Optimizing Haptics for AR/VR Training

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ABSTRACT

Haptics, including touch, pressure, temperature, proprioceptive and kinesthetic, and vibratory sensors, can provide critical cues for successful task completion in many military domains. To date, integration of haptic cues has been limited within augmented reality (AR) and virtual reality (VR) due to technology limitations and challenges in appropriately activating this broad, sensitive perceptual system. With the establishment of the Army Futures Command in 2018 (Lacdan, 2018), the Army is positioned to push innovation at a fast pace to meet the needs of future operations. As the Army moves towards development of the Synthetic Training Environment (STE) under this Futures Command, critical research questions regarding how humans best perceive and comprehend information and interact with innovative training technologies in a team environment – localized or distributed – need to be considered. When and how to integrate haptics cues into synthetic training capabilities to optimize human learning and capabilities for operational success requires a guiding framework for haptic cue integration – covering technologies available, cues provided, and human perceptual capabilities and limitations across experience levels. Further, cross-modal impact of haptics plus other sensory cues need to be considered, as design advantages can be realized to produce psychological fidelity critical for optimal training (Straus, Lewis, Connor, et al., 2018).

This paper presents a haptics framework for synthetic training integration. This framework was built based on sensory cue fidelity assessments for tactical combat casualty care (TCCC) Tier 1 and 2 training for All Service Members (ASM) and Combat Lifesavers (CLS), and was reviewed using sensory cue fidelity assessments of tactical crew training for Close Combat Tactical Trainer (CCTT) to assess generalizability of the framework. Human perceptual capabilities and limitations against available technology solutions were considered to guide appropriate integration of haptics capabilities to maximize psychological fidelity for the human operator, resulting in optimal learning and training transfer.

ABOUT THE AUTHORS

Dr. Kelly Hale is the Sr. Vice President of Applied Research at Design Interactive, Inc., a woman-owned small business focused on human-systems integration. She has over 18 years experience in human systems integration research and development across areas of augmented cognition, multimodal interaction, training sciences, and virtual and augmented reality environments. She received her BSc in Kinesiology/Ergonomics Option from the University of Waterloo in Ontario, Canada, and her Masters and PhD in Industrial Engineering, with a focus on Human Factors Engineering, from the University of Central Florida.

Claire Hughes is a Research Associate in the eXtended Reality Division at Design Interactive. Her focus is on emerging technology delivery to diverse stakeholders, including the Office of Naval Research, and the Army Futures Command. Her current work is centered around the design and delivery of XR training technologies across the Department of Defense, with a focus on driving user-centered design for scalable adoption of AR/VR/MR training and job aid solutions. She holds a Master of Science in Human Factors and Systems Engineering from Embry-Riddle Aeronautical University and a Bachelor of Science in Mathematics from Hillsdale College.

Christina Padron is the Deputy Division Head of the XR Division at Design Interactive, and has 10 years of experience in the design, development and evaluation of virtual assessment and training tools for Defense customers. Her work focuses on the design, development, and usability of AR/VR/MR training and job aid solutions, specifically ensuring that the solutions are optimized for their specific users, tasks, and context of use. She holds a Master's degree from Penn State University in Industrial Engineering with a Human Factors focus, and a Bachelor's degree from Purdue University in Industrial Engineering.

Nadine Baez is the Vice-President of Research and Commercialization at SynDaver where she currently leads the design, development, and fielding of next generation medical models supporting training and readiness. Ms. Baez has 11 years of experience in the Medical Modeling and Simulation field, specifically combat casualty care education and training requirements analysis, gap analysis, and system design and development for medical simulation operational architectures, assessment platforms, manikins, and part-task trainers.

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INTRODUCTION

Motor learning is a requirement for nearly all warfighter tasks, and as the push for synthetic training increases, the gap associated with haptic cue presentation and applicable training opportunities to maximize motor learning is ever increasing. Best practices for motor learning incorporate active movement, whereby students are encouraged to perform gross and fine movements and receive feedback to perfect body positioning and muscle memory (Ericsson, Krampe, & Tesch-Romer, 1993). Given the state of the art with extended reality (xR) technologies, these platforms can afford such active movement learning environments, and provide enhanced learning experiences through objective performance assessment and feedback that is not available using today's training protocols – particularly if there is better integration of haptics input and feedback. "While vision is our most important sense for quickly exploring our environment, sound and touch are also powerful ways of understanding the world." (Chandler et al., 2015, p. 5) Using advanced haptic design strategies and techniques, one can provide a realistic space to perform essential motor tasks for effective hands-on tasks such as medical treatment or collective training for the M1A2 SEPv2, and can further enhance the learning experience for expert performers by integrating in virtual assets/entities to influence stress/realism of the training environment using a small footprint.

To optimize training transfer from xR training solutions, however, improvements in haptic capabilities of xR technologies is required. Military tasks rely heavily on a variety of psychomotor skills and abilities that produce various touch sensations. For example, casualty care providers are required to feel for injury sites with hands, apply appropriate pressure for covering a wound, and manipulate tools for treatment. Duplicating the haptic experience of these real world tasks is currently limited in virtual reality and augmented reality training environments, and thus training with xR solutions is limiting. Enhanced learning and training transfer with xR solutions will be accomplished through incorporation of appropriate haptic interactions to support the necessary cues given the user's experience level and learning objectives.

This paper presents a high level, theoretically-driven haptics cue framework for synthetic training integration. This framework is used to assess haptic cue presentation across xR systems against sensory cue fidelity data for Tactical Combat Casualty Care (TCCC) treatment (specifically Respiration: Tension Pneumothorax) and collective training tasks for the M1A2 SEPv2 Abrams main battle tank (specifically driver and gunner tasks) to assess generalizability of the framework. Human perceptual capabilities and limitations against available technology solutions were considered to guide appropriate integration of haptics capabilities to maximize psychological fidelity for the human operator, resulting in optimal learning and training transfer.

BACKGROUND

Haptics refers to the application of physical touch and movement within a simulated computer interface using a combination of exteroceptive (i.e., from outside the body) and interoceptive (i.e., from within the body) cues (Hale, et al., 2009). Figure 1 summarizes the human haptic sensor systems, and how they combine to provide a variety of haptic sensations that influence spatial and temporal perceptions of and interactions within a surrounding environment. Proprioceptive and kinesthetic sensors are found in joint ligaments, capsules, tendons and muscles, and coordinate to provide static and active position indications for the human body. Cutaneous sensors are found in glabrous (skin found on palms, fingertips and soles of the feet) and hair skin (other body surfaces), and provide sensations of detailed tactile information and vibration. When combined via active or passive movement (with kinesthetic sensors), perceptions of texture, 2D and 3D form/shape, softness and weight are experienced.

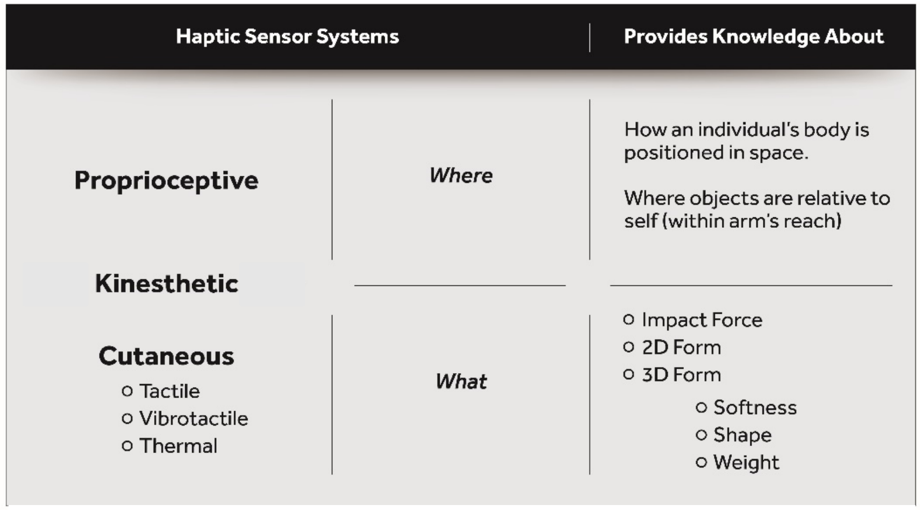

Figure 1: Human Haptic Senses

While distinct sensory systems are outlined, perception of touch/ position/ force is a combined feeling that seamlessly integrates across these distinct sensory systems, as well as combines with other sensory cues (visual, auditory) to create a combined sensory experience. Psychomotor skills and abilities require a coordinated sensory motor experience – blending physical movement/inputs with visual and haptic (and auditory) feedback into a full body sensory experience. For example, medics are required to complete gross motor skills such as full body blood sweeps, positioning and placement of patients for interventions, and movement of casualties for evacuation, as well as fine motor skills such as applying appropriate pressure for covering a wound, palpating for anatomical landmarks, insertion of needles and airway devices, and manipulating instruments/tools for treatment. Continuous feedback from multimodal sensory systems (visual, auditory, and haptics) are used to effectively guide and adapt physical interactions to successfully complete such tasks. Thus, it is the combined sensory experience of active touch interaction with multimodal feedback that is needed to optimize sensorimotor learning – a haptics device must be able to seamlessly integrate with a synthetic training environment to synchronize actions and feedback across modalities such that accurate muscle memory and self-efficacy can be achieved and improved training value realized.

MOTOR LEARNING

From a learning perspective, Fitts and Posner's Motor Learning model (1967) incorporates three distinct learning stages: Cognitive, Associative, and Autonomous (Figure 2). The first, Cognitive, stage of learning focuses on declarative knowledge, and requires working memory to think through step-by-step actions. Within the second stage of motor learning, associations between specific stimuli/positions and associated actions are made, and the load on working memory to perform that movement is reduced. Finally, the autonomous stage is said to require minimal working memory and attentional resources to perform the correct motor action. As complex motions are integrated to complete tactical decision making, experts who have achieved autonomous levels of psychomotor behavior across distinct movements for assessment and treatment are effective at executing assessment procedures while actively using working memory resources for diagnosing and treatment decision making. These three distinct learning stages from Fitts and Posner (1967) align closely with other learning stages models such as Simpson's psychomotor learning model based on Bloom's Taxonomy (Simpson, 1972), Dreyfus and Dreyfus (1980), Miller's Pyramid, and the BAIT model (Costello et al., 2012) (Figure 2). The type and volume of feedback can impact learning, as concurrent, frequent feedback has been found detrimental for simple task learning, while more complex tasks can benefit from concurrent feedback (Sigrist, Rauter, Riener & Wolf, 2012).

	Novice	Advanced Beginner	Competent	Proficient	Expert
Fitts & Posner (1967) Model of Skill Acquisition	Cognitive		Associative		Autonomous
Simpson (1972) Psychomotor	Perception	Set/Guided Response	Mechanism	Complex Overt Response/Adaption	Origination
Dreyfus & Dreyfus (1980)	Rigid adherence to rules/plans	Limited situational perception	Deliberate planning; some perception of actions in relation to goals	Hollistic view of situation; prioritization of aspects	Intuitive grasp of situation; vision of what is possible; analytical approach in new situations
BAIT Model (Costello et al., 2012)	Basic Declarative Knowledge; Passive learn exercises; low fidelity	Procedural knowledge; passive and active learning; low-medfidelity	Integrative knowledge via active learning; simulator/med fidelity	Higher order skills and transfer of training; active learning; high fidelity xR/RW	
Miller's Pyramid (Miller, 1990)	***KNOWS:*** Fact gathering	***KNOWS HOW:*** Interpretation/ Application	***SHOWS:*** Demonstration of learning	***DOES:*** High tempo performance	

Figure 2: Learning Stages Models

HAPTIC FRAMEWORK

Figure 3 outlines a haptics framework to guide xR development in incorporating critical haptic feedback sensations/perceptions (via active and passive motion) to optimize psychomotor learning and skill transfer based on current technologies available. This framework was developed based on extensive literature reviews of the xR haptics space (e.g., Bau & Poupyrev, 2012; Escobar-Castillejos, 2016; Culbertson, Schorr & Okamura, 2018; MacLean, 2008; Perret & Poorten, 2018). Considering the learning progression stages and capabilities of xR solutions, this theoretically-based framework suggests:

- Virtual Reality (VR; no haptics) solutions can be used to train the cognitive stage of motor learning (introducing procedural steps) and provide spatial knowledge of position in egocentric space and limited body orientation awareness via monitoring of physical movement within the virtual space (e.g., reach and point to a virtual object) – here, visual cues may be used to indicate 'object contact' to replace force feedback cues that are not available with a visual system alone,
- VR (with haptics) can extend capabilities into the associative stage of learning and incorporate impact forces and initial aspects of form perception. These systems can also be effective through the autonomous stages, particularly when a grounded force feedback aperture system is used to train a tool-based interactive task constrained to a small space (e.g., laparoscopic surgery), or when tangible interfaces are incorporated with VR when hand motions occur within egocentric space without visual guidance (e.g., where controls in the real world are manipulated without visual guidance)
- Augmented Reality (AR) combined with tangible interfaces can be applicable across all three states of motor learning, providing applicable fidelity haptic cues when integrated with appropriate physical objects within the environment. While the cognitive phase is often covered in classroom settings (at schoolhouses), this introductory information regarding motor learning could also be provided in AR, such as embedding reference learning material and walking a student through the cognitive steps.

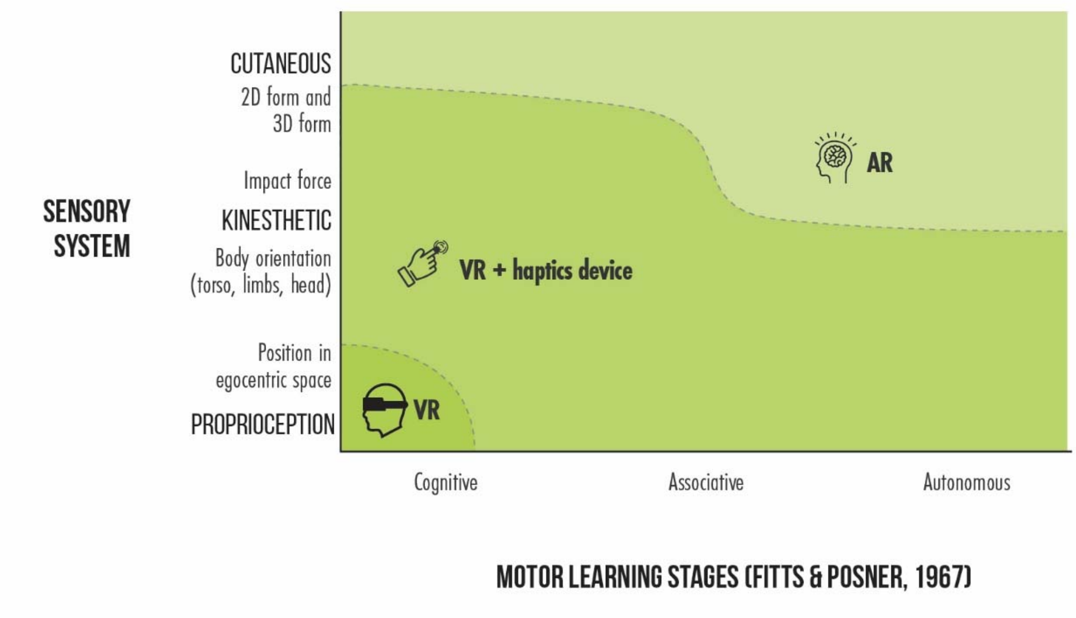

Figure 3: Haptics Framework for xR

Utilizing the haptics framework combined with output from a sensory task analysis (Champney et al., 2008), designers can determine which xR technology can best suit their simulated training environment. Table 1 outlines haptic technology systems available and emerging for xR/synethetic training environments, and identifies whether technology is best suited for VR and/or AR integration. This determination was made based on existing literature reviews of haptic systems and perceptual interactions that were used to formulate the haptics framework in Figure 3.

Two use cases are presented below that outline specific haptic cues critical for skill acquisition. For each cue, the tables below note whether VR, VR + haptics, or AR systems are capable of providing the cue based on the framework from Figure 3.

TCCC USE CASE

Tactical Combat Casualty Care (TCCC) guidelines were introduced in 1996 through an article appearing in Military Medicine (Butler, Jr., Butler, & Hagmann, 1996). The benefits of TCCC have been demonstrated through review of battlefield casualty data. The 75th Ranger Regiment was one of the first to require all members to complete TCCC. Over a 10 year period, their survival rate of battlefield casualties was 92%, with "no deaths related to the 3 major potentially survivable causes of death" (Kotwal, et al., 2011, p. 1352). This is in contrast to a larger population sample, where 24.3% of pre-medical treatment facility (pre-MTF) deaths were deemed potentially survivable, with 90.9% associated with hemorrhage and 8.0% associated with airway (Eastridge, et al., 2012). Thus, while success of TCCC implementation is evident as per Ranger success with 100% training, continued focus and training is needed to enhance the psychomotor tasks associated with tactical medical assessment and treatment in the battlefield.

Since the inception of TCCC, the program has expanded, and is now formalized as 18 distinct skill sets based around the MARCH (Major external hemorrhage, Airway, Respiration, Circulation, Head Injury/Hypothermia) principle, that is delivered across four tiered levels of responders: [1] All Service Members (ASM), [2] Combat Lifesaver (CLS), [3] Combat Medic/Hospital Corpsman (68W/8404/4N), and [4] Combat Paramedic/Provider (Joint Trauma System, 2019). Thus, this training is far reaching, with all service members receiving at minimum basic training in TCCC. To support this training need, effective hands-on training is required, particularly for novice learners, to effectively learn not only cognitive knowledge regarding injury assessment and treatment methods, but also substantial psychomotor skills to effectively perform assessment and treatment actions, including appropriate body and hand positioning for care as well as using a sense of touch to assess injury severity and treatment effectiveness.

Table 1: Haptic Devices for xR that support interaction/feedback in 3D space

Device Category	Example Tools	Description	Benefits/*Limitations*	AR	VR
Gesture Recognition (no handheld device) – Position sensing and user input;	AR HMD w integrated tracking capabilities (e.g., HoloLens; Magic Leap)	Discrete gestures captured for input control	Can capture position/location of fingers/hand at adequate resolution; Portable system effective within arm's reach of user for input interactions and positional sensing *Limited ROM for hand/arm movement due to FOV;* *Limited gesture library;* *Lacks force feedback capabilities*	X	
	Hardware/software for limb tracking (e.g., Leap Motion; Crunchfish); OmniTouch	Gesture capture within system FOV		X	X
	Camera-based system Kinect	Captures user movement with camera		X	
Gesture Recognition (via handheld device/ controller)	VR HMD with controllers (e.g., Occulus Touch, HTC Vive)	Controllers that provide real-time position and orientation, and vibration feedback	Capture position/location of fingers/hand at adequate resolution; Portable system effective within arm's reach of user for input interactions and positional sensing; Can provide vibration/contact feedback *Lacks force feedback; prevents natural, hands-on interaction with physical objects*		X
	Wii Remote; Controllers; mobile phone	Accelerometers in control device that pick up relative spatial position of device relative to a user		X	X
Active Surfaces	Surface that hands can interact naturally with	Haptic actuators built into an interaction surface (e.g., vacuum air-based, pin array)	Can provide cutaneous feedback at a given area; Supports natural hand interaction via 2.5D interaction *Limited fine tactile textures*	X	X
Mid-Air Tactile Feedback	Ultrasound transducers (e.g., Ultrahaptics)	Provides tactile feedback to users with ultrasonic/ ultrasound project sensation of touch	Can simulate different sensations e.g., light touch, pulse, heat *Device size is limited to single hand; Must be in close proximity to the device; Not mobile; Instrumenting all surfaces not feasible*		X
Force Feedback Systems – Exoskeleton/ Glove (Wearables)	Plexus Gloves	Hand and finger tracking with 5 actuators (1 per finger)	Passive/active systems provide low/mod force feedback; Most capture fingers/hand placement at adequate resolution; Portable system; Effective within arm's reach of user *Actuators can limit ROM for hand; Often requires focused feedback on specific actions – grasp vs touch vs pull; Size and weight concerns; VR limits hand-eye coordination training; Prevents natural interaction with physical objects*		X
	HaptX Haptic glove/ exoskeleton	Incorporates 130 touch points and can provide 4 lb force per finger using magnetic motion tracking			X
	VR Gluv	Hand and finger tracking, 5 lb force per finger, wireless			X
Force Feedback Systems – Grounded	Falcon 3D Touch	Interaction with a handle/aperture to provide force feedback	Low cost, high resolution position accuracy; Provides force feedback through aperture – simulates virtual tool/object in user's hands *Must grasp device; Limited workspace area/mobility; Limited touch sensation –focused on force feedback alone*		X
	Virtuose 6D TAO				X
	PHANToM				X
Tangible Interfaces	Use existing physical objects; marker-based AR objects	Use physical objects or markers to place virtual objects	Displays physical properties of object; can support natural interaction *Tactile feedback cannot be computationally controlled*	X	X

Current training for CLS Responders (Tier 2 TCCC training as observed at Ft. Bragg's MSTC site in 2019) involves 4 days of training, with practical skills training on Day 1 (tourniquet application) and Day 2 (Nasopharyngeal Airway [NPA]; Needle Chest Decompression [NCD]), combat scenario-based training on Day 3 (2 casualty sites) and combat scenario-based evaluations on Day 4 (see Table 2). Duplicating the spectrum of this psychomotor sensory experience on the battlefield is challenging within simulation-based training scenarios with current haptics technology (Bau & Poupyrev, 2012; Escobar-Castillejos, 2016; Culbertson, Schorr & Okamura, 2018; MacLean, 2008; Perret & Poorten, 2018). No device or technology today can come close to meeting the perceptual sensitivity of the human haptic system, which includes spatial resolution of 10^{-6} to 10^{-3} meters for tactile displacement, and temporal resolution approaching 1000 Hz (Biswas & Visell, 2019), and thus training such skills with xR solutions is limiting. For example, the subtleness of cues associated with activating a needle and feeling the haptic 'pop' as the needle enters the pleura is not achievable as a haptically believable percept. Further, transfer of skills is limited due to the spatial distortions that happen to the visual VR, which impacts muscle memory development of where and how hands are placed in the space. To develop a training capability using existing xR in support of TCCC training and appropriately assess which xR solution may best support critical haptic cues for optimal motor learning, detailed task information is needed to outline specific cues throughout each task. Table 3 focuses specifically on treatment for Respiration: Tension Pneumothorax, and outlines steps required to assess and treat the injury. Haptic cues associated with each task step are outlined. These cues are then considered against xR technologies in general for their ability to provide adequate physical representation of these cues. Here, VR (visual only) is compared against VR (with haptics), AR/m (assumed to have a low fidelity physical mannequin representation) and AR/M (assumed to have a high fidelity physical mannequin that mimics tissue properties of touch/pressure/puncture where needed to support the task). In the table, 'x' is used to represent that some xR solutions in the category are capable of supporting the identified haptic cue, while 'X' indicates that most xR solutions in the category are capable of supporting the identified haptic cue. This table demonstrates previous findings from literature (e.g., Hale & Stanney, 2004; Bau & Poupyrev, 2012; Escobar-Castillejos, 2016; Culbertson, Schorr & Okamura, 2018; MacLean, 2008; Perret & Poorten, 2018), where VR with added haptics and AR/m/M capabilities that merge haptics and visual cues are particularly beneficial for object interaction and target location cues compared to VR (visual) alone. In the example of needle chest decompression, a VR visual system can support students in learning cognitive awareness of where a needle should be placed and how to visually identify the correct intercostal space. Yet, even with haptic technology incorporated with VR, current tools are limited in simulating the fine motor haptics associated with live needle interaction to represent the touch/feel of the needle, fine motor movement required to activate the needle, and the subtle force feedback associated with puncture and 'haptic pop' as the needle inserts.

Table 2: Ft. Bragg CLS Training –Haptics-Relevant Training Components of Curriculum

Day	Task	Skill	Description	Benefits	Limitations
1 PM	Massive Hemorrhage	Tourniquet Application *	Apply tourniquets on partner: validate application-checking pulse below tourniquet	Minimal equipment /setup time; feedback on tourniquet tightness	Risk of fellow student injury if improper use
2 PM	Airway/ Respiration	Evacuations – drags and carries* (NPA) (NCD)	Rescue Randy used for drags/ carries Head/torso low fidelity mannequin used for NPA and NCD	Robust and realistic casualty weight; NPA/NCD – ability to use medical tools for fine motor training	Lack of/inappropriate haptic feedback from fine motor tasks of tool manipulation; needle insertion does not happen as on a real patient
3	Combat Scenario-based Training	Above skills within a scenario context	Outside – utilize RR for care under fire; transition to torso/head for tactical casualty care	RR – robust and realistic casualty weight to lift/ carry NPA/NCD – ability to use medical tools for fine motor training	Transition between mannequins to simulate one patient; lack of/ inappropriate fine motor haptic feedback
Day 4	Combat Scenario-based Evaluations	Above skills within a scenario	Outside – utilize RR for care under fire; transition to SIMMAN 3G for casualty care	SIMMAN – more realistic, multimodal mannequin	Limited fine motor haptic cues: inaccurate rep. of needle depth; lack of haptic tissue rep.

*Skills also applicable to Tier 1 TCCC training (ASM)

Table 3: Haptic Cues associated with TCCC Guidelines – Respiration/Breathing – Tension Pneumothorax Treatment Examples

Step	Haptic Cues*	VR	VR/H	AR/m	AR/M
If chest seal in place, burp or remove chest seal	Position self within arm's reach of casualty			X	X
	Reach out to seal location on patient chest	X	X	X	X
	To burp, grasp corner of seal and lift, allowing air to be released				
	· Contact force when hand reaches seal		X	X	X
	· Ability to perform pinch motion to grasp corner		x	X	X
	· Force needed to lift seal		X	X	X
	· Force needed to burp seal		X	X	X
	To remove, grasp corner of seal and pull off of casualty				
	· Contact force when hand reaches seal		X	X	X
	· Ability to perform pinch motion to grasp corner		x	X	X
	· Force needed to remove seal		X	X	X
Place casualty supine or recovery position (unless conscious and sitting to keep airway clear)	Position self within arm's reach of casualty			X	X
	Reach out and place hand on shoulder and hip				
	· Contact force when casualty is touched		X	X	X
	Roll casualty to desired position				
	· Force required to roll body weight to desired position			X	X
Decompress chest on side of injury with 14-gauge or 10-gauge, 3.25-inch needle/catheter unit	Obtain needle, catheter unit and strip of tape from aid bag				
	· Select aid bag	X	X	X	X
	· Select/Pull out needle and catheter	x	x	X	X
	· Open packaging		x	X	X
	· Rip off strip of tape			X	X
	Locate insertion site				
	· Reach out with non-dominant hand and feel for second intercostal space just above third rib		X	x	X
	· Use dominant hand to position needle perpendicular to chest cavity		X	X	X
	Firmly insert needle into skin at 90^0 angle				
	· Use dominant hand to press needle tip firmly				X
	· Feel 'pop' as needle enters chest cavity		x		X
	· Hold position for 5-10 seconds		X		X
Remove after NDC performed	Withdraw needle while holding catheter in place				
	· Use dominant hand to pull up on needle		x		X
	· Use non-dominant hand to hold catheter in place		x	x	X
	· Set needle aside for disposal			x	X
	Secure catheter in place with tape				
	· Use dominant hand to grab tape		x	x	X
	· Stick tape down with fingers to hold catheter in place			x	X

*Assumes integration with (m) a physical mannequin structure with low fidelity tissue representation, and (M) a physical mannequin structure with high fidelity tissue representation

CCTT USE CASE

Specialized vehicle training systems such as the Close Combat Tactical Trainer (CCTT) are critical to support training and preparing warfighters to operate in live environments. However, the cost of developing specialized platforms for multiple systems can be prohibitive, especially because the cost of logistical requirements such as housing the training equipment and paying support personnel is added on top of the initial investment costs (Padron, Mishler, Fidopiastis, & Stanney, 2018). These costs increase even more when accounting for the need for separate training platforms to support individual crew member skill training versus integrated team training, and the need to upgrade training platforms as new battlefield systems are rolled out (e.g., M1A1, M1A2, and M1A2 System Enhancement Package variants of the Abrams tanks).

One factor in the cost of such training systems is the fact that that they have traditionally focused on high sensory and functional fidelity accomplished with a hardware-centric approach. As a result, a new hardware platform must be created for every vehicular variant that requires a simulated training environment. This requires a complete physical replication of user environments such as cockpits or crew stations - an expensive prospect for both creation and maintenance. This hardware-centric approach is not scalable, cannot deliver timely training, and its cost is rapidly becoming unsustainable, especially as military training budgets tighten.

However, creating a full VR training solution for these types of training systems can present challenges as well. It is necessary to consider the possibility of negative transfer. Training systems like these need to be designed with the training objectives in mind. Haptic cues are often vital to task performance (which are of limited presentation in full VR solutions), and if a training system does not address these then it loses training effectiveness and adoptability. Further, the haptic cues critical to this task environment differ from those in the TCCC use case. Here, drivers and gunners typically have their vision 'out of the vehicle' and must rely on muscle memory and physical touch to know which controls are where and how to activate each. Thus, this environment does not allow for hand-eye coordination or visual guidance of movement. Here, the physical interactions are done solely on muscle memory, and training should consider incorporating haptic cues that are critical to learning, retention and forming this muscle memory. The following sections focus on two of the positions within an M1 Series tank, and the haptic cues necessary for each of their stations

The driver tasks requiring haptic cues are listed in Table 4. Many of these tasks rely on muscle memory in isolation to identify and manipulate controls, as eyes are 'locked in' on the view scope. Because of this, VR/H cues in this case considered a mixed modal design approach, where physical elements were integrated with VR visuals to provide a multimodal experience. As shown in Table 4, the haptic cues were considered against xR technologies in general for their ability to provide adequate physical representation of these cues. Here, VR (visual only) is compared against VR/H (with haptics) and AR. The basic components for steering, shifting, and braking rely heavily on haptic cues such as reaching out and feeling the shift control go into a new position, feeling the resistance of the brake pedals as they are pressed, and feeling the steering handgrips move in the correct directions with the correct level of resistance (along with complimentary visual cues of seeing changes in scenery through the vision blocks as the tank moves).

The gunner tasks requiring haptic feedback are listed in Table 5. Under normal conditions, the gunner employs the Gunner's Primary Sight (GPS) and associated controls to view and find the range to the targets, and the Gunner Control Handle (GCH) to aim and fire at targets. Because the gunner primarily looks through the GPS during collective tasks, much of the instrumentation requires haptic feedback so that the gunner can operate controls by touch (Figure 4).

Figure 4: Gunner Control Interface

Table 4: M1 Series Tank Driver Position Example Tasks

Task	Haptic Cues	VR	VR/H	AR
Drive an M1 Series Tank	Operate Transmission Shift Controller			
	· Use hands to release transmission knob from one position (neutral (N), reverse (R), low (L), drive (D), pivot (P) and move to another without visual feedback		X	X
	· Reach out to touch knob		X	X
	· Move knob in desired position		X	X
	Operate Steer-throttle Controls			
	· Have 2 hands on T-handle grips		X	X
	· Feel contact force of T-handle		X	X
	· Turn T-handle left/right to control movement of vehicle		X	X
	· Turn T-handle grips forward and rearward to establish speed of the vehicle		X	X
	· Feel force feedback/resistance related to moving		X	X
	Operate Service Brake Controls			
	· Place foot on brake pedal		X	X
	· Feel contact force of brake		X	X
	· Depress brake pedal		X	X
	· Force feedback that represents resistance		X	X
Use Driver's Vision Enhancer (DVE) for Rearward Viewing	Operate the Driver's Vision Enhancer (DVE)			
	· Use hand to depress menu buttons until a click is felt		X	X
	· Use hand(s) to rotate knobs left/right until a click is felt		X	X
Start the Engine of M1 Series Tank	Set Shift control to Neutral (N)			
	· Use hand to ensure knob is in N		X	X
	· Reach out to touch knob		X	X
	· Move knob in desired position		X	X
	Press POWER SOURCES button			
	· Use hand to depress menu button		X	X
	Press PUSH TO START button			
	· Use hand to depress menu button		X	X

Table 5: M1 Series Tank Gunner Position Example Tasks

Task	Haptic Cues	VR	VR/H	AR
Identify target in reticle view in order to engage	Look through the Gunner's Primary Sight (GPS) eyepiece			
	· Move head to GPS eyepiece	x	X	
	· Feel forehead contact sight		X	X
	· Use hands to operate switches and buttons using muscle memory		X	X
Engage maximum magnification	Change magnification from 3X to 10X			
	· Use hands to operate lever by muscle memory		X	X
	· Feel force feedback/resistance as lever moves to correct position		X	X
Lay the Main Gun on target	Squeeze Gunner's Control Handle (GCH) palm switches			
	· Use hands to operate handle by muscle memory		X	X
	· Feel switches depress		X	X
	· Feel force feedback as switches are held down		X	X
	Rotate GCH to track a moving target			
	· Use hands to operate handle by muscle memory		X	X
	· Feel handle rotate		X	X
Respond to a Warning Message with GPS sight view	Release GCH palm switches			
	· Use hands to operate handle by muscle memory		X	X
	· Feel palm switches pop out		X	X
	Reset AIR/GROUND and Laser Range Finder (LRF) push buttons			
	· Use hands to locate and depress buttons by muscle memory		X	X
	· Feel buttons depress		X	X
	Recycle Laser Range Finder (LRF) switch			
	· Use hands to toggle switch by muscle memory		X	X
	· Feel switch move into correct position		X	X

LIMITATIONS OF HAPTIC FRAMEWORK

The framework presented here is a high level, theoretically-driven guide based on currently available technology that promotes high fidelity haptic cue integration where possible. There are tradeoffs within simulated training design, where multimodal cue criticality and cost/space constraints of incorporating the cue into an xR solution need to be considered. For example, while Table 3 shows that AR is a superior xR solution for training tension pneumothorax, this solution requires a physical mannequin to be successful. Mannequins in use in the field can range from low cost mannequins (~1K price range) that provide physical size/weight of casualty with low fidelity tissue representation to high cost mannequins (~20-50K price range) that provide higher fidelity capabilities in symptom presentation, yet often still have low fidelity tissue representation. Thus, relying on a mannequin comes with increased cost and footprint requirements (for training, as well as equipment storage). The optimal solution would consider integration of AR with existing mannequins and training curriculum that saves on cost and footprint requirements (as they are already present), yet expand mannequins (particularly low fidelity) with 'haptic kits' that can provide high fidelity tissue representation for key body regions to support training requirements and optimal presentation of critical haptic cues. This can provide a training solution that minimizes additional cost while providing necessary haptic cues to enhance motor learning. Similarly, Table 5 shows that the both VR/H and AR can provide the critical haptic cues for the identified tasks. Because the gunner is visually focused outside of the tank using the Gunner's Primary Sight (GPS), AR vision capabilities are not required for this task, and may in fact negatively impact training, as the real world does not support visual guidance of hand placement. Further, the AR headset would interfere with placing the forehead against the GPS. Within a VE, however, this physical cue of contact with the GPS is also not present, although the VR headset itself can provide a haptic cue of physical contact with 'a system' on the forehead. Thus, the haptics framework presented here is high level guidance – specific sensory cues need to be identified and considered in the context of the multimodal task environment, and prioritized in terms of how best to provide high fidelity haptic cues where needed to optimize learning and training transfer for motor skill acquisition.

CONCLUSIONS

This paper reviewed existing haptic technologies applicable for xR solutions, and provided a haptics framework that can guide which xR solution may be most applicable to support motor skill acquisition within a simulated environment. While the framework provided is high level, it provides guiding principles that were demonstrated through two use cases. Utilizing sensory task analysis data, which outlines specific haptic cues critical to training tasks and objectives, one can compare technology capabilities from Table 1 to the critical cues and identify which technology best suits the haptic cue needs. Should multiple technologies meet the needs, other factors such as cost, maintenance, and generalizability of the technology may also be considered to identify the optimal option to support the xR training environment. Thus, conducting front end sensory task analyses that break down training objectives and tasks to identify the specific multimodal cues[1] needed to afford learning are critical to optimizing xR learning environments. While current technologies may be unable to support all haptic cue needs required today, research and development in optimizing presentation of these critical cues is ongoing. Future R&D is poised to develop technologies that not only provide relevant haptic cues in VR, but also in an AR environment, such that physical interaction with virtual entities will be haptically experienced in a natural, meaningful way. Great strides have been made in recognition and integration of haptics into xR solutions – the merging of virtual and live training will continue to perfect where, when and how to present critical haptic cue interactions to support motor learning and optimize immersive, effective, and efficient training experiences.

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[1] This paper focuses on haptic cues, but sensory task analyses can and are often completed across all sensory modalities to identify critical cues for learning.

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