Enhancing Physical Human Evasion of Moving Threats Using Tactile Cues

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***Abstract*—New human-centric approaches to safety can combine over-head camera views with situational awareness tools to enable humans to avoid rapidly evolving threats such as moving machines or falling debris. This paper explores how 360º information can be used to inform humans of potential collisions. Specifically, we quantify how different individual (tactile, audio, and visual) and combined cue modalities affect failure rates and reaction times. Human-subject experiments were conducted in a custom virtual reality environment that simulates objects rapidly moving toward the subject. In order to successfully perform their task, the human subject must physically move their body out of the path of the moving threat before a collision occurs. This exploration of full body physical response differentiates this work from previous related studies. The results of the 18-subject study provide quantified data on a range of cues and cue combinations. The study quantified failure rates and reaction times as a function of index of difficulty (Fitt's Law) and threat directionality. The results confirm the hypothesis that the addition of tactile cues statistically improve performance compared to non-tactile cues with regards to failure rate and reaction time. This demonstrates how sensory cues can improve human physical response to rapid threats.**

***Index Terms*—tactile feedback, situational awareness, virtual reality, sensory augmentation, human-machine communication.**

I. INTRODUCTION

A. Overview

The unstructured and dynamic nature of many environments such as construction zones, busy factory floors, and disaster sites create risks of collisions between human operators and other objects/systems. In addition, the growing interaction between humans and robots presents similar risks to human safety. To ensure safety, many industries currently physically separate personnel from areas of risk. While this is effective, it can reduce efficiency and restricts the types of tasks that can be performed.

The growth in machine vision technologies and mobile systems means that the area around human workers can now be monitored [1]. Broad coverage of the human workspace can potentially detect impending collisions between humans and moving objects (robots, tools, falling objects). However, utilizing this information to rapidly assist human operators

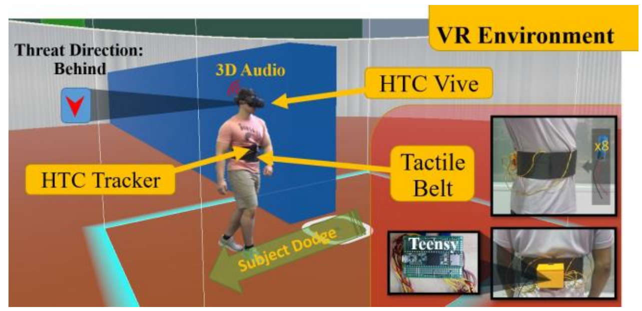

Fig. 1. Subject in custom Virtual Reality (VR) game receives audio, tactile, and visual cue of an oncoming threat from behind and physically moves to evade it. On the right is the adjustable tactile belt used.

remains a relatively unexplored area. With this human-centered approach, it is important to understand how moving threat information can be effectively communicated, and situational awareness increased, in order to elicit a rapid physical escape response. Situational awareness is defined as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future [2]. In this work, we consider how 360º threat information can be rapidly communicated to a human subject in order to enable them to successfully avoid a collision. We study tactile, visual, and audio modalities. We are particularly interested in the performance of tactile cues because there are many environments where visual or audio cues may be relatively ineffective. For example, many tasks such as driving or visual inspection are already visually taxing. Target fixation, for example, can prevent the recognition of important visual information [3]. Similarly, environments with noise may be ill-suited for audio cues. Humans operating in dangerous environments often utilize tactile methods [4].

This work differs from previous similar works on tactile communication and situational awareness, which have primarily focused on (1) communicating static scene information for navigation [5-7] or (2) using multisensory cues to enable better control over vehicles [8-10]. In contrast, our work seeks to understand which cue modalities and combinations can provide the most effective physical escape response in the presence of rapidly moving threats. We focus on two quantitative metrics: reaction time and failure rate. Moreover, threat variation and subject response are characterized with an adjusted index of difficulty [11], which elucidates the effect of threat size and

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speed on human subject performance. **The core contribution of this work is quantification of reaction time and failure rates of different sensory cue modalities and combinations of modalities during physical escape maneuvers.** Specifically, we find that the addition of tactile cues provided the largest statistically significant reductions to reaction times (by 74.4 ms) and failure rates (by 10.8%) when examining aggregated data compared to not using tactile cues.

B. Prior Work

Enhanced situational awareness via sensory cues has been studied extensively for control of military systems, cars and remote systems. Furthermore, many studies involving different sensory cues have primarily focused on reaction times [4-10, 11-25]. However, these studies did not elicit dynamic whole-body physical responses. Instead, they relied on manual human inputs to electro-mechanical control systems. These studies showed, in general, that in single-choice and multiple-choice tasks, the lowest reaction times are evoked with tactile information over visual and audio.

These prior studies on situational awareness do not directly address how to assist human subjects in the presence of dynamic physical threats. Physical evasion motions are inherently different from controlling robots or vehicles. This is because a physical escape response requires multiple joint coordination patterns. Previous work has only considered initiating upper limb movements, but escape maneuvers rely on lower limb joint coordination. For example, directional dependency has been characterize for upper limbs but has not been examined for lower limbs [26]. Moreover, Lower limb mechanics are known to have varying neurological response and reflexive times [27].

Since we are interested in the ability to avoid dynamic objects, we define failures as cases where the simulated object collides with the human. We define reaction times as the time to initiate a motion after a cue is sent to the human. Based on these definitions, and our review of the existing literature, we formulated two hypotheses. The first hypothesis is that the average failure rate will be reduced when tactile cues are introduced. The second hypothesis is that reaction times will be reduced when adding tactile cues. These hypotheses are tested through rigorous physical experiments on human subjects in a custom virtual reality environment.

II. Experimental Methods

A. VR Based Quantitative Dynamic Environment

Virtual Reality is an ideal experimental environment for research into dynamic threat avoidance. Large, rapid, virtual threats can be simulated without any physical danger to the subject. In addition, this approach can limit variability apart from subject ability/performance. Our VR environment enables the ability to change cues seamlessly and vary the difficulty in trials to look for statistical differences in reaction time and failure rate among cue modes. A Unity based environment was created consisting of a floor, a cylinder representing the subject, a circular wall (which hides the exact initial location of threats, radius of 10m), and eight threats represented by long walls. Walls were used as threats as it requires the subject to completely step and ambulate to safety instead of ducking or swaying out of the way. Subjects interfaced with the environment via a HTC Vive headset and HTC tracker (located approximately on Xiphoid Process for center of mass tracking).

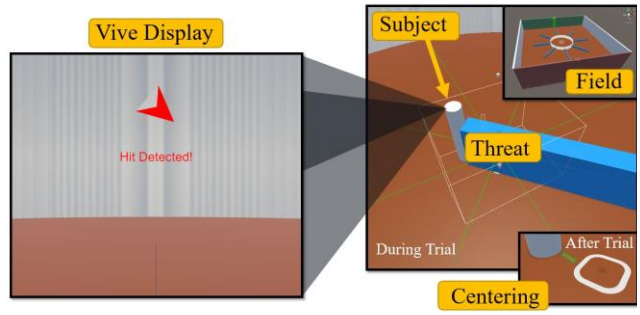

Fig. 2. Virtual reality game example. The subject, aided by the visual cue, has unsuccessfully dodged and will come back to center when the object resets.

Each time a threat was activated, the subject was instructed to dodge to the best of their ability, then return and place their body (cylinder) inside of a painted marker on the ground to center themselves. They received a visual readout informing them once centered. If the dodge was unsuccessful, the subject was notified that they were hit. Subjects were not instructed on how to dodge (i.e. taking one step or multiple steps), but the majority would take single steps to avoid collision. Tracking data was collected at 90 Hz and a low pass filter (at 15 Hz) is applied to the raw velocity data.

B. Perceptual Modality Implementation

While we propose the use of audio, tactile and visual cues there are many different types of each. A wealth of previous research has investigated different perceptual modalities as a means of communicating information quickly to reduce reaction time and/or inform a direction [4-10, 11-25].

Previous work explored reaction time to tactile stimulation of the torso, finger, wrist, forearm, tongue, and head [12-17]. The torso has been identified as an ideal location for tactile feedback for its sensitivity and adaptability in comparison to the forearm [17]. Lower limbs were not considered an option as we wanted to avoid hindering movement. To minimize reaction time associated with tactile cues, we designed a custom tactile belt with eight motors positioned at the cardinal and intercardinal directions. The belt is rapidly adjustable as motors are secured in position with hook-and-loop fastening on the inside of the belt (Fig. 1). The belt uses counterweight cylindrical 3VDC 12000 RPM Parallax vibrational motors, and is controlled by a Teensy 3.6 microcontroller and tethered to the VR computer (Fig. 1) which dispatches commands. Vibrations cycle off and on (for equal time) at 2 Hz in the direction of the moving threat. A small ($n = 3$) subject experiment was done to determine the angular accuracy of the tactile communication. Subjects were able to move in a specific direction within 7.12 degrees (standard deviation of 4.4 degrees and median of 4.9 degrees). Since this study focuses on dodging objects rather than precise navigation, this error was within tolerance for our experiments.

It is known that increasing the volume of a sound decreases reaction time [18], however, due to discrepancies in subject audio sensitivity we let subjects adjust the volume level within a tolerance. Adjustment was done starting at a known noticeable threshold of 80 dB and subjects could request an increase up to 85 dB. This hard maximum was set as the NIH has noted that exposure to noise above 85 dB can cause hearing loss [28]. 3D audio was selected over clock direction as it incites faster reaction times [19] and was more easily understood by our subjects than clock directions in pilot testing. The sound selected was a police siren originating from the threat with linear volume roll-off from 0.2 m to 11 m (note: threats were 10m at initiation) and Unity Doppler level of 0.5.

To minimize reaction time associated with visual cues, the location and nature of the visual signal were carefully considered. A top down view arrow selected for easy human interpretation [20]. Additionally, the color red has been seen to elicit the fastest reaction time [21, 22]. This red arrow points in the direction of the threat and activates once the threat starts moving. It is an overlay laterally centered and 10 degrees above the VIVE display's central point. Furthermore, the arrow dynamically rotates so the arrow points the correct direction even if the subject changes their head orientation. (Fig. 2). Previous work has identified alerts with some movement may be more effective [30]. Visual stimuli of longer duration elicit faster reaction times, the fastest reaction time occurs when stimuli are directly in the field of view rather than in the periphery (picked up by cones rather than rods) [29]. This leads the arrow to be placed not in the corner of the screen but the upper center (Fig. 2).

While visual and audio were simulated by the VR system, the tactile belt was validated per subject as the locations of the motors were adjusted based on the subject's torso. First a random series of motors were activated with repeats and the subject was to point in the direction of vibration once sensed. If hesitation was apparent or the direction wrong, the belt was adjusted until the subject no longer made mistakes. The tactile belt was then considered fitted.

While each modality may provide an advantage on its own, cross-modal benefits have also been show in previous literature [30] and are included in this research. Each modality was tuned in pilot studies to be clearly distinguishable from others and activated in unison when a threat was activated. Table 1 highlights the different cue types employed.

C. Experiment Procedure and Metrics

An experimental protocol was created and approved by the Georgia Tech Institutional Review Board (IRB H18363). Eighteen able-bodied subjects (thirteen males and five females) with an average (± standard deviation) age of 21.7 ± 2.7 years, body mass of 76.8 ± 22.4 kg, and height of 1.75 ± 0.23 m participated in this study. The number of required subjects was determined by an a priori matched pairs power analysis. After the subjects gave written, informed consent, subjects were placed in the virtual environment and oriented with the space (3 m x 3 m area). Subjects wore the tactile belt, HTC Vive headset and tracker. The experiment consisted of trial blocks with a different cue modality for each.

A trial block consisted of 27 trials which were combinations of nine threat directions (four cardinal, 4 intercardinal, and 1 null case with the threats front edge 10 m from the center of the game), three speeds (7 , 9, and 11 m/s) and three widths (0.1 m, 0.35 m, 0.5 m). The block ensured an even distribution of threat speed, width, and direction. The trial block values were randomized across subjects. However, for each subject, the trial block values were held constant but order randomized. This ensured that intra-subject comparisons were fair and had the same difficulty.

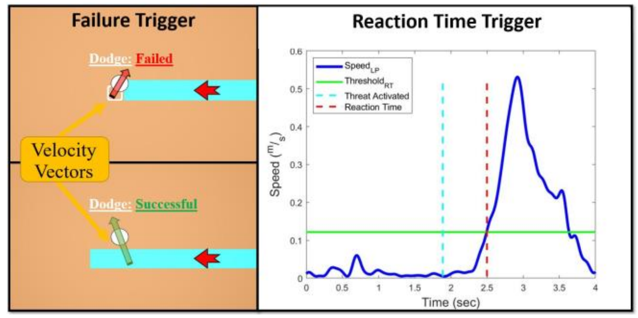

Fig. 3. Examples of the failure and reaction time triggers. The left panes represent a top down view of what a failed (A) and successful (B) maneuver looks like. The right pane details filtered velocity data from the subject's approximated center of mass location for the reaction time calculation.

At the beginning of each trial block, a training period was given to get the subject acclimated to the current cue modality [31]. The training period was held constant between trial blocks across subjects and longer than the actual trial block (~40 threats per training vs. 27 threats per trial). By the end of this period, the failure rate had reached a steady state, and subjects preceded to the recorded trial block. For each trial, the subject started at the center of the environment. Once the subject was centered and looking forward in a relaxed position, the next trial initiated a random threat at a random time between two to five seconds (random time was double blind). The subject attempted to dodge the threat to the best of their ability. Once the threat passed by, a failure or success was logged automatically and communicated to the subject. The subject then returned to the center of the environment for the next trial. After the trial block for a given cue was over, the subject had a two to three-minute break before beginning the next trial. While subjects were encouraged to take as many breaks as they need (to prevent reaction time fatigue [32]), a mandatory ten to fifteen-minute break was given after four back to back trial blocks.

The two primary metrics used in this study include the failure rate and reaction time. The failure rate was determined per trial block as the percent of the time the subject was hit by a threat. The reaction time was measured by subtracting the time the cue(s) were sent to the subject from the time the subject velocity exceeded a threshold. This threshold was determined to be when the filtered velocity exceeded two times the max filtered velocity of a waiting period (Fig. 3) before a threat is activated.

The cue combinations are denoted using letters. The control, which consists of no assistance for a forward-facing subject, is denoted using "C." Thus for this condition, only their own forward-facing visual feedback was available. Similarly, tactile-only (T), audio-only (A) and visual-only (V) are denoted with a single letter.

An additional metric that can be used to analyze the results is the index of difficulty, I_d. This is a metric that is often used to examine human performance. Fitt's law [11], originally designed to model pointing, has been applied to many physical movements [33-35]. However, it has not been applied to dynamic whole-body responses. Applying this framework to this research we adjust the original law:

$$I_d = -\log_2 \frac{W_s - \frac{w}{2}}{2s} \tag{1}$$

where s and w are the speed and width of the object and W_s is an offset. The target the subject aims to reach is the area out of the path of the object. The subject chooses one side to dodge toward so the lower bound of a safe dodge is the width of the object itself while the upper bound is dependent on the size of the VR area (in this case 1.5 m). Averaged across the trials, the index of difficulty was 3.72 ± 0.03.

D. Statistical Methods

To assess the normality of the data, Anderson-Darling tests were used on each individual cue distribution. To investigate for other aggregated statistical differences, two sets (failure rate and reaction time) of three pairwise Wilcoxon tests were performed. These tests included audio (A, AV, AT) vs. non-audio (T, V, TV) and analogous comparisons for tactile and visual (Fig. 4C and 4D). Control and ATV were removed from these groupings to reduce bias in testing. This method provides an aggregated comparison across conditions.

Additionally, two one-way repeated measures ANOVA tests were conducted for failure rate and reaction time. The post-hoc test was a pairwise two-sided t test with Bonferroni corrections with α = 0.05. Finally, for each of the nine indices of difficulty, ANOVA tests and accompanying post-hoc tests (analogous to those above) were conducted for failure rate.

III. Results

A. Failure Rates

Based on the aggregated data (Fig. 4C) for failure rate, audio was found to be statistically worse ($p<0.05$) than non-audio (failure rate increased by 7.7%). Visual provided a statistical advantage ($p<0.05$) over non-visual and decreased failure rate by 6.5%. Finally, tactile was statistically better ($p<0.05$) than non-tactile and provided the largest performance increase by reducing the failure rate by 10.8%.

The ANOVA and subsequent Bonferroni post-hoc testing across all cue modalities showed that all other cue conditions provided statistically significant ($F \approx 70.1$, $p<0.05$) lower failure rates when compared with audio. These tests also showed that any cue provided statistically significant ($p<0.05$) reductions in failure rate when compared with the control.

Examining the data in the context of direction (Fig. 5A) indicates that failure rate is dependent on direction and this asymmetry shows it is more difficult to escape threats approaching from the sides in comparison to those approaching from the front or behind.

B. Reaction Time

Based on the aggregated data (Fig. 4D) for reaction time, audio was found to be statistically worse ($p<0.05$) than non-audio as reaction time increased by 31.5 ms. Visual cue performance did not provide a statistical difference ($p=0.08$) in

TABLE I
PERCEPTUAL MODALITIES SUMMARY - 95% CONFIDENCE INTERVALS

Modality	Failure Rates (%)	Reaction Time (ms)
Control	79.40 ± 2.91	614.3 ± 92.8
Audio (A)	50.23 ± 6.62	561.9 ± 41.3
Tactile (T)	25.93 ± 5.51	414.7 ± 33.0
Visual (V)	27.78 ± 6.02	463.2 ± 47.0
A-T	26.62 ± 4.90	420.0 ± 35.7
A-V	32.18 ± 5.15	461.5 ± 34.0
T-V	24.77 ± 6.88	426.8 ± 49.9
A-T-V	26.39 ± 5.60	422.0 ± 40.1

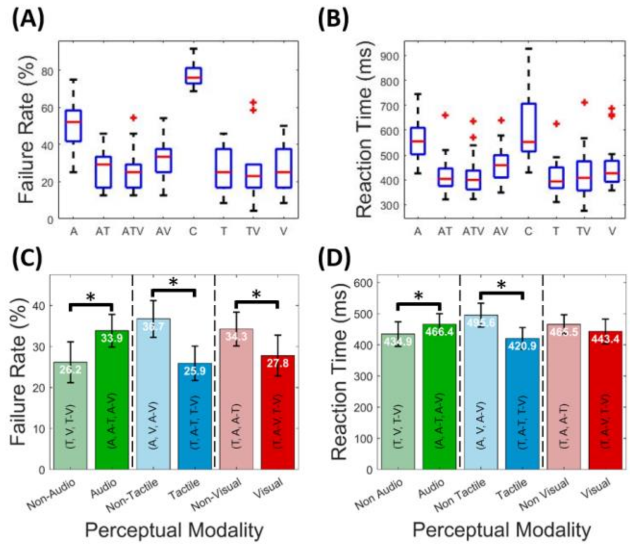

Fig. 4. Comparison of cue modality performance across subjects. The top row (A and B) shows box-and-whisker plots detailing comparisons of each condition of individual and combined cue modalities in terms of failure rate (A), and reaction time in ms (B). Red + marks denote outliers. The lower row aggregates data to include all conditions with and without a specific cue modality to represent the effect of each cue modality holistically across conditions. Aggregated data (cues in each bar's aggregation listed on bar plot) is shown across N=18 subjects for failure rate (C) and reaction time (D) in ms. Error bars represent 95% confidence intervals and stars (*) represent significant differences between not having or having a specific cue modality in C and D ($p<0.05$).

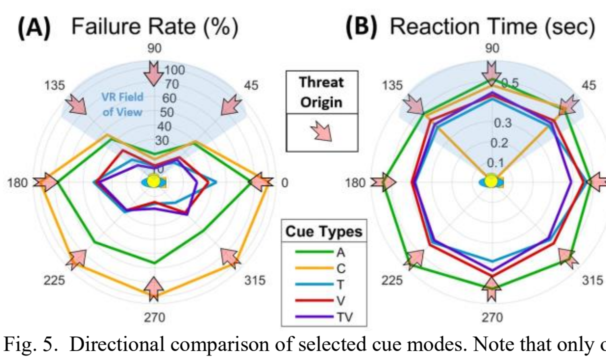

Fig. 5. Directional comparison of selected cue modes. Note that only one object was ever activated at one time. 90 degrees is the direction the subject is initially facing. This polar plot highlights the differences between failure rate (A) and reaction time (B) and their relationship to the threat's approaching direction. In both, only four conditions are displayed, missing conditions do not show any statistical difference (from T, V, TV) and are omitted.

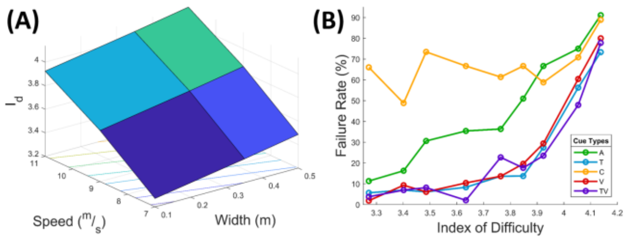

Fig. 6. Index of Difficulty. On the left (A) a contour plot shows the index of difficulty's relationship with speed and width. On the right (B), failure rates of certain cues are plotted against I_d. In (B), only four conditions are displayed, missing conditions do not show any statistical difference and are omitted.

reaction time compared to non-visual cues. Finally, tactile is statistically better ($p<0.05$) than non-tactile and provides the largest decrease in reaction time (74.4 ms).

The ANOVA and subsequent Bonferroni post-hoc testing across all cue modalities showed that all other cue conditions provided statistically significant ($F\approx22.2$, $p<0.05$) lower reaction times when compared with audio with the exception of visual only ($p\approx0.09$) and audio-visual cue conditions ($p\approx0.08$). Additionally, these tests also showed that all cue conditions provided statistically significant ($p<0.05$) reductions in reaction time when compared with the control.

Viewing the data in the context of direction (Fig. 5B) indicates that reaction time is fairly symmetric indicating no clear directional dependence.

C. *Index of Difficulty*

An index of difficulty contour for our experiments is displayed in Fig. 6A. This plot shows how index of difficulty is much more sensitive to speed than to width. Failure rates can be plotted against the index of difficulty, I_d, in order to examine how different cues fare with different difficulty levels. These results are shown in Fig. 6B. Difficulty indices between 3.3 and 3.4 provide qualitatively similar responses for all cue types. Between indices of 3.5 and 4.0, visual and tactile cues provide statically lower failure rates than audio ($p<0.05$). For indices above 4.0, all cue types exhibit similarly high failure rates with no noticeable statistical difference ($p>0.05$).

IV. Discussion

A. *Primary Metrics: Failure Rate and Reaction Time*

The aggregated comparisons confirmed our hypothesis that the addition of tactile cues would provide reduced failure rates and reaction times. In addition, we find that adding audio increased failure rate and reaction times compared to non-audio cues. Finally, visual cues while statistically significantly decreasing failure rate, it does not exhibit a statistical difference for reaction time. The best overall performance for both reaction time and failure rates for any single cue modality was tactile.

The Bonferroni post-hoc testing also showed that all cues reduced failure rates and reaction times when compared to the control. While the improvement of tactile (and other) cues versus the control would appear intuitive, the relative performance of tactile cues when compared with audio and visual cues is interesting. For example, tactile cues clearly outperformed the 3D audio even though the environment was largely bereft of external noise. 3D audio is known to have a "cone of confusion" where there is difficulty in determining directionally in the medial plane, especially, front and back directions [10]. Moreover, it is likely that 3D audio is difficult for untrained human subjects to translate rapidly and with high fidelity. Verbal direction commands may provide benefit, but are known to be slower with regards to reaction time [25].While trained pilots and military personal may be comfortable with a clock system, untrained civilians subjects are not.

Tactile cues provided a statistically significant benefit for reaction time while visual cues did not. The overall reduction in failure rates with tactile cues was also higher than with visual cues (10.8% vs. 6.5%). Visual cues are extremely common and widely utilized. The relative performance of tactile cues means that this method is a promising alternative when visual cues are unlikely to succeed. Visual cues suffer from several drawbacks that were not explored in this work. These include target fixation, and the heavy dependence on vision for performing many tasks. This study illustrates a set of conditions where tactile cueing should be considered a viable method alongside if not in place of visual cues to enable faster and higher fidelity response.

B. *Directionality*

The data provides other interesting insights into assisted dynamic escape behaviors. For example, Fig. 5 provides polar plots that graph the failure rate or reaction time against the relative angle of the incoming threat. Since the subject faces forward (90° on the plot) when starting the experiment, failure rates and reaction times are lowest within their visual field.

The plots in Fig. 5 clearly illustrate how different cues reduce failure rates relative to the control. The smallest shapes represent the best methods (T, V, and VT). Interestingly, the shapes for failure rate are not radially symmetric (although they are for reaction time). This is likely because single-step side to side motions are faster than single-step forward and back motions due to human limb dynamics of shifting the body's center of mass [27]. This result illustrates how failure rates are dependent on more than the ability to perceive the environment. The threat's direction clearly affects the failure rate, and this should be taken into account when determining escape paths and assessing risk.

C. *Index of Difficulty*

Using the index of difficulty and failure rates together, (Fig. 6B) we can understand how a particular threat (speed, width) should be relayed to the human operator. Additional ANOVA testing at each index of difficulty reviled that at low difficulty indices ($I_d < 3.5$) all modalities work similarly. Generally, at intermediate levels ($3.5 < I_d < 4.0$), the addition of tactile and visual cues provide a statistically significant benefit over audio. Finally, at high difficulty indices ($4.0 < I_d$), none of the methods studied here provide significant benefit. Threats that fall into this difficulty are too fast/large for humans to dodge with their current abilities. For tasks of such difficulty, additional methods such as earlier warning, exclusion areas, or physical assistance, may be required.

V. Conclusion

This work showed how tactile, audio, and visual cues (and combinations) can enhance the ability of human subjects to physically avoid collisions with moving objects. Tactile, audio, and visual cues provided statistically significant reductions in failure rates and reaction times when compared with the control. We also showed how the addition of tactile cues provided statistically significant reductions in both failure rate and reaction time.

The performance of tactile cues illustrates how such a modality can be used to increase human safety. Specifically, tactile cues provide a promising way of eliciting rapid and effective physical escape maneuvers. Since tactile cues performed slightly better than visual cues, they can serve as a complementary technique when the human operator is relying on vision for other important tasks.

Our results also provide quantitative data on all three cues, their combinations, and the index of difficulty of the trials. The index of difficulty illustrates how certain threats are well-tailored to tactile cues while others are too difficult. This provides quantitative methods for safety analysis and helps illustrate the complementary role of exclusion areas, speed limits, and physical assistance.

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