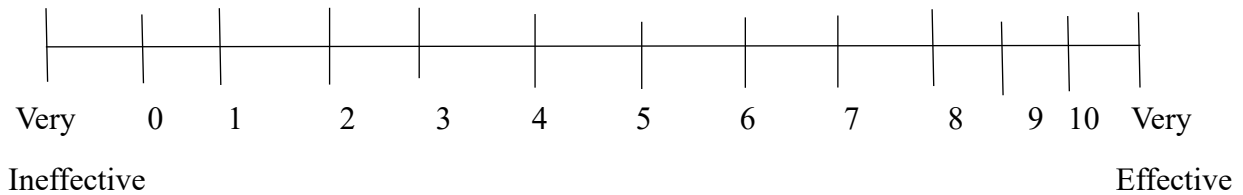
1. How comfortable or uncomfortable did you feel during the trial?



2. Overall, which warning cue(s) did you perceive during the trial?

- e. Flashing “Colored letters”.
- f. Beep.
- g. Vibration.
- h. None

3. How effective was that warning cue(s)?



4. Would you recommend this type of warning cue(s)?

Yes                      No

5. Why?



**B5: Modality-Specific Support for Comprehension and Projection Study (Part 1)- Post-training Assessment Form**

Subject ID: \_\_\_\_\_

Post-Training Assessment

- Please select the response that best describes the different flashing “Colored Letters” that was used during the experiment:

It was barely visible                      It was clearly visible

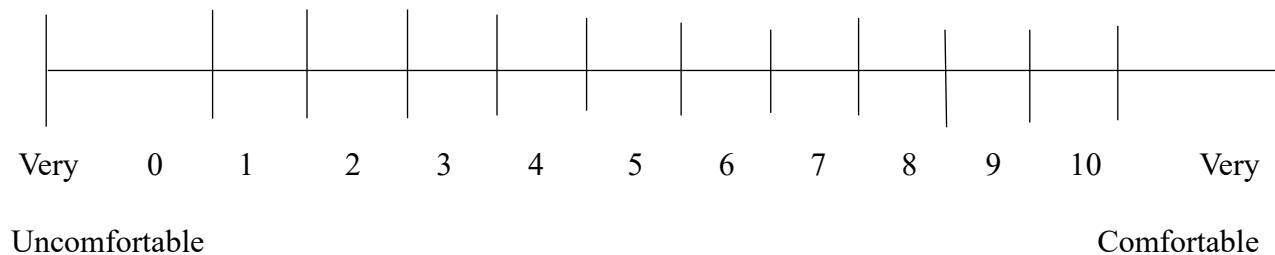
- How comfortable or uncomfortable were you when presented with the different flashing “Colored Letters”?



- Please select the response that best describes the auditory “beep” sound levels that was used during the experiment:

I could barely detect it                      I could easily detect it

- How comfortable or uncomfortable were you when presented with the different auditory “beep” sound levels?





## PARTICIPANTS NEEDED



### Purpose of study:

You are invited to participate in a study that will be carried out in a Lab. to determine which medium would be suitable to proffer comprehension to the supervisor of an autonomous agricultural machine during emergencies. The study should take no longer than one hour to complete.

### Role of participants:

You will be asked to do the following: (1). Conduct an internet search task to answer specific agronomic questions (on a screen) and then move focus to another computer monitor (where you will be informed about the statutory information of a simulated autonomous sprayer using different stimuli levels of various warning methods- visual, auditory and tactile) once you hear a notification sound. (2). You are to select the right choice of condition based on perceived warning from a list of possible conditions to acknowledge comprehension. (3). You will be presented a trial questionnaire and an end-of-experiment questionnaire to rank each warning mode(s) and give your personal experience during the entire experiment respectively.

### Inclusion/exclusion criteria:

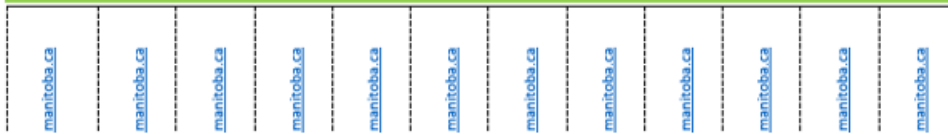
Potential participants must be willing to submit to auditory, visual and tactile screening with or without farming experience (specifically with the knowledge of spraying of fertilizer and herbicides) or tractor driving experience and also should be in the age bracket of 18-35 years old. Participants who are less than 18 years old or more than 35 years old would not be eligible. Also, participants with impaired vision and hearing would be ineligible.

### Contact Information:

Interested participants can email Anita (Principal Investigator): [ezeagbaa@myumanitoba.ca](mailto:ezeagbaa@myumanitoba.ca), Phone: [REDACTED] or Dr. Danny Mann (Advisor): [danny.mann@umanitoba.ca](mailto:danny.mann@umanitoba.ca) for more information.

This research has been approved by the Research Ethics Board at the University of Manitoba, Fort Garry Campus. If you have any concerns or complaints about this project, you may contact any of the above-named persons or the Human Ethics Coordinator at 204-474-7122, [humanethics@umanitoba.ca](mailto:humanethics@umanitoba.ca).

A \$25 UM bookstore gift card will be provided as honorarium.



## B7: Modality-Specific Support for Comprehension and Projection Study (Part 2)- Consent Form

Assessment of Warning Modalities for Remotely Supervised Autonomous Agricultural Machines: Experiment III.

### Principal investigator:

**Anita Eze**  
Ph.D. student  
Dept. of Biosystems Engineering  
University of Manitoba

### Advisor:

**Danny Mann**, Ph.D., P.Eng.  
Professor and Head  
Dept. of Biosystems Engineering  
University of Manitoba

Phone: 204-474-7966  
Email: ezeagbaa@myumanitoba.ca.

Phone: 204-474-7149  
Email: Danny.Mann@umanitoba.ca.

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**This consent form, a copy of which will be left with you for your records and reference, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. Please take the time to read this carefully and to understand any accompanying information. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask.**

---

**RESEARCH OBJECTIVE:** The purpose of this study is to determine which warning modality would be most suitable to convey projection of future status to the supervisor of an autonomous agricultural machine during emergencies. The study should take no longer than two hours to complete.

**RESEARCH PROCEDURE:** Before you begin the experiment, your visual, hearing and tactile abilities and comfort levels respectively, will be assessed. You will then be asked to conduct an internet search to answer specific agronomic questions (visible on a computer monitor) and then move focus to another computer monitor (where you will be informed about the statutory information of a simulated autonomous sprayer using different stimuli levels of various warning methods- visual, auditory and tactile) once you hear a notification sound. An SMI eye tracking device will be worn to monitor your head/eye movement. During the experiment, you are expected to select the right choice of condition based on perceived warning from a list of possible conditions to acknowledge comprehension.

The experiment comprised of 3 trials which will be completed in one session. There are also three training trials to enable you to become familiar with the experiment. Each trial will adopt the warning modalities (visual, auditory and tactile) at the different stimuli levels to alert you and you are expected to select the right choice of condition based on perceived warning from a list of possible conditions to acknowledge level of a perceived urgency. At the end of each trial, you will be asked to share your experience by completing a trial questionnaire. After you have finished the session, you will be given an “end-of-experiment questionnaire” to comment on your overall experience.

The questions presented in this study are **NOT** intended to test your intellectual competence. They are only meant to gather your opinion with regards to the experiment.

**RISKS:** You will be exposed to physical stimuli such as; flashing light, loud sounds, and tactile stimulations. But the quantity and duration of exposure to these conditions during the experiment are below the allowable maximum recommended limits. However, there are scheduled breaks within sessions to minimize such discomfort. Nevertheless, if you indicate fatigue and/or discomfort during the experiment, you can either request for an unscheduled break or discontinue the experiment if it persists. Prior to the training session, you will be asked as part of the recruitment process while filling the Participant’s Information form if you have underlying

conditions that will predispose to sensitivity/reactions to: flashing light, loud sounds, or tactile indication (buzzing). If yes, you undertake the experiment at your own risk.

**COSTS:** Your participation in this study does **NOT** require any financial commitment on your part.

**COMPENSATION:** You will be offered a twenty-five-dollar UM bookstore gift card as honorarium upon receipt of your consent as compensation for your time.

**CONFIDENTIALITY:** Your personal information will be strictly confidential. It will not be cited nor used directly during analysis, publications or any presentation. In all cases, only group average or summary will be presented to protect your identity. To further ensure the safety of your information, only the principal investigator, Ms. Anita Eze will have access to your identifiable data while her supervisors, Dr. Danny Mann and Dr. Cheryl Glazebrook will have access to both your identifiable & coded/de-identifiable data. A password protected laptop will be used to access and analyze your information. All documents containing identifiable information will be store in a locked drawer of a secured filing cabinet while all de-identifiable information will be store in a second locked drawer of the same filing cabinet.

By December 2030, hard copies of this consent form, and other documents containing your personal information will be deleted or destroyed to protect your identity.

**DEBRIEFING:** A formal feedback will not be provided immediately after the experiment. However, the principal investigator will be willing to answer any questions that may arise. A summary of the study will be made available upon completion by December, 2023 to participants who will indicate interest by providing their email and mailing addresses at the end of this consent form.

**DISSEMINATION:** Results from this study will appear in a PhD thesis of the Department of Biosystems Engineering at the University of Manitoba as well as articles published through MSpace, in peer-reviewed scientific journals and conferences. The results will also be included in oral presentations that are open to the public. Some data and information from this study may be sent outside of the University of Manitoba to other researchers, organizations, or made publicly available. This is for further analysis, testing, as part of the research study, or a requirement by a granting agency or journal. Any information sent out of the University of Manitoba will not show your name or address, or any other identifiable personal information about you. However, despite efforts to keep your personal information confidential, absolute confidentiality cannot be guaranteed. Your personal information may be disclosed if required by law.

**WITHDRAWING:** Your participation in this study is voluntary. You are free to withdraw anytime you wish by notifying the principal investigator, and there are no consequences for withdrawing from the study. If you decide to withdraw from the study while in progress, the Principal Investigator, Ms. Anita Eze will delete all your data collected including those from the data

collection computer and any back-ups on hard drives. Once the study process is complete, it would not be possible to remove your data which is approximately by December, 2023 (withdrawal deadline).

---

Your signature on this form indicates that you have understood to your satisfaction, the conditions regarding your participation in this study and have given your consent. In no way does this waive your legal rights nor release the researchers, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time, and /or refrain from answering any questions you prefer to omit, without prejudice or consequence. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation.

The University of Manitoba may look at our research records to see that the research is being done in a safe and proper way.

**This research has been approved by the Research Ethics Board at the University of Manitoba, Fort Garry Campus. If you have any concerns or complaints about this project, you may contact any of the above-named persons or the Human Ethics Coordinator at 204-474-7122, [humanethics@umanitoba.ca](mailto:humanethics@umanitoba.ca).**

A copy of this consent form has been given to you to keep for your records and reference.

---

-----  
Participant Name: \_\_\_\_\_

Participant Signature: \_\_\_\_\_ Date: \_\_\_\_\_

Researcher Signature: \_\_\_\_\_ Date: \_\_\_\_\_

- Please, check the box and provide your email and/or postal address if you are interested to receive a summary of the findings of this research.

Email address: \_\_\_\_\_

Postal Address: \_\_\_\_\_

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**B8: Modality-Specific Support for Comprehension and Projection Study (Part 2)-  
Participant's Information Form**

Name: \_\_\_\_\_

Subject ID: \_\_\_\_\_

Participant's Information

**Instruction:** Please answer the questions below as honestly and accurately as possible. Circle the answer that best describes you. For questions with a blank, open responses are encouraged.

Participant's information:

1. Age?

18 - 24

25 - 30

31 - 35

2. Location of residence (Province/City)?

\_\_\_\_\_/\_\_\_\_\_

3. Did you previously live on a farm?

Yes

No

If yes, please indicate the number of years: \_\_\_\_\_

4. Have you ever operated an agricultural sprayer?

Yes

No

If yes, please indicate the number of years of experience: \_\_\_\_\_

5. Have you ever driven an agricultural tractor?

Yes

No

If yes, please indicate the number of years of experience: \_\_\_\_\_

6. Do you have any underlying condition that will predispose you to sensitivity/reactions to:  
flashing light, loud sounds, or tactile indication (buzzing)?

Yes

No

**B9: Modality-Specific Support for Comprehension and Projection Study (Part 2)- Trial Questionnaire**

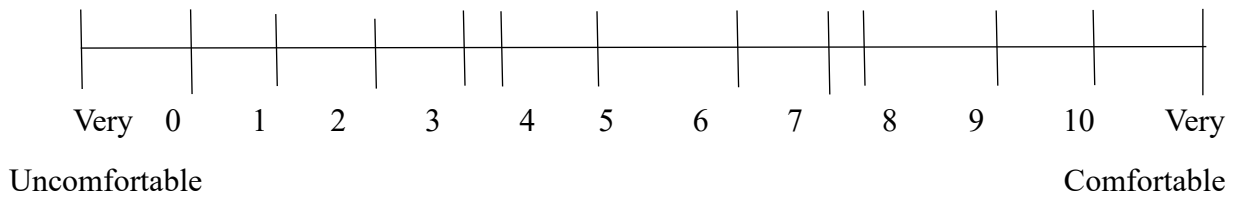
Trial Number: \_\_\_\_\_

Subject ID: \_\_\_\_\_

Trial Questionnaire

**Instruction:** Please circle the answer that best matches your opinion. Multiple responses are ONLY allowed in question 2.

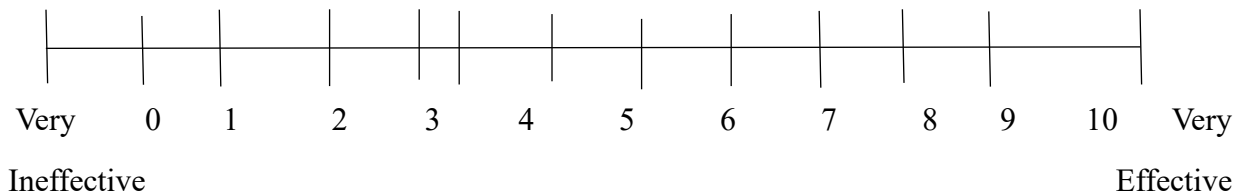
1. How comfortable or uncomfortable did you feel during the trial?



2. Overall, which warning cue(s) did you perceive during the trial?

- a. Flashing “Colored letters”.
- b. Beep.
- c. Vibration.
- d. None

e. How effective was that warning cue(s)?



f. Would you recommend this type of warning cue(s)?

- Yes
- No

g. Why?

Additional comments (if any):

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**B10: Modality-Specific Support for Comprehension and Projection Study (Part 2)- End-of-Experiment Questionnaire**

Subject ID: \_\_\_\_\_

**APPENDIX E: End-of-Experiment Questionnaire**

**Instruction:** Please answer the questions below as honestly and accurately as possible. Circle the answer that best describes your experience. For questions with blank spaces, written responses are encouraged.

4. Which warning cue would you recommend for remote supervision of an autonomous sprayer?

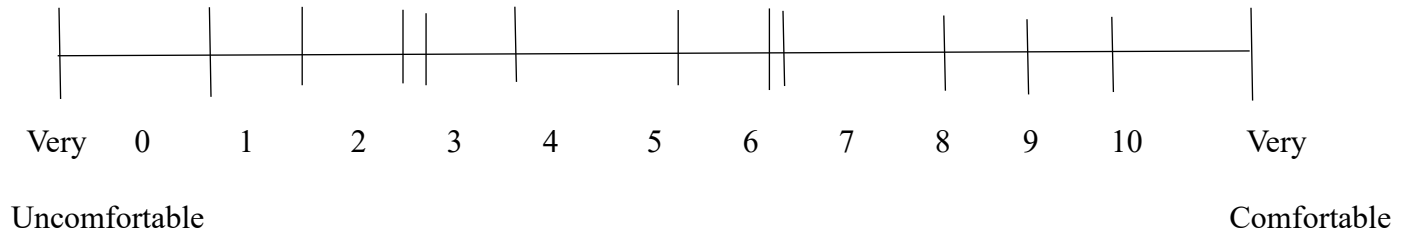
- f. Visual.
- g. Auditory.
- h. Tactile.

5. Why would you recommend this warning cue?

6. Do you have any suggestions that might be beneficial to this study?



- How comfortable or uncomfortable were you when you felt the different tactile vibration levels?



## B12: Modality-Specific Support for Comprehension and Projection Study (Part 2)- Recruitment Poster

PARTICIPANTS NEEDED

Department of Biosystem Engineering  
 E2-376 EITC  
 Winnipeg MB R3T 5V6  
 Canada

**Purpose of study:**  
 You are invited to participate in a study that will be carried out in a Lab. to determine which medium would be suitable to proffer comprehension to the supervisor of an autonomous agricultural machine during emergencies. The study should take no longer than two hours to complete.

**Role of participants:**  
 You will be asked to do the following; (1). Conduct an internet search task to answer specific agronomic questions (on a screen) and then move focus to another computer monitor (where you will be informed about the statutory information of a simulated autonomous sprayer using different stimuli levels of various warning methods- visual, auditory and tactile) once you hear a notification sound. (2). You are to select the right choice of condition based on perceived warning from a list of possible conditions to acknowledge level of perceived urgency. (3). You will be presented a trial questionnaire and an end-of-experiment questionnaire to rank each warning mode(s) and give your personal experience during the entire experiment respectively.

**Inclusion/exclusion criteria:**  
 Potential participants must be willing to submit to auditory, visual and tactile screening with or without farming experience (specifically with the knowledge of spraying of fertilizer and herbicides) or tractor driving experience and also should be in the age bracket of 18-35 years old. Participants who are less than 18 years old or more than 35 years old would not be eligible. Also, participants with impaired vision and hearing would be ineligible.

**Contact Information:**  
 Interested participants can email Anita (Principal Investigator): [ezearbaa@myumanitoba.ca](mailto:ezearbaa@myumanitoba.ca), Phone [REDACTED] or Dr. Danny Mann (Advisor): [danny.mann@umanitoba.ca](mailto:danny.mann@umanitoba.ca) for more information

This research has been approved by the Research Ethics Board at the University of Manitoba, Fort Garry Campus. If you have any concerns or complaints about this project, you may contact any of the above-named persons or the Human Ethics Coordinator at 204-474-7122, [humanethics@umanitoba.ca](mailto:humanethics@umanitoba.ca).

A \$25 UM bookstore gift card will be provided as honorarium.

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itoba.ca

**B13: Modality-Specific Support for Comprehension and Projection Study (Part 2)-  
Recruitment Email**

**Phase II: Comprehension of Warning Modalities for Remotely Supervised Autonomous  
Agricultural Machine.**

Hello Dr. XXX,

My name is Anita Eze, a PhD student from the department of Biosystems Engineering in the University of Manitoba. I am currently conducting a study that aim at determining which warning modality would be most suitable to convey projection of future status to the supervisor of an autonomous agricultural machine during emergency and need to recruit students in the Faculty of Agricultural Sciences to participate in the study. It is on this basis we want to request your assistance in disseminating the attached poster to your students.

This research has been approved by the Research Ethics Board in the University of Manitoba, Fort Garry campus and participants will be given a \$25 UM Bookstore gift card as compensation for taking part in this study.

Thanks for your cooperation and I look forward to hearing back from you.

Yours sincerely,

***Principal investigator:***

**Anita Eze**

Ph.D. Student

Dept. of Biosystems Engineering

University of Manitoba

Phone: 204-474-7966

Email:

ezeagbaa@myumanitoba.ca.

***Advisor:***

**Danny Mann, Ph.D., P.Eng.**

Professor and Head

Dept. of Biosystems  
Engineering

University of Manitoba

Phone: 204-474-7149

Email:

Danny.Mann@umanitoba.ca.

## 10. APPENDIX C: Chapter 5 STUDY MATERIALS

### C1: Usability Study- Consent form

Usability Evaluation of Warning Modalities for Remotely Supervised Autonomous Agricultural Machines.

***Principal investigator:***

**Anita Eze**  
Ph.D. student  
Dept. of Biosystems Engineering  
University of Manitoba  
Phone: 204-474-7966  
Email: ezeagbaa@myumanitoba.ca.

***Advisor:***

**Danny Mann, Ph.D., P.Eng.**  
Professor and Head  
Dept. of Biosystems Engineering  
University of Manitoba  
Phone: 204-474-7149  
Email: Danny.Mann@umanitoba.ca.

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**This consent form, a copy of which will be left with you for your records and reference, is only part of the process of informed consent. If you want more details about something mentioned here, or information not included here, feel free to ask any of the people named above. Please take the time to read this document and any accompanying information carefully. It is very important that you understand:**

- **What is being asked of you,**
- **What the risks and benefits of participation are, and**
- **How the information you provide will be used and stored.**

---

**PURPOSE OF THE STUDY:** The purpose of this study is to evaluate the usability and effectiveness of the warning interface for a remotely supervised prototype autonomous agricultural machine. Participants will be asked to provide feedback that will inform future design. The study should take no longer than one hour to complete.

**STUDY PROCEDURES:** Before you begin the experiment, your visual, hearing, and tactile abilities and comfort levels respectively, will be assessed. You will then be asked to conduct an internet search to answer specific agronomic questions (visible on a computer monitor) and then move focus to another computer monitor (where you will be informed about the statutory information of a simulated autonomous agricultural machine using combination warning methods-visual-auditory and visual-tactile). An SMI eye-tracking device will be worn to monitor your head/eye movement. During the experiment, you will be presented with various conditions of the operation of an autonomous agricultural machine using the warning methods and the study assessment will be focused on the overall layout of the warning interface in relation to its content, visibility, feedback, safety, and situation awareness.

The experiment comprised of 2 trials which will be completed in one session. Also, there are training trials to enable you to become familiar with the experiment. Each trial will adopt the warning methods (visual-auditory and visual-tactile) to alert you, and you are expected to select the right choice of condition based on perceived warning from a list of possible conditions to

acknowledge comprehension. At the end of each trial, you will be asked to share your experience with the warning interface by completing a computer system usability questionnaire (CSUQ). After you have finished the session, you will be given an “end-of-session questionnaire” to comment on your overall experience.

The questions presented in this study are **NOT** intended to test your intellectual competence. They are only meant to gather your opinion with regards to the warning interface.

**STUDY RISKS:** You will be exposed to physical stimuli such as; flashing lights, loud sounds, and tactile stimulations. But the quantity and duration of exposure to these conditions during the experiment are below the allowable maximum recommended limits (Human Body Vibration Guidelines- ISO 2631 and Acoustics – Noise emitted by machinery and equipment [ISO 11204:2010]). Furthermore, there are scheduled breaks within sessions to minimize such discomfort. Nevertheless, if you indicate fatigue and/or discomfort during the experiment, you can either request an unscheduled break or discontinue the experiment if it persists. Prior to the training session, you will be asked as part of the recruitment process while filling the Participant’s Information form if you have underlying conditions that will predispose to sensitivity/reactions to flashing light, loud sounds, or tactile indication (buzzing). If yes, you undertake the experiment at your own risk.

**STUDY BENEFITS:** The research will give the participants a better understanding about the idea of how autonomous agricultural machines can be employed when they become commercially available. Also, the research will expose participants to various means for receiving feedback from an autonomous agricultural machine.

**COMPENSATION:** You will be offered a twenty-five-dollar Tim Hortons gift card as an honorarium upon receipt of your consent as compensation for your time. We may collect additional personal information from you to record giving you an honorarium. The researchers will keep this information separate from any research information. This information will be kept in a secure location for 7 years in case the University of Manitoba has to account for the money during a financial audit.

**STORAGE AND USE OF DATA:** All the information you provide as part of this study is confidential. This means that only members of the research team will see your information. For safety, your information will be kept on a UM-approved secure platform. It will not be cited nor used directly during analysis, publications, or any presentation. In all cases, only the group average or summary will be presented to protect your identity. To further ensure the safety of your information, only the principal investigator, Ms. Anita Eze and her supervisors, Dr. Danny Mann and Dr. Cheryl Glazebrook will have access to both your identifiable & coded/de-identifiable data. A password-protected laptop will be used to access and analyze your information. All documents containing identifiable information will be stored in a locked drawer of a secured filing cabinet while all de-identifiable information will be stored in a second locked drawer of the same filing

cabinet. By December 2032, hard copies of this consent form, and other documents containing your personal information will be deleted or destroyed to protect your identity.

At the end of this document, you will have a chance to tell us whether you will allow your information to be shared outside of the University of Manitoba. Your information may be shared with researchers outside of the University of Manitoba; shared with other organizations; made publicly available. The information is being shared for further analysis or testing; as part of the research study; because it is required by a funder or journal. It will not include your name or any information that could identify you.

**DISSEMINATION:** Results from this study will appear in a PhD. thesis of the Department of Biosystems Engineering at the University of Manitoba as well as articles published through MSpace, in peer-reviewed scientific journals and conferences. The results will also be included in oral presentations that are open to the public. Some data and information from this study may be sent outside of the University of Manitoba to other researchers, organizations, or made publicly available (through a granting agency or scientific journal). To maintain confidentiality, your individual information will not be cited nor used directly during analysis, publications or presentation. In most circumstances, only average or summary information will be presented, but that an alphanumeric system (e.g., P1, P2, P3, etc.) will be used if it is necessary to discuss individual results. However, despite efforts to keep your personal information confidential, absolute confidentiality cannot be guaranteed. Your personal information may be disclosed if required by law. A formal feedback will not be provided immediately after the experiment. However, the principal investigator will be willing to answer any questions that may arise. A summary of the study will be made available upon completion by June, 2025 to participants who will indicate interest by providing their email addresses at the end of this consent form.

**WITHDRAWING:** Your participation in this research is voluntary. You can choose to do only the activities and/or answer only the questions that you are comfortable with. You may withdraw from the study for any reason. You do not have to explain why. You will not be penalized in any way. You may withdraw from the study until June, 2025. Should you withdraw, all gathered responses will be destroyed. After this date, we will start to analyze the information so it may not be possible to withdraw your information. To withdraw, please contact the Principal Investigator, Ms Anita Eze at the phone number or email above.

**QUESTIONS OR CONCERNS:** A designated University of Manitoba auditor may check that this study is being done safely and properly. To do this, they may visit the study site or review the research records. We will tell you if someone outside the research team will be there while you are participating. If this makes you uncomfortable, please tell the Principal Investigator, who will ask the auditor to return at another time.

**This study has been reviewed and approved by the Research Ethics Board at the University of Manitoba, Fort Garry Campus. However, this does not mean that participation is risk-free. If you have any questions or concerns, or complaints about this study, you may contact any members of the research team listed on the first page or the office of Human Research Ethics at [humanethics@umanitoba.ca](mailto:humanethics@umanitoba.ca) or 204-474-7122.**

**CONSENT:**

By signing this document, I have read the above information and have had the opportunity to ask and have answered any questions I may have.

I understand that:

- I will be taking part in a research study.
- I may freely leave the research study activities at any time.
- I do not waive my legal rights by participating in the study.

Please review the following statements. For each statement, please check if you agree or do not agree.

I agree to participate in this study.	<input type="checkbox"/> YES	<input type="checkbox"/> NO
---------------------------------------	------------------------------	-----------------------------

I agree to have (check one): <input type="checkbox"/> a general descriptor used instead of my name when results are shared for this study.
---

I agree that the information I provided to the research team can be used for future research purposes by members of this study’s research team and/or their students.	<input type="checkbox"/> YES	<input type="checkbox"/> NO
I agree that the information I provided to the research team can be share with or used by other researchers, funders, research or community organizations, journals, or other third parties for any future research purposes <b>only if anonymized.</b>	<input type="checkbox"/> YES	<input type="checkbox"/> NO

I agree to be contacted by a member of this research team for future phases related to this research study.	<input type="checkbox"/> YES	<input type="checkbox"/> NO
If yes, please provide an email address: _____		
By agreeing to be contacted, you are not required to participate in any future phases. If you wish to withdraw your name from this list, please contact Ms. Anita Eze- <a href="mailto:ezeagbaa@myumanitoba.ca">ezeagbaa@myumanitoba.ca</a>		

If I choose to withdraw partway through the study, I agree that the research team may still include the responses I have completed in their analysis.	<input type="checkbox"/> YES <input type="checkbox"/> NO
---	--

\_\_\_\_\_

\_\_\_\_\_

Name of Participant

Participant's Signature

Date

I read and explained all of the information in this consent form to the participant before receiving the participant's consent, and the participant had knowledge of its contents and appeared to understand it.

\_\_\_\_\_

\_\_\_\_\_

Name of Participant

Researcher's Signature

Date

**SUMMARY OF RESULTS:** Please provide an email address below if you would like to be sent a summary of the results and/or my individual results.

Email address: \_\_\_\_\_

### **Notice Regarding Collection, Use, and Disclosure of Personal Information**

Your personal information is being collected under the authority of *The University of Manitoba Act*. The University of Manitoba is committed to preserving your right to privacy. The information you provide will be used by the University to support our research. Your personal information will not be used or disclosed for other purposes, unless permitted by *The Freedom of Information and Protection of Privacy Act* or *The Personal Health Information Act*. If you have any questions about the collection of personal information: Ph: 204-474-9462 or Email: [fippa@umanitoba.ca](mailto:fippa@umanitoba.ca)

### **C2: Usability Study- Participant's Information Form**

Name: \_\_\_\_\_

Subject ID: \_\_\_\_\_

#### **Participant's Information**

**Instruction:** Please answer the questions below as honestly and accurately as possible. Circle the answer that best describes you. For questions with a blank, open responses are encouraged.

**Participant's information:**

1. Age?

18 - 30          31 - 46          47 - 65

2. Location of residence (Province/City)?

\_\_\_\_\_ / \_\_\_\_\_

3. Do you work on a farm?

Yes          No

If yes, please indicate the number of years: \_\_\_\_\_

4. Have you ever driven an agricultural tractor?

Yes          No

If yes, please indicate the number of years of experience: \_\_\_\_\_

5. Do you have any underlying condition that will predispose you to sensitivity/reactions to:  
flashing light, loud sounds, or tactile indication (buzzing)?

Yes          No

**C3: Usability Study- Computer System Usability Questionnaire (CSUQ)**

Trial Number: \_\_\_\_\_

Subject ID: \_\_\_\_\_

Warning Cue: \_\_\_\_\_

The Computer System Usability Questionnaire		Strongly Agree							Strongly Disagree			
		1	2	3	4	5	6	7	NA			
1	Overall, I am satisfied with how easy it is to use this system.											
2	It is simple to use this system.											
3	I am able to complete my work quickly using this system.											
4	I feel comfortable using this system.											
5	It was easy to learn to use this system.											
6	I believe I became productive quickly using this system.											
7	The system gives error messages that clearly tell me how to fix problems.											
8	Whenever I make a mistake using the system, I recover easily and quickly.											
9	The information (such as online help, on-screen messages and other documentation) provided with this system is clear.											
10	It is easy to find the information I needed.											
11	The information provided with the system is effective in helping me complete my work.											
12	The organization of information on the system screens is clear.											
13	The interface of this system is pleasant.											
14	I like using the interface of this system.											
15	This system has all the functions and capabilities I expect it to have.											
16	Overall, I am satisfied with this system.											



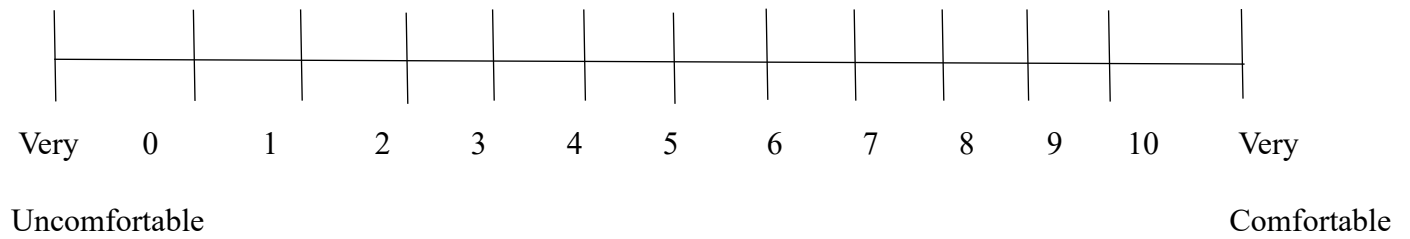


- Please select the response that best describes the tractor sound that was used during the experiment:

I could barely detect it

I could easily detect it

- How comfortable or uncomfortable did you feel hearing the tractor sound?



**C6: Usability Study- Recruitment Poster (Non-farming Group)**

## PARTICIPANTS NEEDED



**Purpose of study:**

You are invited to participate in a study that will be conducted in a Lab. to evaluate the usability and effectiveness of the warning interface for a remotely supervised prototype autonomous agricultural machine. The study should take no longer than one hour to complete.

**Role of participants:**

You will be asked to do the following: (1). Conduct an internet search task to answer specific agronomic questions (on a screen) and then move focus to another computer monitor (where you will be informed about the statutory information of a simulated autonomous machine using combination warning methods- visual-auditory and visual-tactile). (2). You are to select the right choice of condition based on perceived warning from a list of possible conditions to acknowledge comprehension. (3). You will be presented with a computer system usability questionnaire (CSUQ) and an end-of-session questionnaire to rank each warning mode(s) and give your personal experience during the entire experiment respectively.

**Inclusion/exclusion criteria:**

Potential participants must be willing to submit to auditory, visual and tactile screening in the age bracket of 18-35 years old. Participants who are less than 18 years old or more than 35 years old would not be eligible. Also, participants with impaired vision and hearing would be ineligible.

**Contact information:**

Interested participants can email Anita (Principal Investigator): [ezeagbaa@myumanitoba.ca](mailto:ezeagbaa@myumanitoba.ca), Phone: [REDACTED] or Dr. Danny Mann (Advisor): [danny.mann@umanitoba.ca](mailto:danny.mann@umanitoba.ca) for more information.

*This study has been approved by the Research Ethics Board at the University of Manitoba, Fort Garry Campus. If you have any concerns or complaints about this project, you may contact any of the above-named persons or the Human Ethics Coordinator at 204-474-7122, [humanethics@umanitoba.ca](mailto:humanethics@umanitoba.ca).*

A \$25 Tim Hortons gift card will be provided as honorarium.



### C7: Usability Study- Recruitment Poster (Farming Group)

## PARTICIPANTS NEEDED



**Purpose of study:**

You are invited to participate in a study that will be carried out in a Lab. to evaluate the usability and effectiveness of the warning interface for a remotely supervised prototype autonomous agricultural machine. The study should take no longer than one hour to complete.

**Role of participants:**

You will be asked to do the following: (1). Conduct an internet search task to answer specific agronomic questions (on a screen) and then move focus to another computer monitor (where you will be informed about the statutory information of a simulated autonomous machine using combination warning methods- visual-auditory and visual-tactile). (2). You are to select the right choice of condition based on perceived warning from a list of possible conditions to acknowledge comprehension. (3). You will be presented with a computer system usability questionnaire (CSUQ) and an end-of-session questionnaire to rank each warning mode(s) and give your personal experience during the entire experiment respectively.

**Inclusion/exclusion criteria:**

Potential participants must be willing to submit to auditory, visual and tactile screening with farming experience (i.e., individuals actively engaged in farming) should be in the age bracket of 18-65 years old. Participants who are less than 18 years old or more than 65 years old would not be eligible. Also, participants with impaired vision and hearing would be ineligible.

**Contact Information:**

Interested participants can email Anita (Principal Investigator): [ezeagbaa@myumanitoba.ca](mailto:ezeagbaa@myumanitoba.ca), Phone [REDACTED] or Dr. Danny Mann (Advisor): [danny.mann@umanitoba.ca](mailto:danny.mann@umanitoba.ca) for more information.

This research has been approved by the Research Ethics Board at the University of Manitoba, Fort Garry Campus. If you have any concerns or complaints about this project, you may contact any of the above-named persons or the Human Ethics Coordinator at 204-474-7122, [humanethics@umanitoba.ca](mailto:humanethics@umanitoba.ca).

**A \$25 Tim Hortons gift card will be provided as honorarium.**



### C8: Usability Study- Recruitment Email (Agricultural Students)

**To: Agricultural Students**

**Subject-** Study: Usability of Warning Cues... your opinion matters.

Hello Students,

Thank you for taking out time to read this email.

The Agricultural Ergonomics team in the Department of Biosystems Engineering, University of Manitoba is conducting a research to determine the effectiveness of a warning interface for remote supervision of a prototype autonomous (driverless) agricultural machine. To give the Agriculture students in the University of “Name” the opportunity to contribute to this advancement, you are

invited to participate in the study to assess the effectiveness of the interface. Your input will be highly appreciated.

The study should take no longer than an hour to complete and you will be offered \$CAD 25 Tim Hortons gift cards in appreciation for your time. You will be required to do the following; (1). Conduct an internet search task to answer specific agronomic questions (on a screen) and then move focus to another computer monitor (where you will be informed about the statutory information of a simulated autonomous machine using combination warning methods- visual-auditory and visual-tactile). (2). You are to select the right choice of condition based on perceived warning from a list of possible conditions to acknowledge comprehension. (3). You will be presented with a computer system usability questionnaire (CSUQ) and an end-of-session questionnaire to rank each warning mode(s) and give your personal experience during the entire experiment respectively.

The principal investigator is a graduate student completing her Ph.D. work and has received approval from the Research Ethics Board (REB) at the University of Manitoba to commence this research ([humanethics@umanitoba.ca](mailto:humanethics@umanitoba.ca); 204-474-7122). The risk involved in this study are no greater than in everyday life and it does not require any financial commitment on your part, and you are free to withdraw anytime you wish without any penalty.

Should you have any questions or concerns regarding this study, please feel free to contact us through any of the emails or phone numbers below.

Thank you in advance for your participation.

***Principal investigator:***

**Anita Eze**

Ph.D. student

Phone: 204-474-7966

Email:

[ezeagbaa@myumanitoba.ca](mailto:ezeagbaa@myumanitoba.ca)

***Advisor:***

**Danny Mann, Ph.D., P.Eng.**

Professor and Head

Phone: 204-474-7149

Email:

[Danny.Mann@umanitoba.ca](mailto:Danny.Mann@umanitoba.ca)

## CONTACT GROUP

Below is a list of the intended universities that was contacted:

**Universities:**

Assiniboine Community College, Brandon

University of Manitoba, Winnipeg

## **C9: Usability Study- Recruitment Email (Farmer Associations)**

**To: Farmer Associations**

**Subject-** Study: Usability of Warning Cues... your opinion matters.

Hello members,

Thank you for taking out time to read this email.

The agricultural ergonomics team in the Department of Biosystems Engineering, University of Manitoba is conducting a research to determine the effectiveness of a warning interface for remote supervision of a prototype autonomous (driverless) agricultural machine. To give members of “**Name**” the opportunity to contribute to this advancement, you are invited to participate in the study to assess the effectiveness of the interface. Your input will be highly appreciated.

The survey should take no longer than an hour to complete and you will be offered \$CAD 25 Tim Hortons gift cards in appreciation for your time. You will be asked to do the following; (1). Conduct an internet search task to answer specific agronomic questions (on a screen) and then move focus to another computer monitor (where you will be informed about the statutory information of a simulated autonomous machine using combination warning methods- visual-auditory and visual-tactile). (2). You are to select the right choice of condition based on perceived warning from a list of possible conditions to acknowledge comprehension. (3). You will be presented with a computer system usability questionnaire (CSUQ) and an end-of-session questionnaire to rank each warning mode(s) and give your personal experience during the entire experiment respectively.

The principal investigator is a graduate student completing her Ph.D. work and has received approval from the Research Ethics Board (REB) at the University of Manitoba to commence this research ([humanethics@umanitoba.ca](mailto:humanethics@umanitoba.ca); 204-474-7122). The risk involved in this survey are no greater than in everyday life and it does not require any financial commitment on your part, and you are free to withdraw anytime you wish without any penalty.

Should you have any questions or concerns regarding this survey, please feel free to contact us through any of the emails or phone numbers below.

Thank you in advance for your participation.

***Principal investigator:***

**Anita Eze**

Ph.D. student

Phone: 204-474-7966

Email:

[ezeagbaa@myumanitoba.ca](mailto:ezeagbaa@myumanitoba.ca)

***Advisor:***

**Danny Mann, Ph.D., P.Eng.**

Professor and Head

Phone: 204-474-7149

Email:

[Danny.Mann@umanitoba.ca](mailto:Danny.Mann@umanitoba.ca)

## **CONTACT GROUP**

Below is a list of the intended farmers' associations that was contacted:

### **Farmers organizations:**

Manitoba Corn Growers Association

Manitoba Canola Growers

Keystone Agricultural Producers

Western Winter Wheat Initiative

Western Canadian Wheat Growers

### **C10: Usability Study- Recruitment Email (Social Media)**

#### **Social media communication:**

Hello,

We are a research group at the University of Manitoba, Winnipeg, MB, Canada, that focuses on providing safe and comfortable agricultural machines and working environments for farmers. We are currently conducting a study to assess the effectiveness of a warning interface for driverless Agricultural machines – which is why we need your assistance to help us share/retweet the message. The study should take no longer than an hour to complete and participants would be offered \$CAD 25 Tim Hortons gift cards in appreciation for their time.

The participants will be asked to do the following; (1). Conduct an internet search task to answer specific agronomic questions (on a screen) and then move focus to another computer monitor (where you will be informed about the statutory information of a simulated autonomous machine using combination warning methods- visual-auditory and visual-tactile). (2). Select the right choice of condition based on perceived warning from a list of possible conditions to acknowledge comprehension. (3). Presented with a computer system usability questionnaire (CSUQ) and an end-of-session questionnaire to rank each warning mode(s) and give your personal experience during the entire experiment respectively.

There is no financial commitment, and participants can exit the study anytime without any penalty.

Thanks for your cooperation

#### ***Principal investigator:***

**Anita Eze**

Ph.D. student

Phone: 204-474-7966

Email: [ezeagbaa@myumanitoba.ca](mailto:ezeagbaa@myumanitoba.ca)

**Social media post:**

We're looking for experienced farmers and custom operators who will assess the effectiveness of a warning interface for driverless Agricultural machines.

The survey should take no longer than an hour to complete and you will be offered \$CAD 25 Tim Hortons gift cards in appreciation for your time.

**SOCIAL MEDIA CONTACT**

Below is a list of the social media groups that was contacted to share or tweet our study:

Farms.com Agriville

MB Corn Growers association

Manitoba Pulse growers

Manitoba Flax Growers association

MB Farm Journal

**11. APPENDIX D: Ethics Certificate**

**D1: TCP2- Core Certificate**



## *Certificate of Completion*

*This document certifies that*

**Anita Eze**

*has completed the Tri-Council Policy Statement:  
Ethical Conduct for Research Involving Humans  
Course on Research Ethics (TCPS 2: CORE)*

007914721

Date of Issue: 24 October, 2021

**D2: PHIA Certificate**



## 12. APPENDIX E: Approval of Studies

### E1: Perception Study Approval



AMENDMENT APPROVAL

March 28, 2023

Principal Investigator: Anita Eze  
Advisor: Daniel Mann, Cheryl Glazebrook  
Protocol Number: HE2022-0323  
Protocol Title: *Assessment of warning modalities for remotely supervised autonomous agricultural machines*

Andrea L Szwajcer, Chair, REB2

Research Ethics Board 2 has reviewed and approved your Amendment Request submitted on March 21, 2023 to the above-noted protocol. The Human Ethics Office (HEO) is constituted and operates in accordance with the current *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans- TCPS 2 (2022)*.

This approval is subject to the following conditions:

- i. Approval is granted for this amendment only.
- ii. Any further changes to the protocol require subsequent amendment approvals from the HEO before implementation.
- iii. Any deviations to the research or adverse events must be reported to the HEO immediately through an REB Event.
- iv. Amendment Approvals do not change the protocol expiry date. Please refer to the original Protocol Approval or subsequent Renewal Approvals for the protocol expiry date.

**E2: Modality-Specific Support for Comprehension and Projection Study (Part 1) Approval**



**PROTOCOL APPROVAL**

Effective: October 3, 2023

Expiry: October 2, 2024

Principal Investigator: Anita Chidera Eze  
Advisor(s): Daniel Mann, Cheryl Glazebrook  
Protocol Number: HE2023-0262  
Protocol Title: *Comprehension of warning modalities for remotely supervising autonomous agricultural machines*

Cameron Hauseman, Acting Chair, REB2

Research Ethics Board 2 has reviewed and approved the above research. The Human Ethics Office (HEO) is constituted and operates in accordance with the current *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans- TCPS 2 (2022)*.

This approval is subject to the following conditions:

- i. Approval is granted for the research and purposes described in the protocol only.
- ii. Any changes to the protocol or research materials must be approved by the HEO before implementation.
- iii. Any deviations to the research or adverse events must be reported to the HEO immediately through an REB Event.
- iv. This approval is valid for one year only. A Renewal Request must be submitted and approved prior to the above expiry date.
- v. A Protocol Closure must be submitted to the HEO when the research is complete or if the research is terminated.
- vi. The University of Manitoba may request to audit your research documentation to confirm compliance with this approved protocol, and with the UM *Ethics of Research Involving Humans* [Ethics of Research Involving Humans](#) policies and procedures.

**E3: Modality-Specific Support for Comprehension and Projection Study (Part 2) Approval**



AMENDMENT APPROVAL

December 8, 2023

Principal Investigator: Anita Chidera Eze  
Advisor(s): Daniel Mann, Cheryl Glazebrook  
Protocol Number: HE2023-0262  
Protocol Title: *Comprehension of warning modalities for remotely supervising autonomous agricultural machines*

Cameron Hauseman, Acting Chair, REB2

Research Ethics Board 2 has reviewed and approved your Amendment Request submitted on December 4, 2023 to the above-noted protocol. The Human Ethics Office (HEO) is constituted and operates in accordance with the current *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans- TCPS 2 (2022)*.

This approval is subject to the following conditions:

- i. Approval is granted for this amendment only.
- ii. Any further changes to the protocol require subsequent amendment approvals from the HEO before implementation.
- iii. Any deviations to the research or adverse events must be reported to the HEO immediately through an REB Event.
- iv. Amendment Approvals do not change the protocol expiry date. Please refer to the original Protocol Approval or subsequent Renewal Approvals for the protocol expiry date.

**E4: Usability Study Approval**

**PROTOCOL APPROVAL**

Effective: November 20, 2024

Expiry: November 19, 2025

Principal Investigator: Anita Eze  
Advisor(s): Danny Mann, Cheryl Glazebrook  
Protocol Number: HE2024-0276  
Protocol Title: *Usability Evaluation of Warning Cues for Remotely Supervised Autonomous Agricultural Machines.*

Liz Millward, Chair, REB2

Research Ethics Board 2 has reviewed and approved the above research. The Office of Human Research Ethics (OHRE) is constituted and operates in accordance with the current *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans- TCPS 2 (2022)*.

Please note the following important information about your protocol approval:

- i. Approval is granted for the research and purposes described in the protocol only.
- ii. Any changes to the protocol or research materials must be approved by the OHRE **before implementation**.
- iii. Any deviations to the research or adverse events must be reported to the OHRE immediately through an **REB Event**.
- iv. This approval is valid for **one year only**. A Renewal Request must be submitted and approved prior to the above expiry date.
- v. A **Protocol Closure** must be submitted to the OHRE when the research is complete or if the research is terminated.
- vi. The University of Manitoba may request to audit your research documentation to confirm compliance with this approved protocol, and with the UM [Ethics of Research Involving Humans](#) policies and procedures.