An HCI based framework to support the design of XR based simulators for training medical residents in orthopedic surgery

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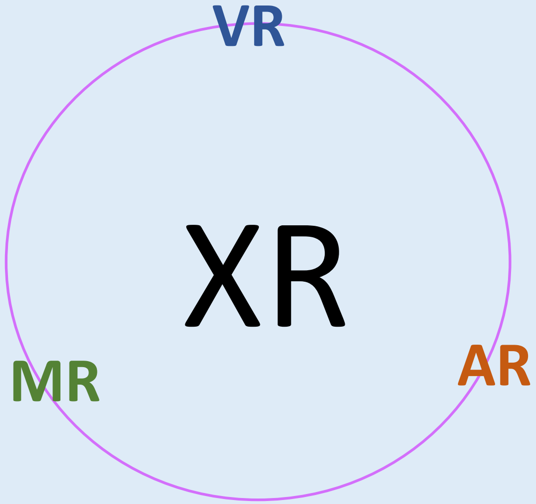
Introduction – Extended Reality (XR)



- Extended Reality (XR) is an umbrella term representing
  - Virtual Reality (VR)
  - Augmented Reality (AR)
  - Mixed Reality (MR)
  - Other related technologies

- VR - enables the creation of simulated environments through extensive use of vision, touch and hearing

- MR - merger of the real and virtual world to create a new environment where there is an interaction and co-existence of real and virtual objects

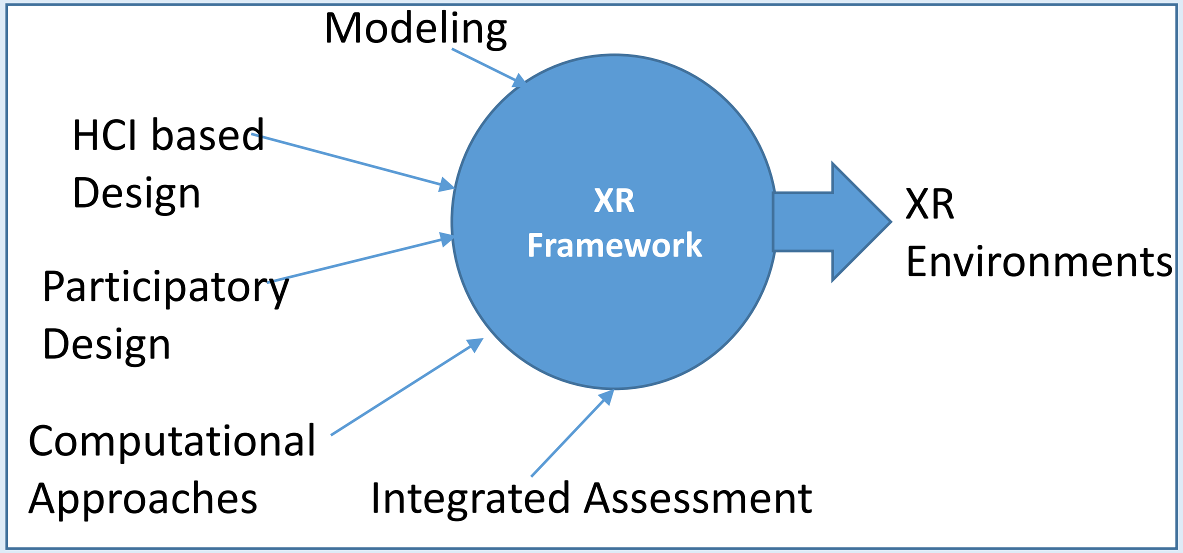
- AR - enhance a user's perception of reality by providing additional computer generated information

- XR Applications
  - Medical Training
  - Education
  - Manufacturing
  - Space systems

Why XR?
  - Safe Training
  - Repeatable
  - No physical equipment and supplies are wasted
  - Ubiquitous

Framework

- Framework
  - A basic structure to support or guide the building of something
- XR Framework
  - Necessary components for the creation of XR environments



- Previous work on XR framework
  - Pfeiffer et al. 18 – Open-source VR framework for surgical application
    - **Patient data handling, visualization, assessment**
  - Fiederer et al. 19 – Framework for VR based Neurosurgery
    - **Data segmentation, visualization, performance evaluation**
  - Xiao et al. 20 – Physics based framework for Neonatal Endotracheal Intubation (Vive and Haptic Interface)
    - **Computational approaches, deformation modeling, haptic modeling, skill assessment and survey**
  - Karabiyik et al. 19 – VR framework for first responder training
    - **Training, evaluation, support for multiple VR platform**

- No comprehensive XR framework for training context
- To fill the gap
  - Holistic framework for the design, development and assessment of XR based training simulators

Voids

- Focus only on certain aspects essential to develop XR-based environments

- No focus on creation of comprehensive framework for development of XR training environments
  - HCI, participatory design, information modeling

- Lack of proper utilization of the participatory design approach during the creation of information models

- Lack of an integrated assessment approach involving assessment of
  - Comprehension, skills, and knowledge as well as the cognitive load

Problem Statement

Based on the voids,

- Need of a holistic framework
  - For design, development and assessment of XR based training environments

- The holistic framework involving components such as
  - HCI based criteria, participatory design, information modeling, integrated design and assessment

- Need of involving subject matter experts (participatory design approach)
  - For the creation of information models

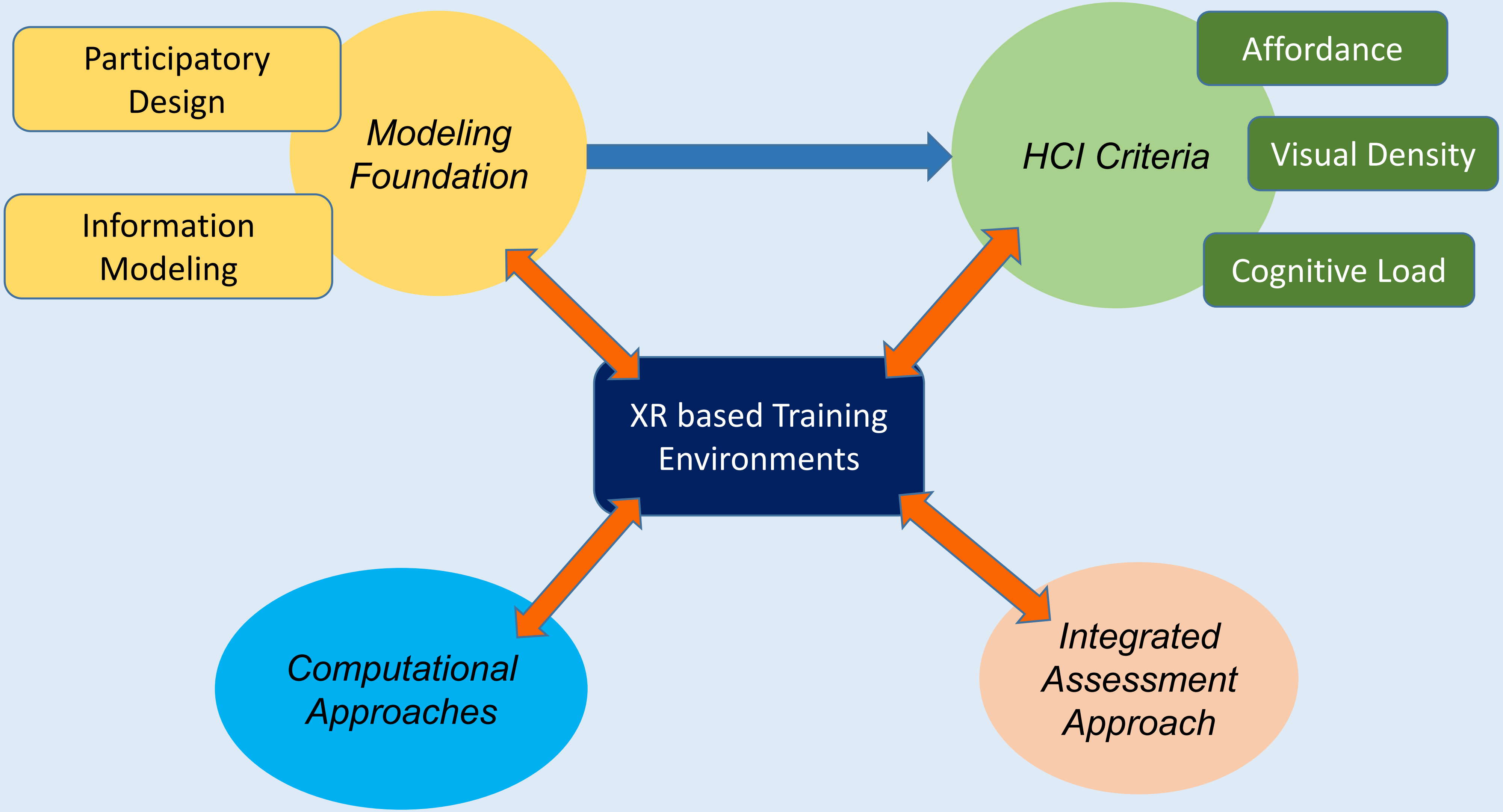
- Need of integrated assessment approach
  - To understand the impact of HCI criteria on skills and knowledge acquisition

	Aspects of the XR Framework								
	HCI Criteria			Modeling Foundation		Computational Approaches	Assessment Techniques		
Paper	Affordance	Cognitive Load	Visual Density	Participatory Design	Information Modeling	Use of Algorithms	Skills Assessment	Knowledge Assessment	Subjective Surveys
Bhargava	✓								
Regia-Corte	✓								
Karanam	✓								
Anderson		✓							
Britt		✓							
Research	✓	✓	✓	✓	✓	✓	✓	✓	✓
Fang								✓	✓
Gonzalez							✓		✓
Shao								✓	✓
El Hariri						✓	✓		
Vankipuram						✓	✓		
Choi						✓	✓		
Westwood							✓		✓
Nemani					✓				
Janin					✓				
Parmer					✓				
Ausburn							✓	✓	

Research Objectives

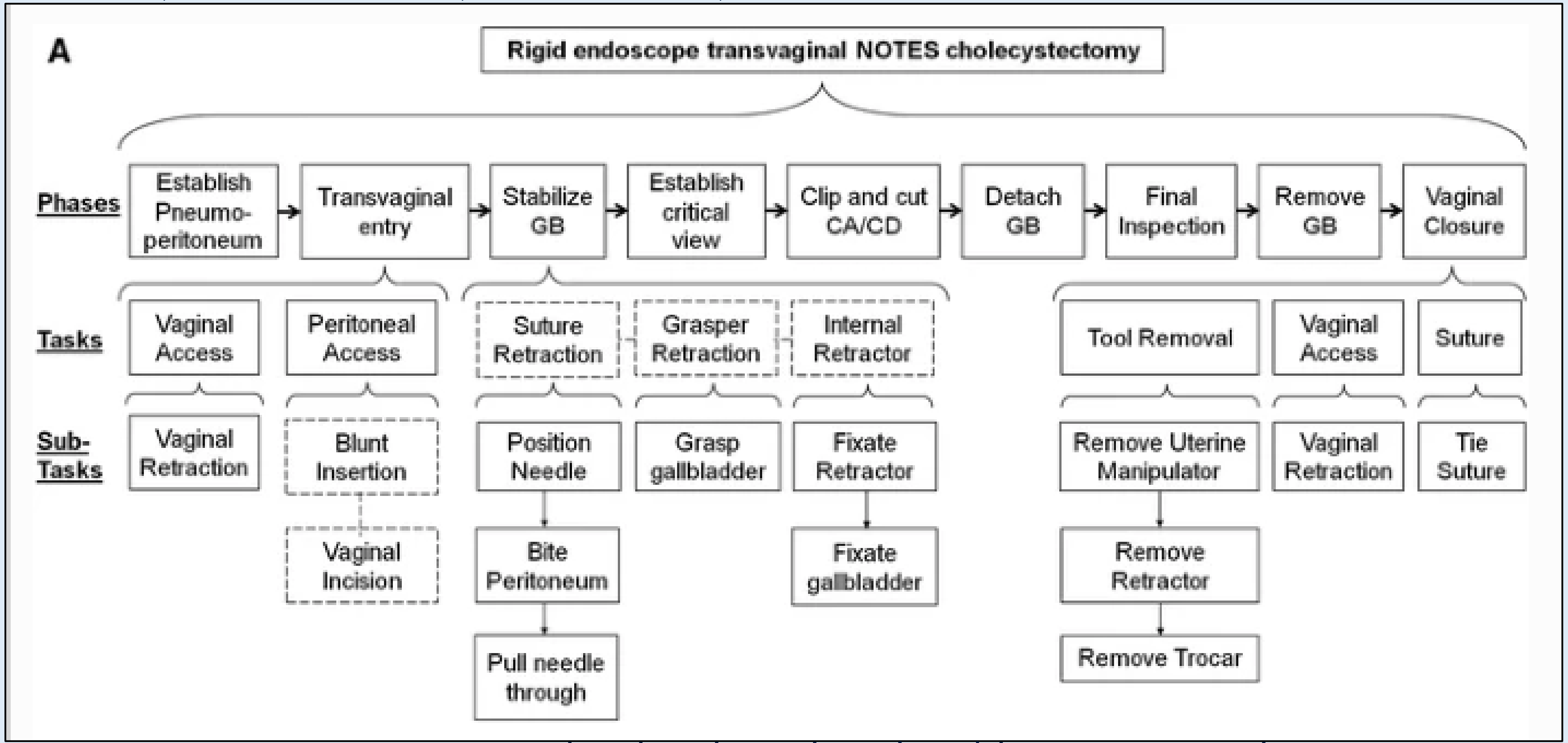
- HCI Based Framework
  - Develop a framework based on HCI principles for the design of XR training environments
- Modeling Foundation for Participatory Design
  - Explore the adoption of information intensive process models
- HCI based Design
  - Integrate the HCI criteria in design and development of XR environments
  - Design of assessment metrics and methods for assessment of XR environments
- Integrated Assessment Approaches
  - Assess the effect of HCI criteria on comprehension, skills and knowledge acquired

Framework and Components



Modeling Foundation: Related Work

- No structured approach to support participatory design
- Prior approaches relied on basic flow charts and hierarchical trees to understand the process
  - Paul et al. 20, Nemani et al. 13, Janin et al. 13, Jalote-Parmer et al. 08



Hierarchical Task Analysis (HTA) by Nemani et al.

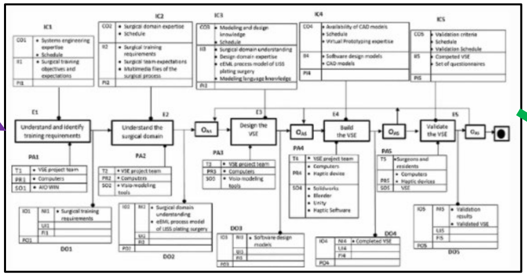
Lin, J. C., Paul, A. A., Scott, I. U., & Greenberg, P. B. (2020). Integrating Mental Practice into a COVID-19 Appropriate Virtual Reality Cataract Surgery Course for Ophthalmology Residents. Journal of Academic Ophthalmology, 12(02), e298-e300.
Nemani, A, Sankaranarayan, G., Roberts, K, Panait, L,m Cao, C., De, S., Hierarchical Task Analysis of Hybrid Rigid Scope Natural Orifice Translumenal Endoscopic Surgery (NOTES) Cholecystectomy Procedures, Proceedings of the 2013 Medicine Meets Virtual R69. Jannin, P.,Surgical Process Modeling: Methods and Applications, Presentation at the 2013 Medicine Meets Virtual Reality Conference (NEXTMED/ MMVR20), February 20-23, San Diego, CA (2013).eality Conference (NEXTMED/ MMVR20), February 20-23, San Diego, CA (2013), pp.293-297.
Jalote-Parmar, A. and P. Badke-Schaub (2008). "Workflow Integration Matrix: A Framework to Support the Development of Surgical Information Systems." Design Studies 29 (4): 338-368

Modeling Foundation: Approach

- Proposing creation of an information intensive process model
- Foundation for this participatory process
- Focuses on the involvement of domain expert e.g. surgeon
  - Involvement of three expert surgeons
- Foundation of the design, building, and assessment

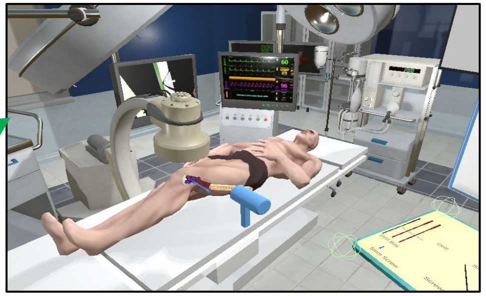
Domain Expert

supports creation of

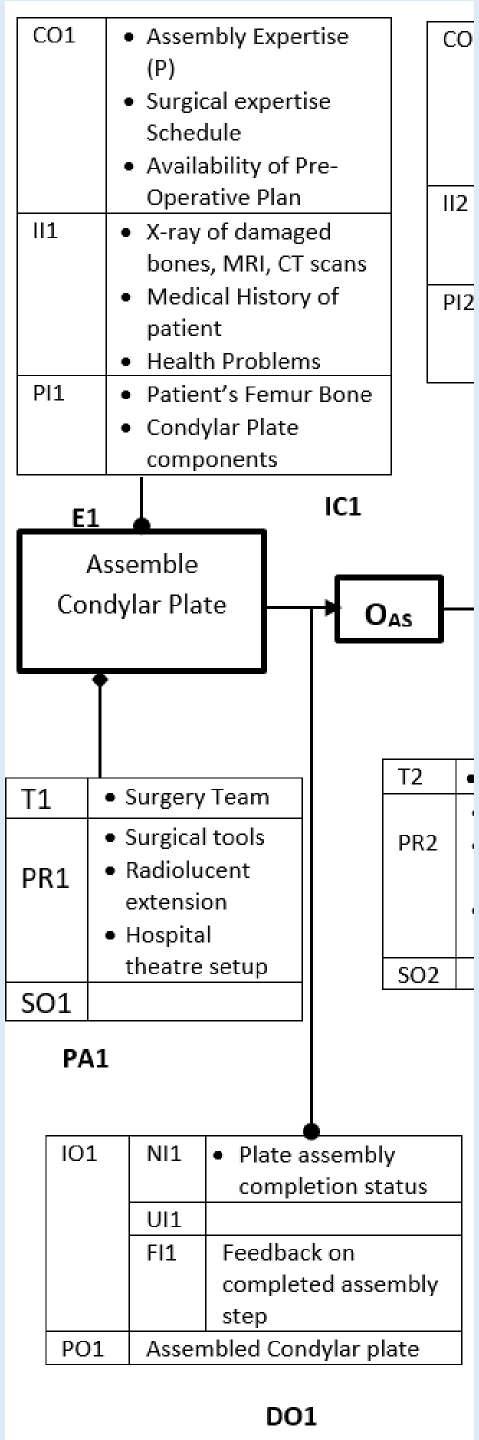


Information Model

foundation for

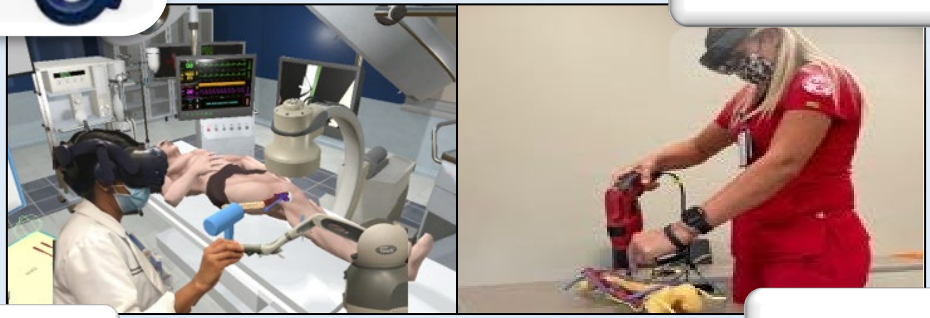


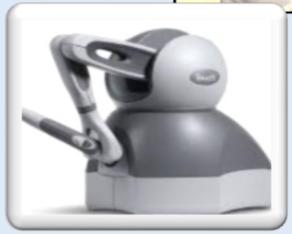
**Avinash Gupta*, J. Cecil, M. Pirela-Cruz, & P. Ramanathan, (2019). A Virtual Reality Enhanced Cyber-Human Framework for Orthopedic Surgical Training. IEEE Systems Journal 13, no. 3 (2019): 3501-3512 (IF: 5.28)*


CO1
Assembly Expertise (P)
Surgical expertise Schedule
Availability of Pre-Operative Plan
II1
X-ray of damaged bones, MRI, CT scans
Medical History of patient
Health Problems
PI1
Patient's Femur Bone
Condylar Plate components
CO
II2
PI2
E1
IC1
Assemble Condylar Plate
OAS
T1
Surgery Team
PR1
Surgical tools
Radiolucent extension
Hospital theatre setup
SO1
PA1
T2
PR2
SO2
IO1
NI1
Plate assembly completion status
UI1
FI1
Feedback on completed assembly step
PO1
Assembled Condylar plate
DO1

Design of Training Environments

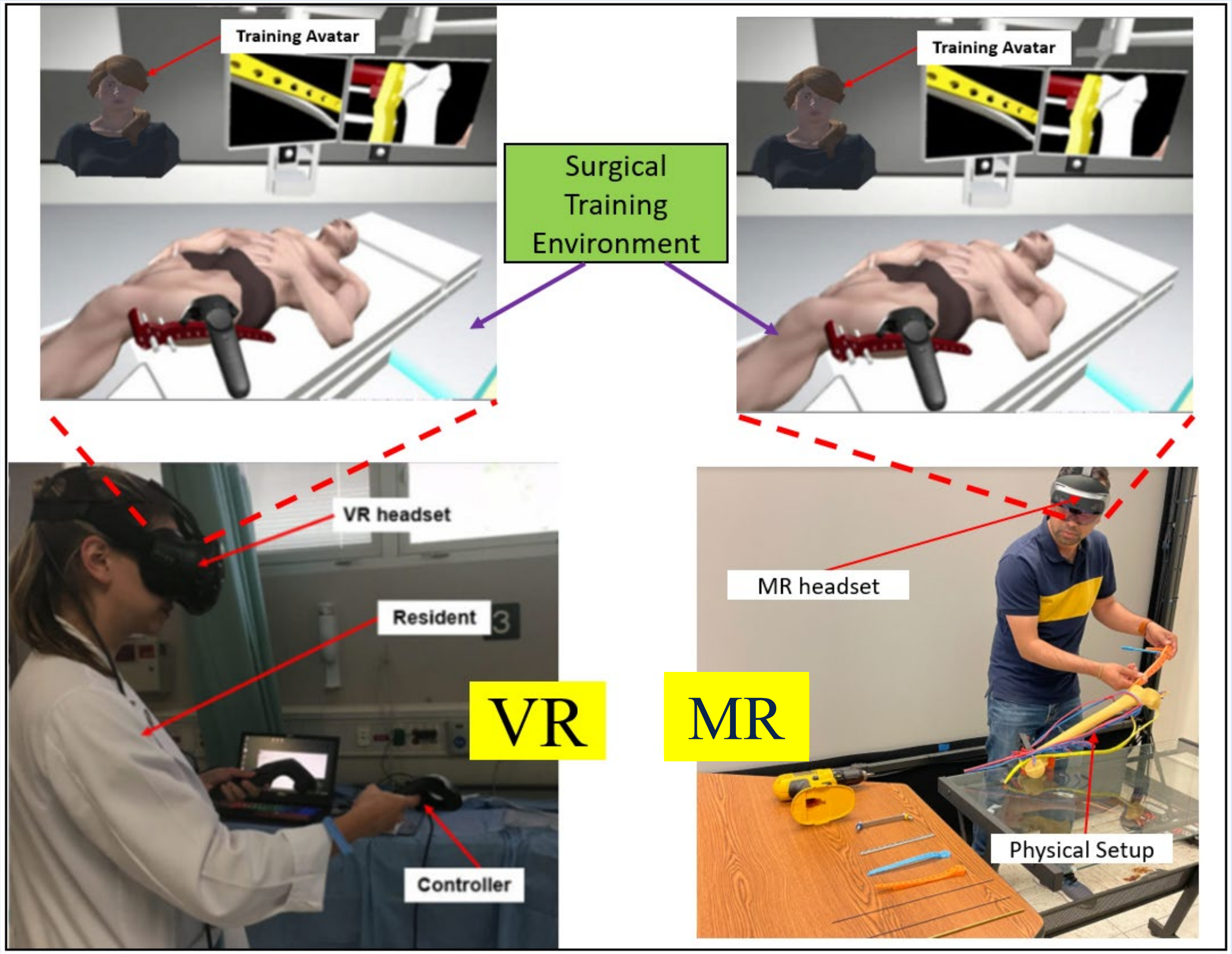
- 3D modeling
  - Solidworks, Sketchup, Blender
- Simulation Development
  - Unity Engine
- Interaction Devices/Platform
  - VR (Vive Pro Eye)
  - MR (HoloLens 2)
  - Haptic (Geomagic Touch)
- Physical Mockup Creation





Development of Training Environments

WHAT USER VISUALIZES



USER

Integrated Assessment: My Approach

Assessment Criteria	Assessment Method
Affordance	• Comprehension
Cognitive Load	• Skills/ Knowledge Assessment • Heart Rate/Pupil Dilation
Comparison Studies	• Skills Assessment • Knowledge Assessment

Integrated Assessment: My Approach

- Comprehension
  - Questionnaire related to understanding of the scene and functional relationships between Objects of Interests (OOIs) in the scene

- Knowledge Assessment*
  - Questionnaire based pre and post-test method (related to surgical procedure)

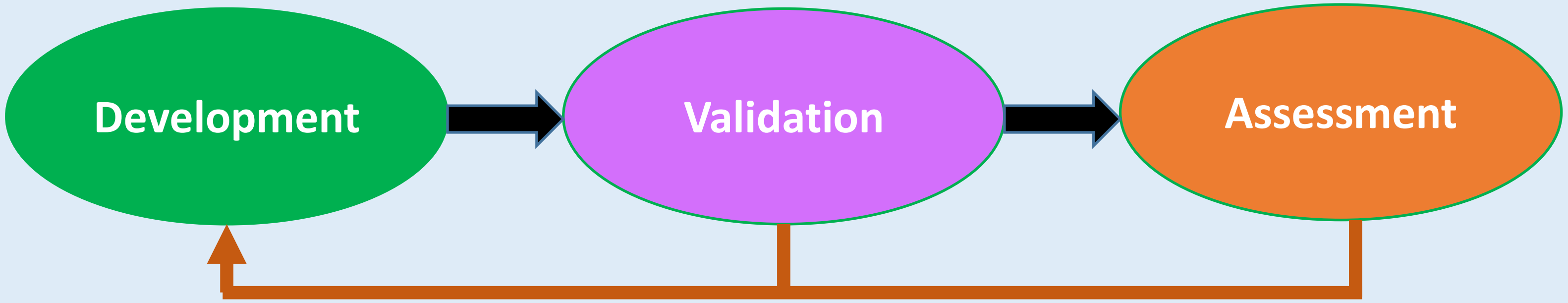
- Skills Assessment**
  - 3 challenge scenarios based on Training environments 1, 2 and 3
  - Provide no voice or text cues
  - Hint reduces score
    - Common for all the training environments
    - (Total no. of hints– no. of hints used)/Total no. of hints*100
  - Environment 2 and 3 are more complicated
    - specific scoring system apart from the hint based assessment

**Cecil, J., Gupta, A., & Pirela-Cruz, M. (2018). An advanced simulator for orthopedic surgical training. International journal of computer assisted radiology and surgery, 13(2), 305-319.*

***Gupta, A., Cecil, J., Pirela-Cruz, M. (2020). A Cyber-Human based Integrated Assessment approach for Orthopedic Surgical Training. In 8th International Conference on Serious Games and Applications for Health, IEEE SeGAH, Aug 12-14, 2020.*

Partner Institutions for Assessment

- Assessment activities were conducted at
  - Texas Tech University Health Sciences Center, El Paso
  - MD Anderson Cancer Center, Houston
  - Dignity Regional Medical Center, Prescott Valley
  - Yavapai Regional Medical Center, Chandler
  - Northern Oklahoma College, Stillwater, Tonkawa, Enid
  - Northwestern Oklahoma State University, Enid

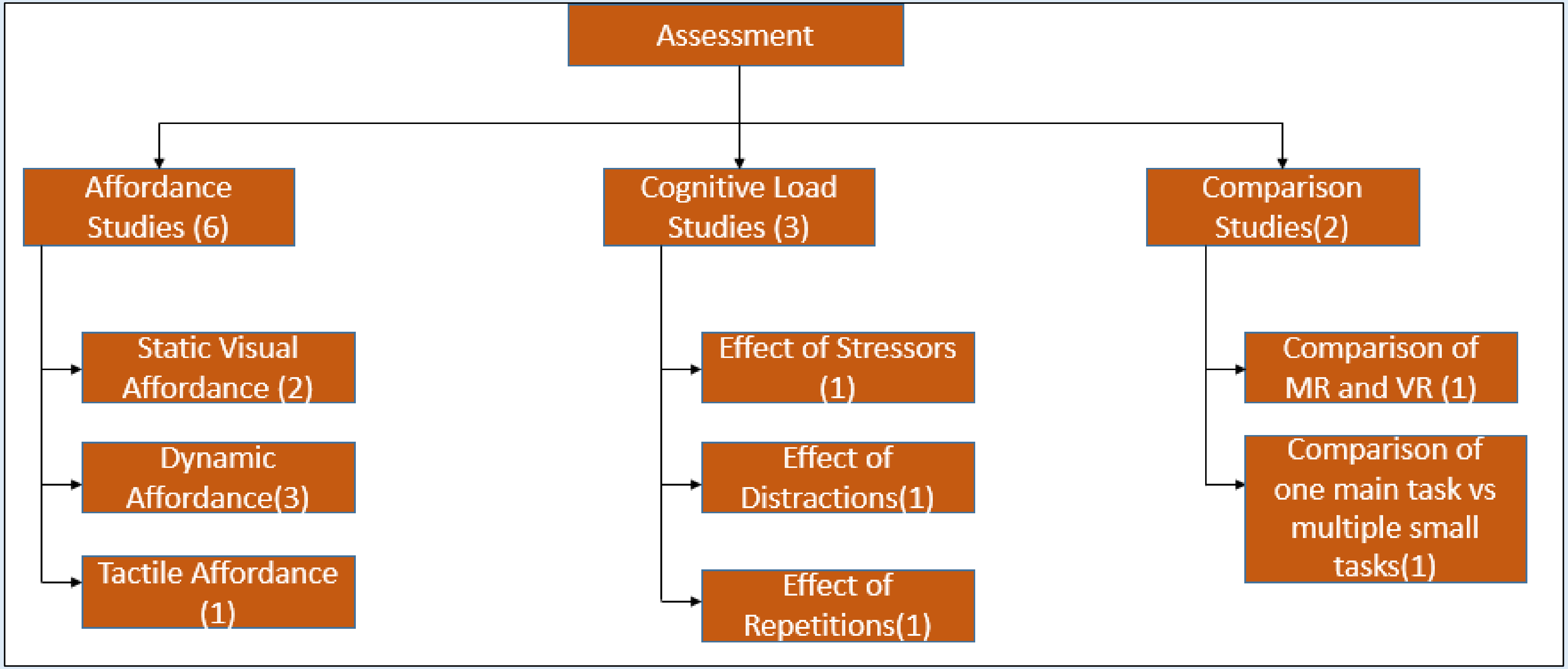


Participants' Demographics for Assessment

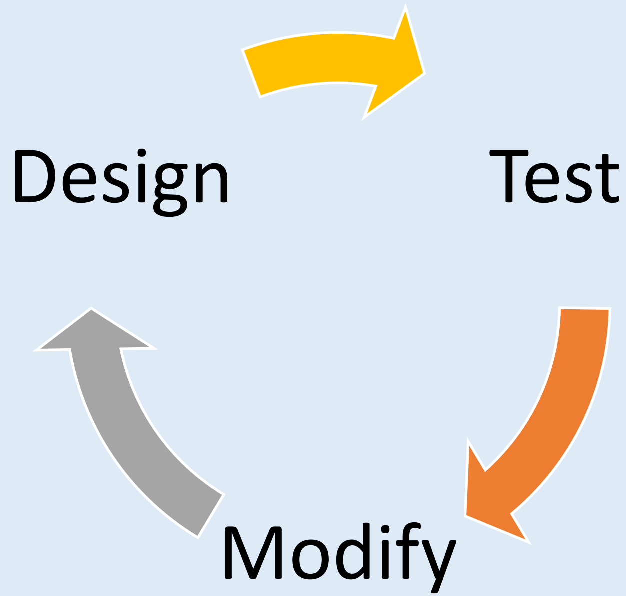
	Nursing Students (n = 58)	Nurse (n = 82)	Medical Students (n = 33)	Residents (n = 18)	Other Medical Personnel (n = 30)
Experience in Years	High: 18 Low:0 Mean: 4	High: 54 Low:0 Mean:16	High: 3 Low:0 Mean:1	High: 5 Low:1 Mean:2	High: 9 Low:3 Mean:5
Age	High: 40 Low: 18 Mean: 26	High: 71 Low: 23 Mean: 41	High:32 Low: 24 Mean: 26	High:32 Low: 27 Mean: 30	High:48 Low: 29 Mean: 38
Prior Experience in VR technology	Yes: 15 No: 43	Yes: 13 No: 69	Yes: 9 No: 24	Yes: 5 No: 13	Yes: 3 No: 17
Gender	Male:2 Female:56	Male: 15 Female:67	Male: 23 Female:10	Male: 12 Female:6	Male:11 Female:19
Prior Experience in Surgical Procedure	Yes: 1 No: 57	Yes: 8 No: 74	Yes: 5 No:29	Yes: 14 No: 4	Yes: 6 No: 14

Design of Experiment for Assessment

- Studies



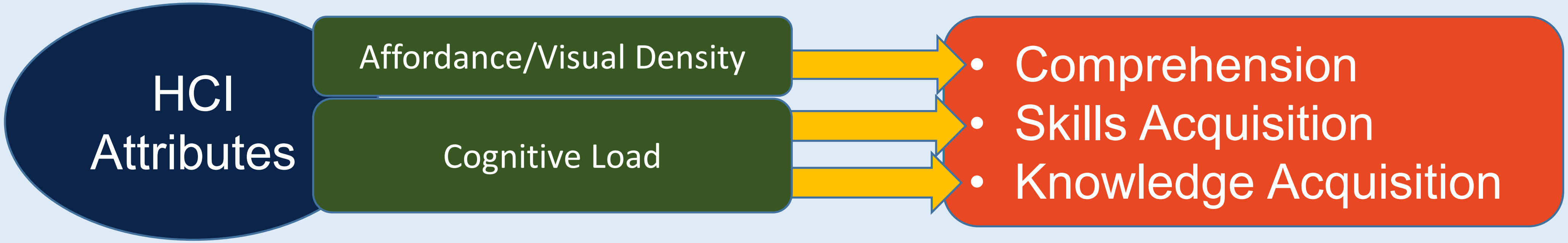
HCI Based Design: Overview



Results of Iterative Design Process

HCI based Design: Overview

- Multi-faceted HCI based design approach is proposed
- Attributes such as affordance, cognitive load, and visual density.
- New measures have been proposed
  - Dynamic Affordance
    - Visual and Tactile Affordance
- Study of the relationships between



Affordance: Related Work

- Affordance
  - Other researchers have focused on static aspects of affordance in terms of spatial affordance *(Bhargava et al. 20, Wu et al. 18, Gagnon et al. 21)*
  - Do not address:
    - Dynamic Aspects
    - Effect of tactility
    - Effect of Visual Density (Focus on information density, Trepkowski et al. 19)
    - Effect of complexity of tasks

Bhargava, A., Lucaites, K. M., Hartman, L. S., Solini, H., Bertrand, J. W., Robb, A. C., ... & Babu, S. V. (2020). Revisiting affordance perception in contemporary virtual reality. Virtual Reality, 24(4), 713-724.

Wu, H., Adams, H., Pointon, G., Stefanucci, J., Creem-Regehr, S., & Bodenheimer, B. (2019, March). Danger from the deep: A gap affordance study in augmented reality. In 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR) (pp. 1775-1779). IEEE.

Gagnon, H. C., Rosales, C. S., Mileris, R., Stefanucci, J. K., Creem-Regehr, S. H., & Bodenheimer, R. E. (2021). Estimating distances in action space in augmented reality. ACM Transactions on Applied Perception (TAP), 18(2), 1-16.

Trepkowski, C., Eibich, D., Maiero, J., Marquardt, A., Kruijff, E., & Feiner, S. (2019, March). The effect of narrow field of view and information density on visual search performance in augmented reality. In 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR) (pp. 575-584). IEEE.

Affordance: Need

- Traditionally affordance defined only in terms of visual understanding of the scene

- Expand the notion of affordance to include
  - 3D visual, audio and text based representations which lends itself or presents to the user

- Dynamic Affordance
  - More encompassing definition of affordance
  - The user is in motion
  - Able to obtain a better understanding of the scene

Design of Experiment – Affordance Studies

Experiment	Independent Variable	Level	Dependent Variable
Static Visual Affordance	Position	Specified Position (Control group)	Comprehension
		User Chosen Position	
Static Visual Affordance – Effect of Visual Density	Visual Density	Low	Comprehension
		High	
	Position	Position 1	
		Position 2	
Dynamic Visual Affordance – Effect of Path	Path	Center Walk	Comprehension – Secondary Attention
		Peripheral Walk	Comprehension – Primary Attention
Dynamic Visual Affordance – Effect of Guidance	Guidance Model	Avatar	Comprehension
		Hand Model	
Dynamic Visual Affordance – Effect of Cues	Instruction Cues	Voice	Comprehension
		Text	
Tactile Visual Affordance	Tactility	Vive based controller	Comprehension
		Haptic device	

Affordance: Approach

Experiments conducted conclude that

- No best position or path that provides the maximum affordance to the user
  - 1.1. Best position or path depends on the nature of the target scene
- For some scenarios,
  - 1.2. the users preferred to walk in the center of the room, observing the target scene as they are rotating about their axis.
  - 1.3. For other scenarios, the users comprehended more while walking on the periphery of the target scene

- Target scene defined by cardinality of the scene as well as the complexity of the scene

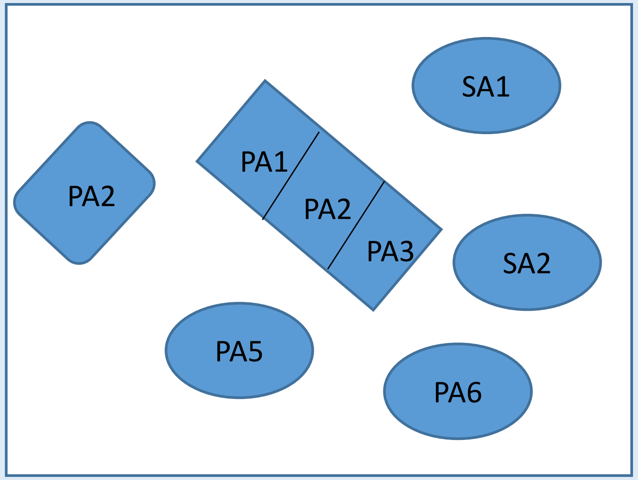
  C (Primary Region) = # of primary areas(PAs)

  C(PR) = PA1 + PA2….Pan; n>1

  When n = 1, C(PR) = PA1

  C (Secondary Region) = everything else in the scene expect PR

  C(SR) = Scene – PR



- In this section, 3 examples (S1, S2 and S3) are provided to support the conclusion

Experiment Summary

Experiment Name	Aim	Statistical test	Finding
Static Visual Affordance – Effect of Position	Understand the effect of Position on Affordance	T-test	No effect of position
Static Visual Affordance – Effect of Visual Density	Understand the effect of Visual Density and Position on Affordance	T-test	Statistically Significant effect of Position and Visual Density
Dynamic Visual Affordance – Effect of Path	Understand the effect of Path on Affordance	T-test	Statistically Significant effect of Path
Dynamic Visual Affordance – Effect of Guidance	Understand the effect of Guidance on Affordance	T-test	Statistically Significant effect of Guidance
Dynamic Visual Affordance – Effect of Cues	Understand the effect of Cues on Affordance	T-test	No significant effect for low complexity environment Statistically Significant effect for high complexity environment
Tactile Affordance	Understand the effect of tactile interface on Affordance	T-test	Statistically Significant effect of tactile interface

S3 Visual Affordance: Dynamic Affordance

Function of **comprehension (C)** walking a specific path **(P')** and observing a scene over a fixed period of **time (T)**

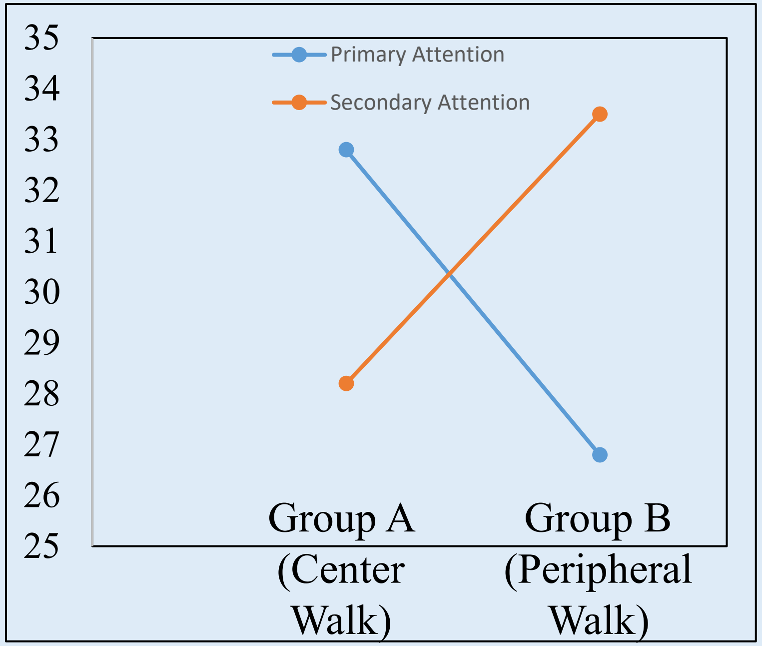
C = f (P, T)

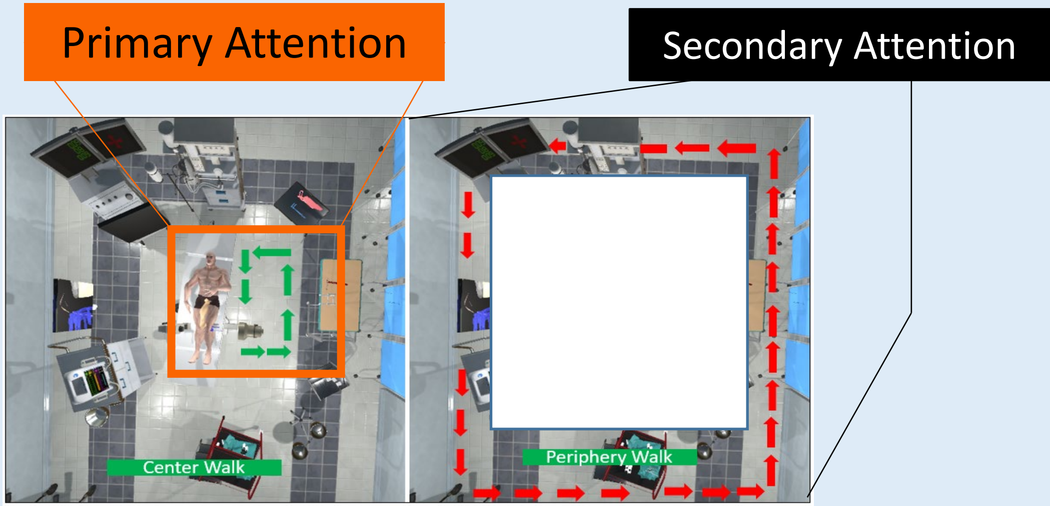
DA <=> C

Movement Allowed, Specific Path

- *Result of Data Analysis*

Path/Attention Area	Mean (SD)
Center/Primary	32.8 (7.73)
Center/Secondary	28.2 (7.7)
Peripheral/Primary	26.8 (5.6)
Peripheral/Secondary	33.5 (6.4)





Observations

- Group A scored significantly higher in questions related to primary attention area
- Group B scored significantly higher in questions related to secondary attention area
- In the next experiments, the users were given freedom to choose their own paths

T-Test Results

- *Statistically significant*
  - *For Center Walk (p-value = 0.004)*
  - *For Peripheral Walk (p-value = 0.001)*

Cognitive Load: Related Work

- Cognitive Load
  - Current research focus on assessing the load on the users using various subjective and objective assessment techniques
    - No focus on developing scenarios within the VR environments which would affect the load on the users *(Zhang et al. 17, Miscovic et al. 08)*

  - Few researchers have used dual-task measures depending on basic tasks such as buzzing sound, identifying letters, among others *(Anderson et al. 20, Britt et al. 2015)*

Zhang, L., Wade, J., Bian, D., Fan, J., Swanson, A., Weitlauf, A., ... & Sarkar, N. (2017). Cognitive load measurement in a virtual reality-based driving system for autism intervention. IEEE transactions on affective computing, 8(2), 176-189.

Britt, R. C., Scerbo, M. W., Montano, M., Kennedy, R. A., Prytz, E., & Stefanidis, D. (2015). Intracorporeal suturing: transfer from fundamentals of laparoscopic surgery to cadavers results in substantial increase in mental workload. Surgery, 158(5), 1428-1433.

Andersen, S. A. W., Frendø, M., & Sørensen, M. S. (2020). Effects on cognitive load of tutoring in virtual reality simulation training. MedEdPublish, 9.

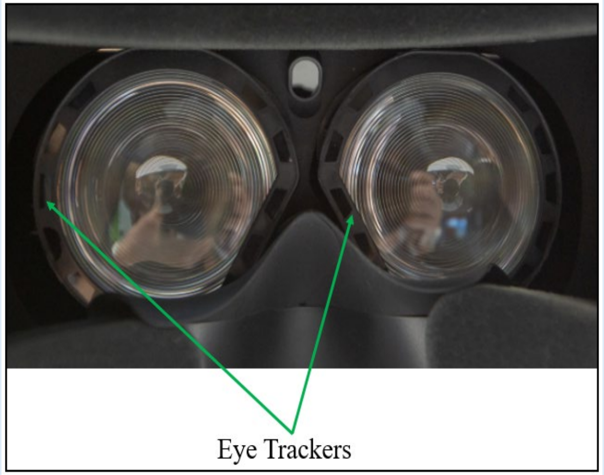
Cognitive Load: My Approach

- Understand
  - Effect of Stress inducers on skills and knowledge acquisition
  - Effect of disturbances and distractions
  - Effect of Repetition

- 3 experiments were performed
  - C1, C2, C3

- Measurements
  - Knowledge and Skills acquisition
  - Pupil dilation
  - Heart rate

Pulse oximeter



Eye Trackers (Vive Pro)

*****Avinash Gupta**, J. Cecil, Miguel Pirela-Cruz, Identification of Human Centered Design Factors and their impact on Design of Cyber-Human training environments for orthopedic surgery. In 9th International Conference on Serious Games and Applications for Health, **IEEE SeGAH**, 4th - 6th of August,2021 **(Accepted)***

Cognitive Load: My Approach

- Focused on including multiple types of cognitive load which impact the user during their interactions
- Types of load
  - Intrinsic to the surgical procedure (stress inducers related to patient)
  - Other loads were external loads (such as outside distractions and disturbances).
- Investigated how repeating a training procedure impacted the load imposed on the users
- Finding #2

  2.1 Stress inducers impact the user's comprehension and skills acquisition negatively

  2.2 Cognitive load experienced by a user depends upon

    (a) the complexity of the 3D training environment

    (b) the healthcare work experience of the users. (Eg. Nursing student and nurses).

  2.3 Audio-visual distractions negatively impacted the learning of the users the most

  2.4 Virtual repetition helped in lowering the cognitive load and improving their skills acquisition

- Showcased three examples to support the conclusion (C1, C2 and C3)

Design of Experiment - Cognitive Load Studies

Experiment	Factor (Independent Variable)	Level	Response Variable (Dependent Variable)
Cognitive Load – Effect of Stressors	Stressor inducers	No Stress inducers	Knowledge
		Stress inducers	Skills
Cognitive Load – Effect of Distractions	Distractions	No distractions	Knowledge
		Audio	
		Visual	Skills
		Audio-visual	
Cognitive Load – Effect of Repetition	Repetition	Low (2)	Skills
		High (5)	

Experiment Summary

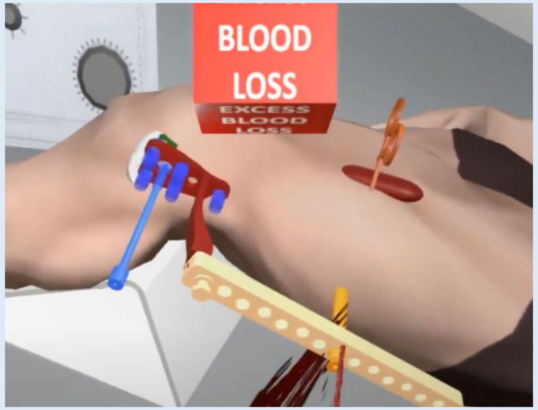
Experiment Name	Aim	Statistical test	Finding
Cognitive Load – Effect of Stressors	Understand the effect of stress inducers on skills and knowledge acquisition	T-test	Statistically Significant effect of Stress Inducers
Cognitive Load – Effect of Distractions	Understand the effect of distractions on skills and knowledge acquisition	ANOVA	Statistically Significant effect on Skills acquisition No significant effect on knowledge acquisition
Cognitive Load – Effect of Repetition	Understand the effect of repetition on skills and knowledge acquisition	T-test	Statistically Significant effect of Repetition

C1. Cognitive Load: Effect of stressors

- *Method*
  - *Task*
    - *Lag Technique*
  - *Stress Inducers*
    - *Patient shaking and making noises (heart rate high)*
    - *Blood hemorrhage*
  - *Data Collection*

No Inducers	Stress Inducers
Subject 1-40	Subject 41-80

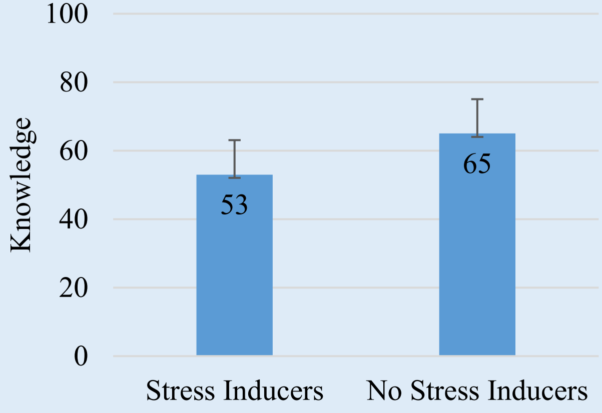
- Data Analysis
    - *Testing for Normality Assumption*
    - *Student T-test*

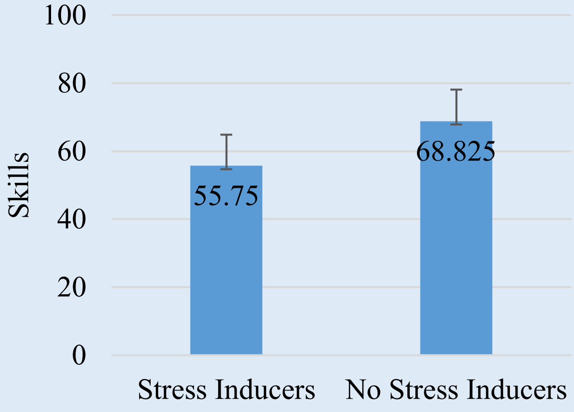


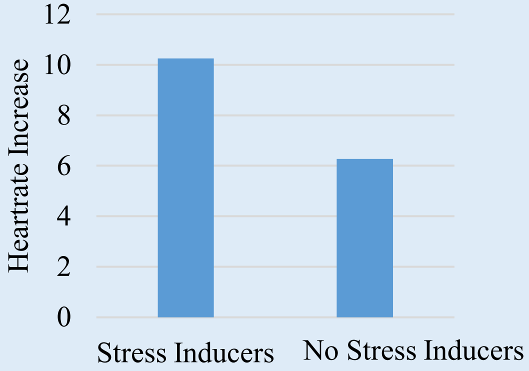
C1. Cognitive Load: Effect of stress inducers

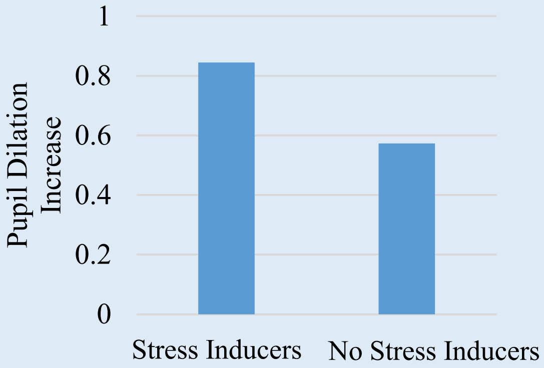
Results

- Normally Distributed data









T-test Results

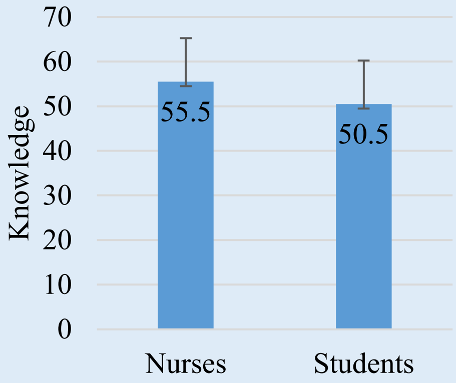
- *Statistically significant*
  - *Knowledge (p-value = 0.001)*
  - *Skills(p-value = 0.0035)*

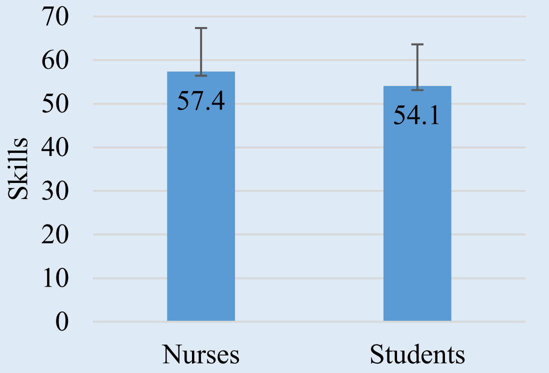
Observation

- Group interacting without stressors received significantly higher scores in skills and knowledge assessment
- Group interacting with stressors had higher heartrate increase and higher pupil dilation

Other Observation

- Experienced nurses were less affected by stressors compared to nursing students





*****Avinash Gupta**, J. Cecil, Miguel Pirela-Cruz, Identification of Human Centered Design Factors and their impact on Design of Cyber-Human training environments for orthopedic surgery. In 9th International Conference on Serious Games and Applications for Health, **IEEE SeGAH**, 4th - 6th of August,2021*

Design of Experiment - Comparison Studies

Experiment	Factor (Independent Variable)	Level	Response Variable (Dependent Variable)
Comparison – MR and VR	Platform	MR	Knowledge
		VR	Skills
Comparison – Main Task and Sub Tasks	Type of Task	Main Task	Skills
		Sub Tasks	Knowledge

Comparison study

- Focused on understanding the usefulness of MR and VR in different scenarios with varying levels of complexity
- The research experiments concluded have led to the conclusion that

  3.1. Participants using MR environments demonstrated significant improvement for complex environment

  3.2. No significant difference between MR and VR environments for low complexity environments

  3.3. Experience level of the users impact the preference of MR and VR based environments
- Experiments conducted with two levels of complexity (high and low)
  - With nursing students and experienced nurses to support the conclusion provided above