Influencing Human Escape Maneuvers with Perceptual Cues in the Presence of a Visual Task

Aakash Bajpai, Karen M. Feigh, Anirban Mazumdar, Aaron J. Young

***Abstract*—Visual engagement is common in many situations where human operators must perform tasks in challenging environments. This visual engagement has the potential to impact the safety of these operators when dealing with dynamic threats. Perceptual cues have been shown to elicit physical evasion maneuvers, thereby improving safety. In this paper, we investigated the effects of cues and visual engagement on rapid whole-body responses. The visual task, inspired by the Trail Making Test (TMT), served as a proxy for visual engagement in the real world. Our continuous TMT minigame and threat simulation were implemented in a virtual reality (VR) environment. Participants attempted to maximize their performance score by quickly solving TMTs and dodging dynamic threats from various in-plane directions. They were provided with no cues (control), visual cues, and vibrotactile cues indicating impending threat directions. Participant's ability to dodge threats was quantified by failure rate and reaction time for within field of view and all approach directions. An index of difficulty highlighted perceptual cue response sensitivity to varying threat speeds and sizes. This paper provides two core key contributions and other interesting findings. The results illustrated that (1) tactile cues enable statistically significantly better dodging rates than visual cues, or with human vision alone (control condition). The study also showed (2) visual engagement degraded human evasion performance in a statistically significant way. Finally, tactile cue responses appeared to be less sensitive than visual cues to visually engaging tasks within the higher portion of difficulty index range that was investigated.**

***Index Terms*—Human-machine communication, sensory augmentation, situation awareness, virtual reality.**

I. Introduction

A. Overview

HUMAN workers in dynamic environments are at risk of harm from collisions with physical objects. The Occupational Safety and Health Administration (OSHA) reports that struck-by hazards are one of the top four cases of construction fatalities in the United States [1]. Human safety in such environments can be improved by increasing situation awareness (SA). This can alert human workers of potential collisions before injury or fatality occurs. Perceptual cues enhance SA [2] by indicating key environmental information [3]. Auditory, tactile, and visual cues have been shown to

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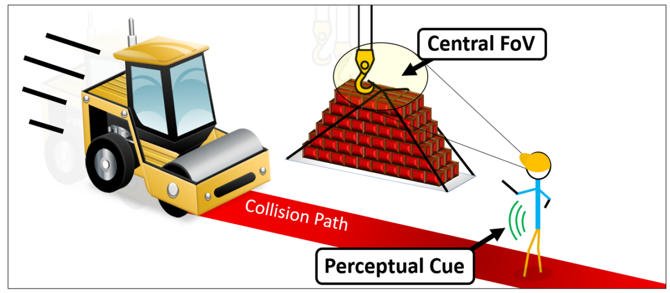

Figure 1: Visual engagement can prevent rapid response to impending threats. Perceptual cues can improve ability to dodge moving threats.

rapidly communicate this critical information [4]–[7]. Our previous work [7] explored how different perceptual cues can influence whole-body reaction time and improve safety. Results showed that the addition of tactile or visual cues to any cue combination, provides significant performance increases.

Relying on visual cues, however, may be problematic. In many cases, workers are visually engaged [8] (Figure 1). These demanding tasks saturate their visual cognitive loading [9]. Vigilance can be viewed as an attentional resource, and is therefore sensitive to varying processing demands [10]. Furthermore, according to overload theory [9], the addition of a visual task can cause cognitive resources to deplete. This saturation of information across the visual pathway could cause performance differences to manifest between responses to tactile and visual cues. The role of visual engagement on visual and tactile cue responses, in the context of human evasion maneuvers, has yet to be explored. This lack of information prevents effective comparison of visual and tactile cues for environments where visual tasks consume attention.

In application, the perceptual cue modality choice is important. Vibrotactile motors are relatively low cost and are readily available in large quantities [11], [12]. This contrasts with more costly [13] and less readily available visual augmentation displays. Additionally, tactors can be easily integrated in specialized clothing/tooling [14], [15].

We are interested in the interplay between visual engagement and the performance of tactile and visual cues. Specifically, we seek to quantify how the visual distraction influences the ability to perform whole-body escape performance in terms of reaction time and dodge failure rate.

The primary study **hypothesis** was that tactile cue responses would outperform visual cue responses in aiding human response to moving threats, especially under the presence of a visually engaging task. The secondary study hypothesis was that visual engagement would significantly degrade dodging performance.

There are two core contributions of this work. First, (1) tactile cues enable statistically significantly better dodging rates than visual cues, or with human vision alone (control condition). The study also showed (2) visual engagement degraded human evasion performance in a statistically significant way. Finally, tactile cue responses appeared to be less sensitive than visual cues to visually engaging tasks within the higher portion of difficulty index range that was investigated.

In this work, we studied how visual engagement influenced the performance of visual and tactile cues for eliciting whole-body motions. We utilized a custom virtual reality (VR) environment where human participants performed in a dual-task paradigm. In *Task 1*, participants attempted to dodge threatening objects. Visual and tactile cues informed the participant of the threat's approach direction. In *Task 2*, participants continuously played a Trail Making Test (TMT) inspired minigame. This research addresses the gap in understanding how perceptual cues can influence physical response in the presence of a sustained visually demanding task.

B. Previous Work

1) Visual Task: Visual engagement in this study can been viewed in the context of vigilance. *Vigilance* is sustained attention or tonic alertness [16]. Tasks quantifying vigilance typically have "sit and stare" procedures, where participants watch for unusual events [17]. Metrics range from physiological measurements [16], [18] to task specific metrics, such as pilots verbally saying attitude call-outs [17]. However, there is not a clear task which measures performance continually while ensuring the participant is under cognitive load.

One possible task, if modified, is the TMT. The TMT has been used as a proxy for cognitive testing, cognitive deficits, attention management, executive function, etc [19]. Participants connect twenty-five numbered/lettered circles in a specified order. The time to complete the two parts is recorded to gauge the level of impairment [20]. The TMT is limited as there are only a few permutations of locations. The creation of a digital continuous TMT is an ideal task for this work.

2) Dodging Task: SA enhancement via perceptual cues has been studied thoroughly for the control of remote systems and navigation [21]–[29]. Previous studies focus on reaction time as a primary metric in addition to some measure of accuracy [21]–[34]. These studies indicated that reaction time was fastest with tactile cues, followed by vision, and then followed by auditory (slowest), though some variance exists across studies.

Effective visual cue characteristics have been previously studied. First, top-down displays have been shown to be easily interpretable [30]. Additionally, dynamic alerts with some movement were more effective than static ones [31]. Also, the color red has been seen to incite the fastest reaction times in both simple-choice [32] and multiple-choice [33] tasks. Finally, cues with longer durations located directly in the central field of view, elicit the faster reaction times than short peripherally located cues [35].

While there are many implementations of tactile cues, vibrotactile motors are the most common. Stimulus location has been shown to have a significant effect on reaction time in comparison to vibrational frequency, number of tactors in the same location, and tactor type [36]. A wide range of locations have been studied [15], [36]–[43]. Generally, distal ends are the slowest while head and torso elicit the fastest responses. The torso is ideal for planar threat alerts, as it has shown well distributed sensory resolution [42] while the head did not exhibit this radial symmetry [43].

There is some evidence that tactile cues can provide faster response than visual cues [50]. In addition, some studies have shown that vibrotactile response can provide improved task performance relative to visual warnings. However, the study suggested that the results were context dependent [60] [Petermeijer].

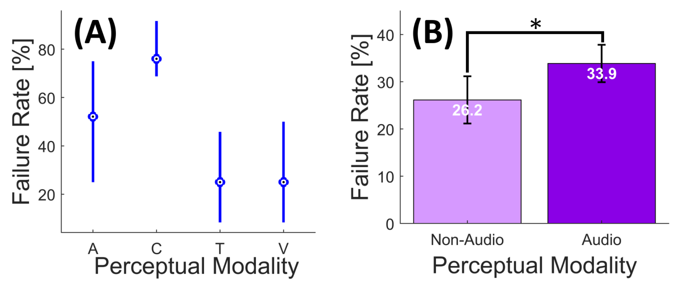

Figure 2: Previous work on perceptual cues to assist in a dodging task. (A) Comparison of the base cases of audio, control, tactile, and visual cue responses (A, C, T, V). (B) Grouping cue combinations into Non-Audio (T, V, T-V) and Audio (A, A-T, A-V) show that the addition of audio cues give significantly higher failure rates.

Our previous work [7] has investigated perceptual cues effects on eliciting whole-body dynamic movement. This study employed a top-down display with a red arrow as the visual cue, a vibro-tactile belt as the tactile cue, and directional 3D audio originating from incoming threats as the audio cue. The results, presented in Figure 2, showed that tactile and visual cue responses exhibited similar performance increases while audio cue responses did not perform as well but better than the control case. Grouping together cue combinations, we found that the addition of tactile or visual cues exhibited statistically significant decreases in failure rate while 3D audio cues increased failure rate and reaction time. This indicates that 3D audio cues may not be a promising perceptual cue to elicit whole-body dynamic movements, such as planar dodging.

II. Experimental Methods

We constructed a virtual reality (VR) based experiment to quantify the role of visual engagement on human evasion maneuvers. VR enables safe study of human evasion, customization of assistive cues, the creation of interactive minigames, and limits variability apart from participant performance.

A. Participant Objectives

This experiment was constructed in a dual-task paradigm. *Task 1* was to dodge threatening objects from varying directions. *Task 2* was to play a continuous TMT inspired minigame displayed in front of the participant. The participant was informed of their performance, in real-time, through a round score, Equation 1, and an overall score, Equation 2.

$$S_r = -S_{r,1} + S_{r,2} \tag{1}$$

$$S = \sum_{r=1}^{n} S_r \tag{2}$$

The objective of participants was to maximize their overall score, S. The overall score was a summation of round scores, S_r. A round was defined as one cycle of connecting the numbers 1-9. The round score, S_r, was the total of the scores from Tasks 1 and 2. If participants were hit by a threat, they received a 100-point penalty, $S_{r,1}$ = 100. If they successfully evaded, no penalty was applied and $S_{r,1} = 0$. Additionally, each successful consecutive connection of buttons 1-9 received a 100-point reward (distributed per button), $S_{r,2}$, for Task 2. The game then updated S, reset S_r, and cycled to the next arrangement with randomized button locations.

B. Virtual Reality Environment

VR allowed for consistent simulation of dynamic threats without placing the participants in any physical danger. Complete control over the virtual space ensured variability was limited to participant ability/performance. Moreover, field resets happened instantly, thereby accelerating experimental procedures and data collections. Experiments were performed in the dedicated VR space in the Georgia Tech Manufacturing Institute (GTMI).

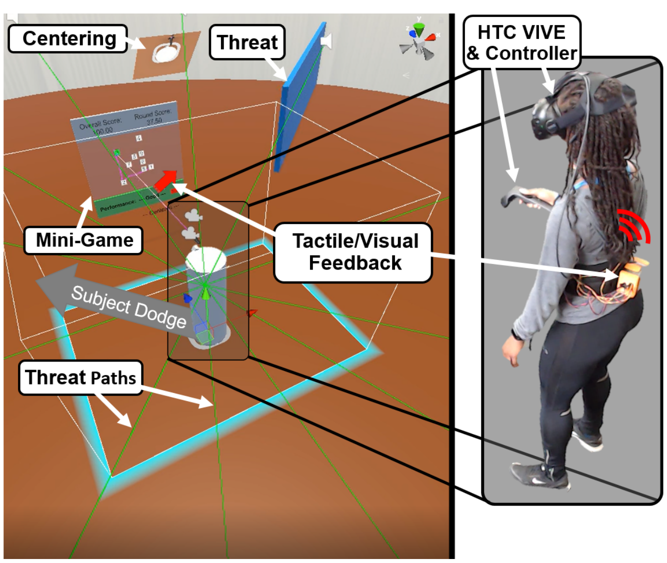

Figure 3: VR environment and game-play overview. Threats were presented as long walls to ensure whole-body dodges. Participants, represented as cylinders to detect when collisions occurred with center of mass, were cued with a haptic belt and visual cues. Position data was collected at 90 Hz.

A custom Unity-based environment was constructed to implement the two tasks and interface with SA cues. This environment was comprised of a large square room, a circular wall (radius of $10m$), and 10 threats hidden behind the wall. A cylinder was used to represent the participant's body (Figure 3). Additionally, the threats were long walls, which required participants to completely move their center of mass (COM). Threats could originate from the cardinal and inter-cardinal directions. In addition, to add threat resolution within the VIVE field of view, two more objects were added in the mid-periphery at 22.5° and -22.5° (0° pointing in front of the participant). Threats were activated at randomized times between ten and fifteen seconds. To deter false starts, a null case, where no threat would approach, was added to the ten possible directions.

Participants interfaced with the simulated environment with an HTC VIVE head mounted display (HMD), VIVE tracker (located approximately on the xiphoid process for COM estimation), and VIVE remote as seen in Figure 3. Key notifications were dispatched as text readouts to the HMD. Participants were instructed to dodge to the best of their abilities, then return to center and look forward after the threat reset. A notification of "Close" was given if their COM was within ten centimeters of the origin, and "Centered" if within five centimeters of the origin. Participants either looked down to track their body representation within a center marker painted on the environment floor or looked up to see a live top-down view camera to help with centering. Once centered and looking forward, the next trial was cued. If the participant's dodge was not successful, they would be notified "Hit Detected". Participants were not instructed on how to dodge but were instructed not to leave the VR area.

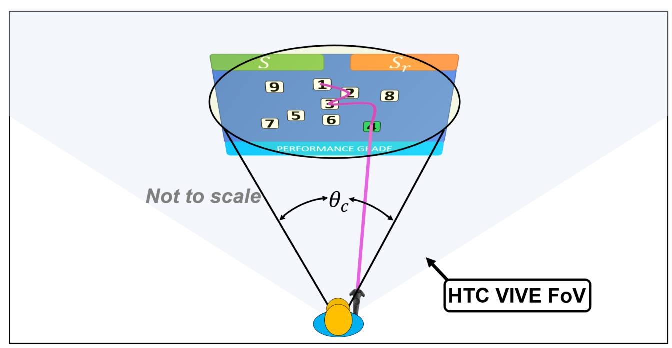

Figure 4: Schematic of Task 2. Participants used the VIVE remote as a cursor. Cursor history was traced on TMT minigame. The overall (S) and round scores (S_r) were displayed at the top right and left, respectively. Additionally, color coded performance grade was placed at the bottom of the minigame. The minigame designed to ensure participants' central focus stayed within a 10° range (θ_c) around their central vision.

A continuous TMT inspired minigame (Figure 4) was located in front of participants and its width was tuned to ensure their eyes did not deviate more than five degrees to either side. This ensured that threats could approach in specific areas of participants' fields of view. Participants used a simulated laser, projected from the HTC VIVE remote, to interact with the minigame. The objective of the minigame was to consecutively connect the numbers 1 through 9. Participants had to hover over a number, press down the touch pad to tag, and then move to the next number. Participants knew that a number was correctly tagged if it lit up green. Additionally, their cursor history was drawn. After completing a round, the minigame would refresh and present a new randomized button layout to be completed next.

In addition to the round and overall scoring, participants received categorical performance feedback. With any given arrangement of numbers, there was a minimum path length, s, to connect ascending values with straight lines. A given participant completed a round in a certain amount of time, t_c. The average completion speed, $\hat{v}$, estimated how well the participant performed, where $\hat{v} = t_c \times s$. Based off of pilot data, speeds were placed into different grades including: poor ($\hat{v} < 0.2\frac{m}{s}$), fair ($0.2\frac{m}{s} \leq \hat{v} < 0.3\frac{m}{s}$), good ($0.3\frac{m}{s} \leq \hat{v} < 0.4\frac{m}{s}$), and excellent ($0.4\frac{m}{s} \leq \hat{v}$). This categorical feedback was presented for five seconds after the round, located below the minigame on a color-coded box. Color-grade pairs included: red-poor, yellow-fair, green-good, blue-excellent. Threats were only activated when the participant was above the poor category to ensure sufficient visual engagement.

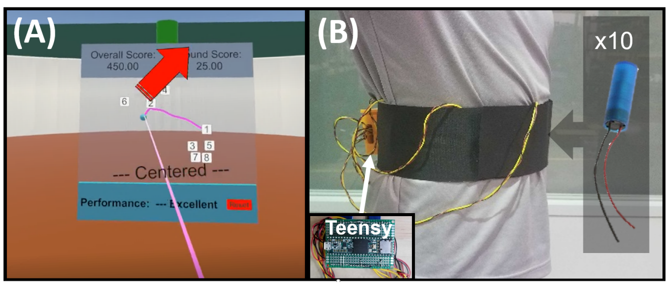

Figure 5: Perceptual cue implementations. The visual implementation (A) was a top-down display red arrow. In this example, a threat is approaching at 45°. Tactile implementation (B) employed a vibrotactile belt composed of a hook-and-loop belt, ten cylindrical tactors, and a Teensy 3.6. microcontroller.

C. Visual Cue Implementation

Leveraging best practices seen in previous literature [4], [7], [32], [33], a visual cue was designed. A red, top-down, arrow was presented as an overlay on the HMD (Figure 5A). The visual cue rotated with respect to the head's frame of reference to ensure it always pointed in the threat approach direction as the participant moved. The arrow activated when a threat started to move and persisted until the threat reset at the end of a trial. Finally, the red arrow appeared in participant's central vision when looking straight ahead as soon as a threat activated. This meant that the visual signature would partially occlude Task 2 play.

D. Tactile Cue Implementation

The torso was selected as the ideal location for vibrotactile simulation. A custom tactile belt was then created (Figure 5B). Hook-and-loop fastening allowed tactor locations to be rapidly adjusted and ensured that the tactile belt could fit a large range of body sizes. Serial commands were dispatched from the VR computer to activate the specific tactor when its associated threat started moving. Vibrations cycled off and on (for equal time) at 2 Hz. The tactors used were 3VDC 12000 RPM Parallax vibrational motors and were controlled by a Teensy 3.6 microcontroller. Tactors were positioned at the same angles of where the threats would originate. Tactor locations were verified by validating if the participant could identify the locations of random vibrations on the belt. If their perceived directions were incorrect, the tactor locations were adjusted, and the checking process repeated until they were accurate.

E. Experimental Procedure and Metrics

Eleven able-bodied participants (eight males and three females) participated in an experimental protocol approved by the Georgia Institute of Technology Institutional Review Board (IRB H18363). After participants gave written informed consent, they were oriented with the VR area by walking around the edge of the space to understand the boundary limits. Six conditions were tested across two independent variables. There were three types of perceptual cues including: (1) control (no cues), (2) visual, and (3) tactile. For each perceptual cue there were two conditions, one with and one without the Task 2 minigame active. To create a condition order for a given participant, the six conditions were numbered and a uniform pseudo-random number generator was employed to select conditions without replacement.

For each condition there were forty-eight trials, composing a *trial block*. This block included combinations of eleven directions (ten threats and one null case), three speeds (8.5, 9.25, and $10\frac{m}{s}$), and three widths (0.1, 0.35, and $0.5m$). The randomized trial blocks were biased to have thirty trials of threats originating within the field of view of the participant and the remaining eighteen were from out of field directions (which included the null case).

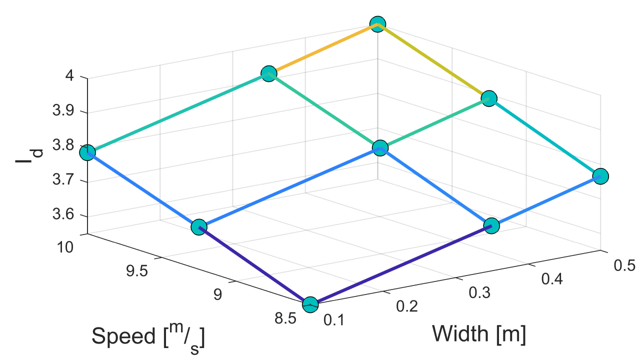

Figure 6: Difficulty contour. Thinner slower objects are less dangerous and have low I_d. Thicker faster objects are more dangerous and have a high I_d. Green points indicate the specific values tested, multicolored lines represent interpolated values.

Due to varying widths and speeds, there were varying levels of dodge difficulty. An adjusted Fitt's law [44] quantified the Index of Difficulty (I_d) related to each combination of widths and speeds (Equation 3) [7]. To successfully avoid a collision, the participant had to move right or left (with respect to the threat) and out of the collision path. This meant the width of the safe region was the inscribed radius of the VR area ($1.5m$ in this case) minus the width of the given object. The adjusted I_d is displayed in Equation 3, where W is the inscribed radius of the physical space, w is the width of the threat, and s is the speed of the threat.

$$I_d = -log_2 \frac{W - \frac{w}{2}}{2s} \quad (3)$$

This I_d (Figure 6) was used to ensure that each direction had similarly distributed difficulty. The trial block difficulty values were randomized across participants. While trial order was randomized within each trial block, the set of trials was held constant per subject across conditions. This ensured that intra-participant comparisons were fair.

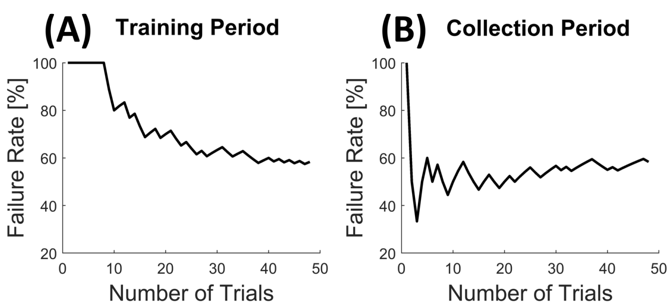

Figure 7: The example (A) shows the participant's training failure rate being high initially and then performing better over time and eventually reaching a steady state. The subsequent collection period (B) exhibits approximately the steady state failure rate quickly.

At the beginning of each trial block, a training period was given to acclimate the participant to the current cue modality and ensure their failure rate reached a steady state value before collection. An example is displayed in Figure 7. The number of threats in the training period was the same length as the trial block. For each trial, a failure or success was logged automatically and communicated to the participant. After completing a trial block for a given condition, the participant had a two to three minute break before beginning the next trial block. While participants were encouraged to take as many breaks as they needed (to prevent reaction time fatigue [31]), a mandatory 10-15 minute break was given after three trial block collections.

The two primary metrics used in this study included failure rate (Figure 8) and reaction time (Figure 9). The *failure rate* was the percent of trials the participant was hit by a threat for a given condition. Hits were determined by geometric collisions from the simulated threats and the cylinder body representation. The *reaction time* was measured by subtracting the time the cue was sent to the participant from the time the participant's speed exceeded a threshold. This threshold was determined to be when the participant's speed exceeded twice the max speed recorded from an at-rest period before a threat was activated. Position data was collected at 90 Hz and differentiated to find velocity. Reaction time was calculated after a 15 Hz low pass filter was applied.

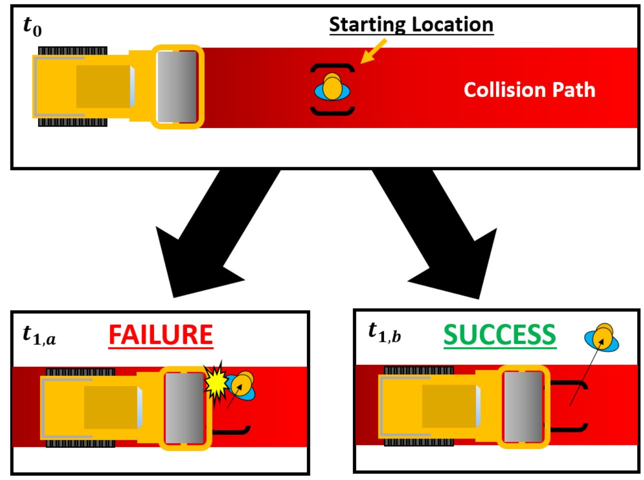

Figure 8: Key Metric: *failure rate* was calculated for each condition from the percent of hits out of the total number of trials. A success was counted when a participant avoids a collision, while a failure was when they do not.

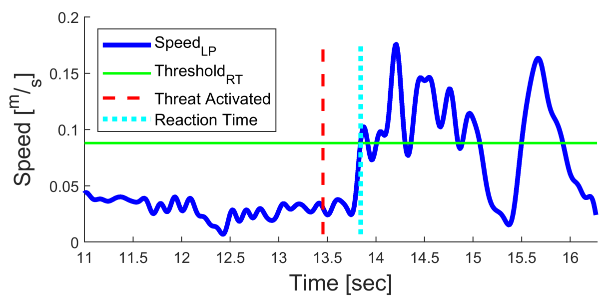

Figure 9: Key Metric: *reaction time* was calculated by the time taken between the activation of an object and the COM speed exceeding a maximum threshold. This threshold was two times the max participant speed before a threat was activated. Speed was calculated by taking the derivative of VIVE Tracker position data and applying a low pass filter of 15 Hz.

F. Questionnaire

After completing a trial block, participants responded to a questionnaire that included statements on a 1-7 Likert scale (Strongly Disagree, Disagree, Somewhat Disagree, Neutral, Somewhat Agree, Agree, Strongly Agree). These statements included: (1) *I prefer the current condition over the previous condition*, (2) *I prefer the current condition over my favorite condition*, (3) *I relied on the given cue (if present)*, (4) *the minigame was distracting (if present)*. An additional section allowed participants to give written comments. Finally, participants ranked conditions by perceived difficulty. Questions 1 and 2 were introduced to help with ranking as participants had difficulty remembering and comparing different questions. The question set was asked after each condition to ensure reliable participant memory and final rank responses are reported.

G. Statistical Methods

This experiment varied two independent variables: the cue condition (control, visual, and tactile) and whether Task 2 was active or not. In the control case, participants could only dodge when a threat was within their field of view which led to two separate statistical analyses. The first, *Category I*, considered all directions for tactile and visual conditions. There was a five to three ratio of trials involving the FoV directions to the outside FoV directions. The second, *Category II*, considered only threats approaching within the field of view for all conditions. These parallel analyses ensured that control was not automatically disadvantaged, as a participant can only dodge what they see when there is no cue present, and would therefore have no measurable reaction time and a 100% failure rate to threats outside their field of view. For each category, we conducted two-way repeated-measures ANOVAs on both reaction time and failure rate to understand Task 1 performance. Additionally, a one-way repeated-measures ANOVA was performed to detect performance differences on Task 2, the TMT minigame. Post-hoc t-tests with Bonferroni corrections were conducted for pairwise comparisons for all ANOVA tests ($\alpha = 0.05$).

III. Results

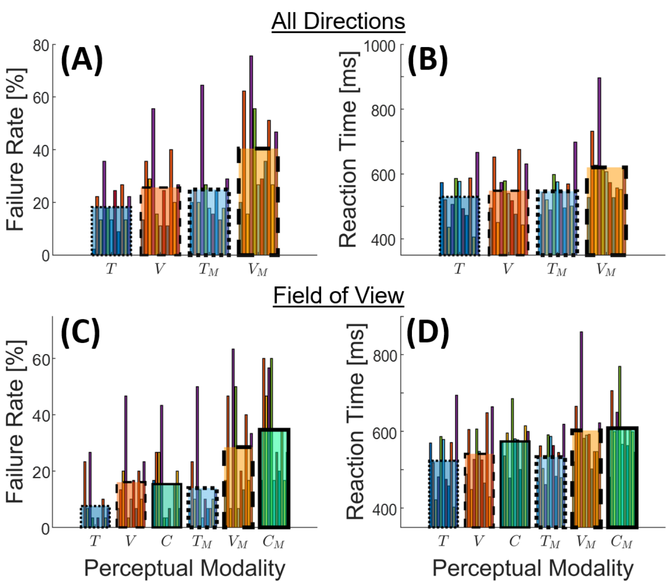

Figure 10: Failure rates (A,C) and reaction time (B,D) results for considering all directions (A,B) and in field of view (A,B). Both average (transparent) and individual performances (solid) bars are provided. Axis notation is defined as the following: tactile (T), visual (V), control (C), tactile with TMT minigame (T_M), visual with TMT minigame (V_M), and control with TMT minigame (C_M).

Table I: Task 1 Performance Means and Standard Deviations

Category	Cond.	F.R. [%]	R.T. [ms]
I	T	18.2 ± 9.3	529 ± 77
	V	25.7 ± 13.9	548 ± 81
	T_M	24.8 ± 14.0	547 ± 64
	V_M	40.4 ± 19.1	620 ± 108
II	T	7.68 ± 9.20	523 ± 86
	V	16.1 ± 12.0	542 ± 81
	C	15.3 ± 13.2	574 ± 56
	T_M	13.9 ± 13.1	533 ± 56
	V_M	28.5 ± 19.2	602 ± 97
	C_M	34.7 ± 18.0	608 ± 78

For brevity, condition specific results are reported and discussed with the following notation: tactile (T), visual (V), control (C), tactile with TMT minigame (T_M), visual with TMT minigame (V_M), and control with TMT minigame (C_M). Performance metrics of failure rate and reaction time for both directional analyses are displayed in Figure 10 and Table I.

Statistical results, presented in Tables II-V, are sorted by category and type of analysis. Variables include failure rate (FR) and reaction time (RT). Cue groups include the control (Con), the visual (Vis), and the tactile (Tac) conditions. Task 2 groups include with the TMT minigame (MG) and no TMT minigame (nMG) conditions. The minimally detectable difference, found by performing a post-hoc statistical sensitivity analysis, in failure rate was approximately 12% with an α of 0.05, power of 0.8, and sample size of 11.

A. *Category I: All Directions*

Table II: All Directions Two-Way ANOVA Tests

Variable	Source	F-Value	P-Value
FR	Cue	19.17	1.34E-4
	Task 2	16.57	3.14E-4
	Cue*Task 2	2.36	1.35E-1
RT	Cue	4.84	3.36E-2
	Task 2	4.47	4.30E-2
	Cue*Task 2	1.67	2.06E-1

Table III: All Directions Post-Hoc Tests

Variable	Source	Pair	T-Value	P-Value
FR	Cue	Vis-Tac	4.38	1.34E-4
	Task 2	MG-nMG	4.07	3.14E-4
RT	Cue	Vis-Tac	2.52	3.56E-2
	Task 2	MG-nMG	2.11	4.30E-2

The statistical results on threats approaching from all direction are presented in Tables II and III. The data for individual performances and the average performances across conditions are displayed in Figure 10A and 10B. Two-way repeated-measures ANOVAs found statistically significant differences in the failure rates between cues ($p < 0.05$) and in the presence of the second task ($p < 0.05$) in both failure rate and reaction time. Interaction effects (Cue*Task 2) were not significant. Tactile conditions have significantly lower failure rates and reaction times than V ($p < 0.05$) conditions. Finally, when Task 2 was present the failure rate and reaction time was significantly higher ($p < 0.05$).

B. *Category II: Within Field of View*

The statistical results on the subset of threats approaching from within a participant's field of view are presented in Tables IV and V. The data for individual performances and the average performances across conditions are displayed in Figure 10C and 10D. Two-way repeated-measures ANOVAs found statistically significant differences in the failure rates between cues ($p < 0.05$) and in the presence of the second

Table IV: Field of View Two-Way ANOVA Tests

Variable	Source	F-Value	P-Value
FR	Cue	15.46	5.93E-6
	Task 2	32.76	5.68E-7
	Cue*Task 2	2.85	6.74E-2
RT	Cue	5.06	9.99E-3
	Task 2	4.46	3.98E-2
	Cue*Task 2	0.80	4.55E-1

Table V: Field of View Post-Hoc Tests

Variable	Source	Pair	T-Value	P-Value
FR	Cue	Con-Vis	1.00	9.62E-1
		Vis-Tac	4.23	2.94E-4
		Con-Tac	5.24	9.74E-6
	Task 2	MG-nMG	5.72	5.87E-7
RT	Cue	Con-Vis	0.94	1.00
		Vis-Tac	2.16	1.07E-1
		Con-Tac	3.10	9.47E-3
	Task 2	MG-nMG	2.11	3.98E-2

task ($p < 0.05$) in both failure rate and reaction time. Interaction effects (Cue*Task 2) were not significant. Tactile conditions have significantly lower failure rates than V and C ($p < 0.05$) conditions. Furthermore, tactile conditions exhibited significantly lower ($p < 0.05$) reaction times than C conditions. Finally, when Task 2 was present the failure rate and reaction time was significantly higher ($p < 0.05$).

C. Directionality

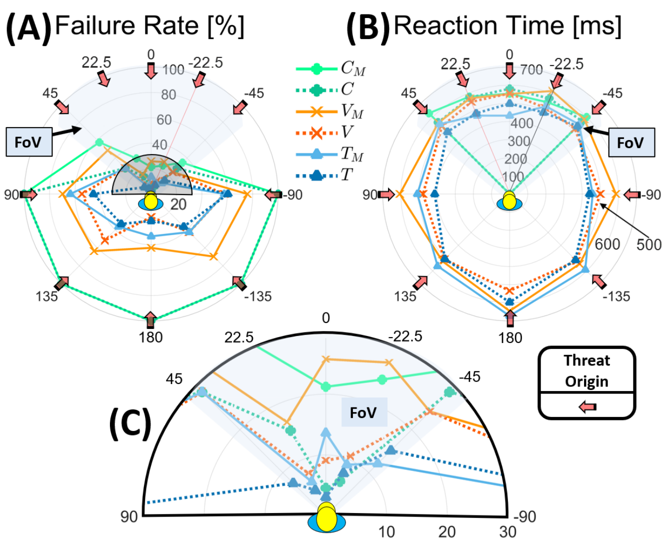

Figure 11: Directionality dependence of key metrics. The failure rate (A) and reaction time (B) results can be separated by direction. In (C), a zoom in of failure rates is shown to highlight differences in the field of view. Red arrows indicate where a threat approached from. The shaded blue region represents the participant's field of view. Legend notation is defined as the following: control with TMT minigame (C_M), control (C), visual with TMT minigame (V_M), visual (V), tactile with TMT minigame (T_M), and tactile (T).

The results for dodge responses to threats approaching within field of view are shown in light blue on Figure 11, where directions were located in the participant's mid-periphery (-45° and 45°), near-periphery (-22.5° and 22.5°), and in their central vision (0°). Category I included the directions within and outside the participants' field of view. Reaction time was shown to be roughly radially symmetric while failure rate was not and had a dependency on direction. Specifically, objects approaching from the sides had higher failure rates than objects from the front or behind the person. Generally, failure rates within participants' field of view were lower than out of view responses.

D. Index of Difficulty

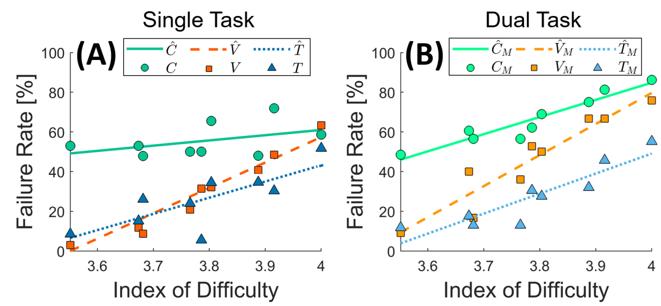

Figure 12: Effect of difficulty index on failure rate in the all directions category. On the left (A) the single task (task 2 not present) results are shown and, on the right, (B) are the dual task results. Legend notation is defined as the following: control with TMT minigame (C_M), control (C), visual with TMT minigame (V_M), visual (V), tactile with TMT minigame (T_M), and tactile (T).

Based on previous work [7], this study tuned the index of difficulty to be in a slim range where the largest change in failure rate has been previously observed to occur. Applying a linear regression can provide a slope and intercept relating difficulty index and failure rate for each condition. The all direction regressions are represented in Figure 12. Y-intercepts presented use a shifted x axis (to zero) for easy interpretation. In the case of V, a negative intercept was found. Having a negative failure rate is not possible so the intercept was forced to zero and the slope recomputed.

Figure 12, showed several behaviors. First, the overall trends are broadly similar with (A) and without visual engagement (B). Second, the linear regression's slope for the visual cue condition is noticeably higher than tactile. This causes the visual cue condition to converge to the control condition at high difficulties.

E. Participant Responses

Table VI: Reported Ranking

Condition	Rank ($\mu \pm \sigma$)
T	1.32 ± 0.64
V	2.68 ± 1.15
C	4.36 ± 1.43
T_M	3.23 ± 1.40
V_M	4.41 ± 1.39
C_M	5.00 ± 1.10

Participant perceived rank data is reported in the form mean ± standard deviation in Table VI. Values correspond to a Likert scale. Likert scaling ranges from 1, strongly disagree, to

7, strongly agree. Response means and standard deviations for questionnaire statements are reported below. Statements 1 and 2 were to assist participants in ranking and are not reported.

Participants' average ranking from easiest (lowest cognitive load) to hardest (highest cognitive load) was T, V, T_M, C, V_M, and C_M. Statement 3 indicated to what degree a participant relied on a given cue. For the tactile conditions participants agreed/strongly agreed (6.55 ± 1.16) with statement 3. This indicated that participants relied heavily on any cue present to evade threats. Participant's somewhat agreed/agreed (5.68 ± 2.0) that they relied on visual cues. Finally, participants agreed/strongly agreed with statement 4 (6.33 ± 0.68), indicating that the participants agreed/strongly agreed with the TMT minigame being distracting.

F. Task 2

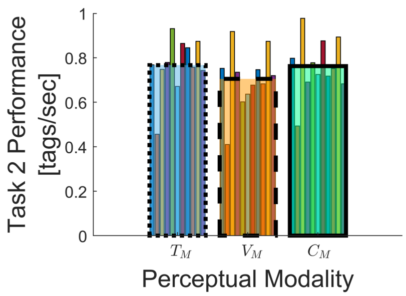

Figure 13: Average scoring rates of different cue conditions. Both average (transparent) and individual performances (solid) bars are provided. No statistically significant differences were detected. Axis notation is defined as the following: tactile with TMT minigame (T_M), visual with TMT minigame (V_M), and control with TMT minigame (C_M).

Table VII: Task 2: Tag Rate Means and Standard Deviations

Cond.	Tag Rate [tags/sec]
C_M	0.767 ±0.127
V_M	0.705 ±0.135
T_M	0.762 ±0.127

The tag rate in Task 2 was tracked throughout conditions as shown in Figure 13 and Table VII. A one-way repeated-measures ANOVA did not find statistically significant differences in the average tag rate between cues ($F = 2.43$, $p > 0.05$) while playing the Task 2 game. This indicates that a significant effect of perceptual modality on Task 2 performance was not detected.

IV. Discussion

The primary study hypothesis was validated in that tactile cues had significantly lower failure rates ($p < 0.05$) compared to visual cues. This effect was greater in the presence of a visually engaging task as tactile cues outperformed visual cues with a 14.6% (15.6% within the field of view) lower absolute failure rate compared to only a 8.3% (7.5% within the field of view) lower absolute failure rate advantage without visual engagement. Thus, when subjects had to perform a visually engaging task, the benefit of tactile cues was roughly double that of visual cues for evading threats. The secondary study hypothesis was also validated in that visual engagement significantly increased failure rate and reaction times regardless of task condition ($p < 0.05$).

A. Primary Metrics: Failure Rate and Reaction Time

For failure rate results, visual cue responses had statistically higher failure rates regardless of visual engagement compared to tactile cue responses. This performance difference may be due to the cues using different perceptual pathways [27], [34]. Previous work has shown tactile to have faster responses with higher accuracy in comparison to visual cues, but are limited to small scale movements, such as interacting with a computer mouse [4]. This significance has not yet been seen in whole-body maneuvers, such as planar dodging [7].

For the reaction time results, tactile cue reactions were significantly faster than visual cue reactions for threats approaching within the visual field regardless of visual engagement. This significance was not detected in the all direction category. Participants continually stayed in the "excellent" ($\hat{v} > 0.5\frac{m}{s}$) category of Task 2 performance, as shown in Figure 13. This may have helped saturate the visual pathway causing participants to need more time to refocus their attention on the cue and threat, even though they were directly in their field of view. Previous work has identified that visual cues consume more working memory [4]. Additionally, this phenomenon has been observed as selective attention, where people are focused on a visual task, such as tracking a ball and missed key information occurring in the scene [45].

B. Directionality

Trends across conditions, as shown in Figure 11, are similar to those previously identified [7]. Reaction time was not directional dependent while failure rate was. This meant that movement time and accuracy were key contributors to threat evasion and ensuring safety. Responses to threats approaching within the field of view had the lowest failure rates, further illustrating that human sight and recognition are key to successful planar dodge maneuvers. Generally, responses to threats approaching at 0° had the best failure rates while increasingly peripheral approaches exhibited increasingly higher failure rates.

Our previous work did not detect a significant difference between visual and tactile cue responses in either failure rate nor reaction time [7]. In this study, this significance was detected. We attribute this difference to the five to three weighting of in field of view trials to out of view trials. The performance differences are higher in the field of view as seen in Table I. Figure 11C highlights this as tactile response failure rates increase at a noticeably lower rate than visual ones when approaching the edges of the participants field of view.

When comparing sagittal and frontal plane dodges, results showed that dodging to the left or right was safer than moving forwards or backwards to evade. These results further confirm previous findings [7], [46]. For threats approaching in the sagittal plane, physical assistance could help cover this evasion vulnerability. In application, perceptual cues could alert a person in advance and ensure they are both looking in the direction of the threat and facing the best direction to maximize safety.

C. Index of Difficulty

This experiment used tuned threat difficulties where performance differences are clear [7]. Comparing across the single task vs. dual task paradigm, at high difficulties, tactile increased 5.9%, while visual and control increased 22.2% and 24.0%, respectively. Our previous work has shown that at higher indexes, it becomes too difficult regardless of the cue type [7]. Even though people can be perceptually augmented, they are inherently limited in their physical capabilities.

Knowledge of the failure rates dependence on cue type and dodge difficulty could be used in deciding which cue would be the most effective. In the presence of slower smaller threats, either tactile or visual cues could be used. However, in more dangerous environments with faster larger threats, tactile cues may be preferred. When threats are too difficult to dodge, perceptual augmentation will no longer increase safety. In these cases, physical assistance could be used to further improve performance.

D. Dual Task Tradeoffs

This research employed a continuous TMT to visually engage participants. In all two-way ANOVAs, when the minigame was active, a significant performance decrease was detected. This quantitative assessment agreed with the qualitative participant questionnaire data produced from statement four. This showed that the TMT inspired minigame was visually engaging and consumed cognitive resources. There was an absolute increase in tactile response failure rate of 6.2% when the secondary task was present. Visual and control were more sensitive as they exhibited 12.4% and 19.4% increases, respectively.

Task 2 tag rate was measured to identify a possible cue dependent trade-off where participants avoid threats at the detriment of tag rate. This was not seen as the level of tag rate (Figure 10) stayed relatively consistent across conditions. The dodging performance benefits of tactile were not necessarily due to less engagement with the visually interactive task.

E. Limitations

There are limitations to this study. First, cue design could be optimized to increase performance. While a larger, more pronounced, visual cue may have improved performance, we did not want to completely occlude participants' sight as threat identification by sight was shown to be a key determiner of success. For tactile cues, there was limited information resolution as there was a finite number of tactors. Additionally, in application, ensuring the tactors are in constant contact with the body is critical but even in this study it required nontrivial adjustment to ensure participants could feel all tactors with adequate intensity. The same need for adjustment would likely be present dynamic environments such as natural disaster areas, construction zones, and complex natural terrain. While vibrotactile signals have shown promise for grabbing attention and being difficult to ignore, they can have issues with suppression effects. Previous studies have shown that physical activities can change human sensitivity to tactile signals [47]. Similarly, environments with vibrations present may present difficulty with using tactile signals [48] and stimulus intensity should be carefully considered [49]. While this study focused on vibrotactile feedback and a top down display signature, there are other methods to improve SA which can be applied to the context of dodge maneuvers. Methods of non-vibrational stimulation, such as heat, skin-stretch, and electric stimulation, could result in different responses to threat evasion maneuvers.

Another limitation was the selected visual task 2. The method of visual engagement employed was a TMT inspired minigame. While this task can serve as a proxy for real world visual engagement, it is not a task done in application. In fact, many tasks while primarily visual, are physically involved.

Task 1 also had limitations. This research was limited to in-plane threat directions. However, there are many examples of out-of-plane threat approach directions, such as falling debris. While the best response to maximize safety in these cases is unknown, our results showed that for responses that require only a few steps of movement, side-stepping had the lowest failure rates. Moreover, this work only considers dodging threats one time at a time from a standing position. In application, workers may be moving, in different initial poses, or evading multiple threats. More work is needed to describe, quantify, and improve different dodge maneuvers.

V. Conclusion

This study provides new knowledge of how perceptual cues can assist physical evasion maneuvers with and without of visual engagement. The results illustrated that (1) tactile cues enable statistically significantly better dodging rates than visual cues, or with human vision alone (control condition). The study also showed (2) visual engagement degraded human evasion performance in a statistically significant way. In addition, tactile cue responses appeared to be less sensitive than visual cues to visually engaging tasks within the higher portion of difficulty index range that was investigated. Finally, this work provided quantitative measures of performance for both failure rate and reaction time. These findings can provide insights into how early-warning and other assistive systems are designed and their performance limits. Many important tasks, including construction, manufacturing, military, and public safety, require human workers to perform visually demanding tasks while risking physical harm. These are cases where new situation awareness enhancements have the potential to provide important benefits and improve human safety.

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