Assessing the impact of virtual reality on surgeons' mental models of complex congenital heart cases

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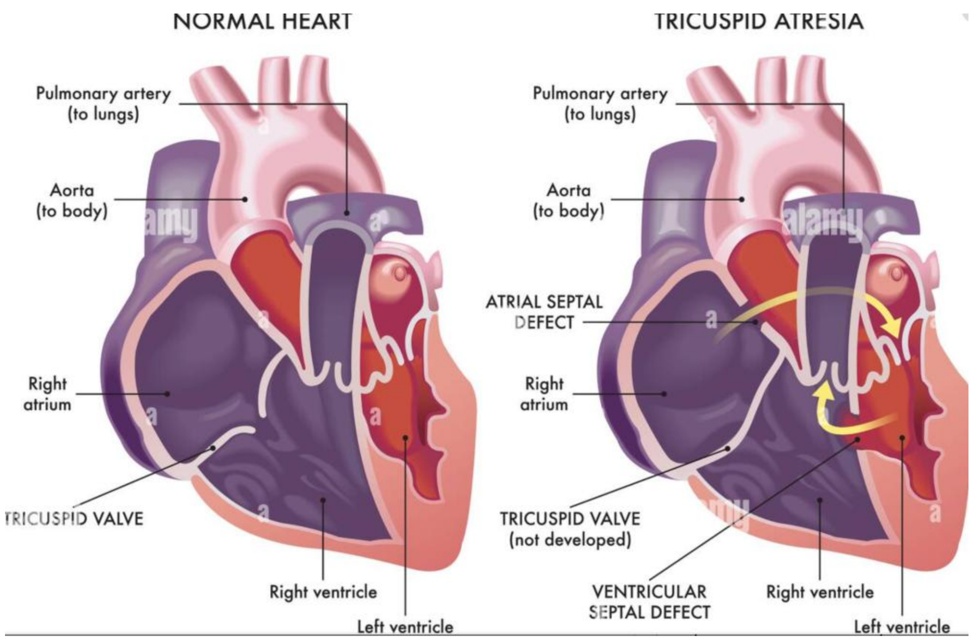
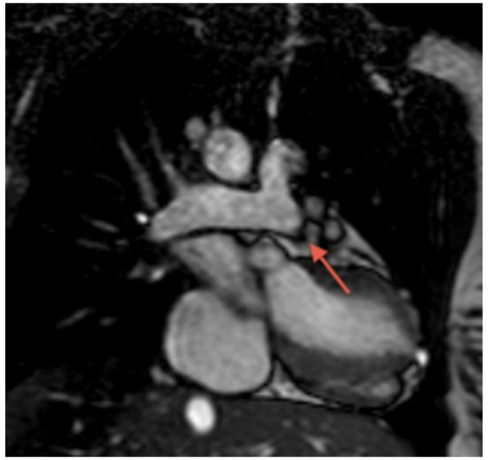
Context

- Planning complex congenital heart surgery requires : imaging (MRI, U/S), clinical history, risks, access to the operative field, and team coordination

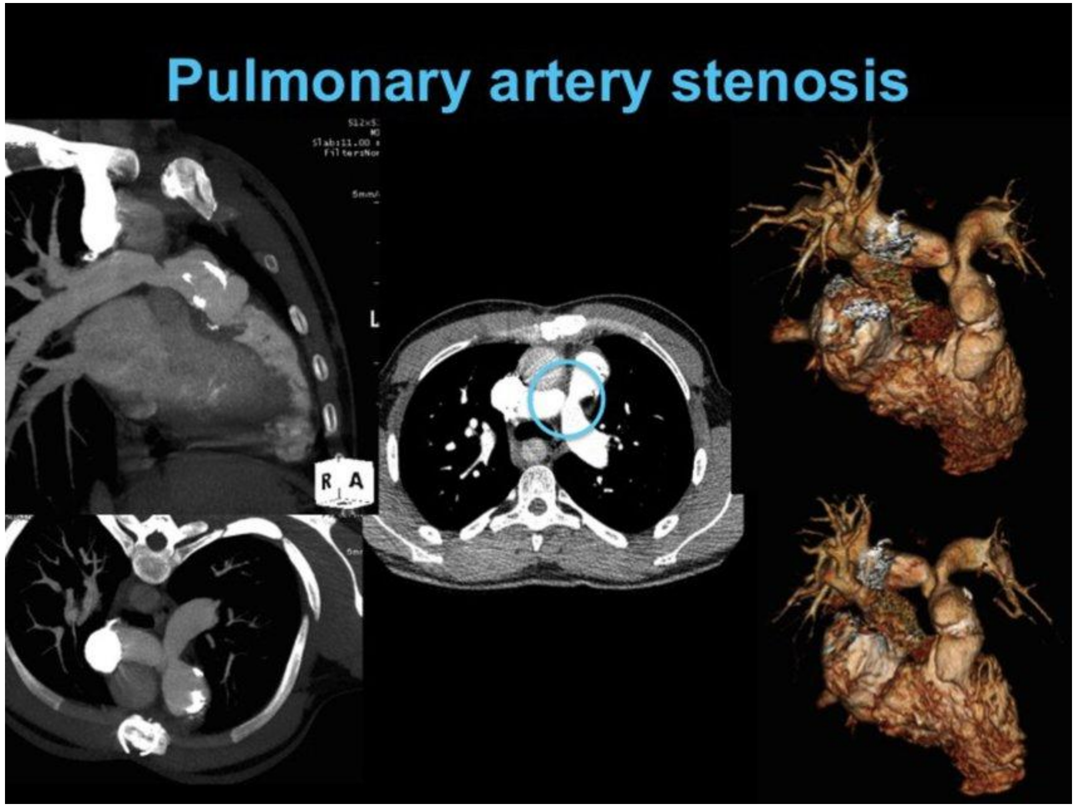
- Congenital heart disease has to be represented in 3D : malformations alter the geometry of chambers and vessels, and the spatial relationships are difficult to understand on 2D images





Context

- Many tools support **pre-operative planning** :
  - ➢ high-resolution monitors
  - ➢ navigation software
  - ➢ advanced imaging analysis
  - ➢ VR immersive 3D visualization



- Existing studies evaluate VR with **task metrics** (time, accuracy), **immersion questionnaires**

- But, these measures **focus on usability** rather than on **how VR changes surgeons' mental models**

  ➡ It is very hard to infer mental models from questionnaires or raw performance data alone

Purpose

- **Problem** : lack understanding of **how VR affects surgeons' reasoning** during pre-operative planning for real congenital heart cases

  ➡ Self-reported confidence and simple surveys **do not capture** the complexity of decision making and model building

- **Aim** : to assess **how VR influences surgeons' mental models** for complex congenital heart cases, and to describe their **navigation and thinking strategies** when exploring 3D models in VR

Methods

- **3 paediatric cardiac surgeons** from a large Midwestern hospital : 2, 5 and 27 years of experience
- Cases : patients for whom the team voluntarily requested a VR model
- Pathologies included :
  - ✓ pulmonary atresia
  - ✓ ventricular septal defects (VSD)
  - ✓ major aortopulmonary collateral arteries (MAPCAs)
  - ✓ patent ductus arteriosus
  - ✓ Coarctation
  - ✓ aortic stenosis
  - ✓ hypoplastic structures
- In total : **10 VR planning sessions** were recorded and analysed (6 cases for surgeon A, 2 for B, 2 for C)

Materials

- Clinical CT or MRI data were de-identified and segmented with **Materialise** (Mimics, Louvain, Belgique) to produce anatomically faithful 3D heart models

- Models were imported into the **Enduvo 1.0 VR application**.
  → The VR environment allowed rotation, translation, scaling, cutting with a slice plane, transparency adjustments and placement of markers

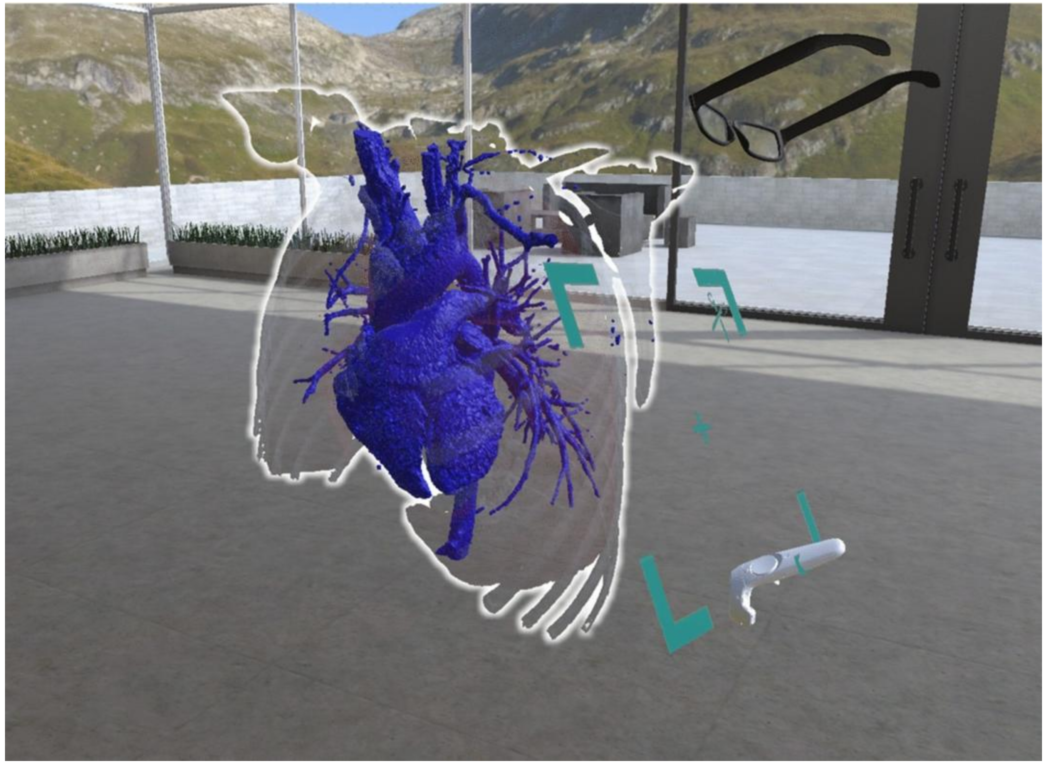


Figure. Enduvo environment

- Multiple stations available : Intel i7-6700 k Windows 10 system, 32 GB ram and NVIDIA GeForce GTX 1080
- VR Headset used : HTC Vive 2.0, Oculus Quest 2, and Quest 3

Experimental protocol

- VR sessions took place after the usual 2D imaging review

- **Before VR :** surgeons answered short questions about **their confidence in understanding the anatomy** and in **their surgical plan**

- **During VR :** they explored the 3D model **freely in a self-directed think-aloud format**, continuously verbalizing what they saw, understood and considered for surgery.

  ➡ No predefined tasks to be completed

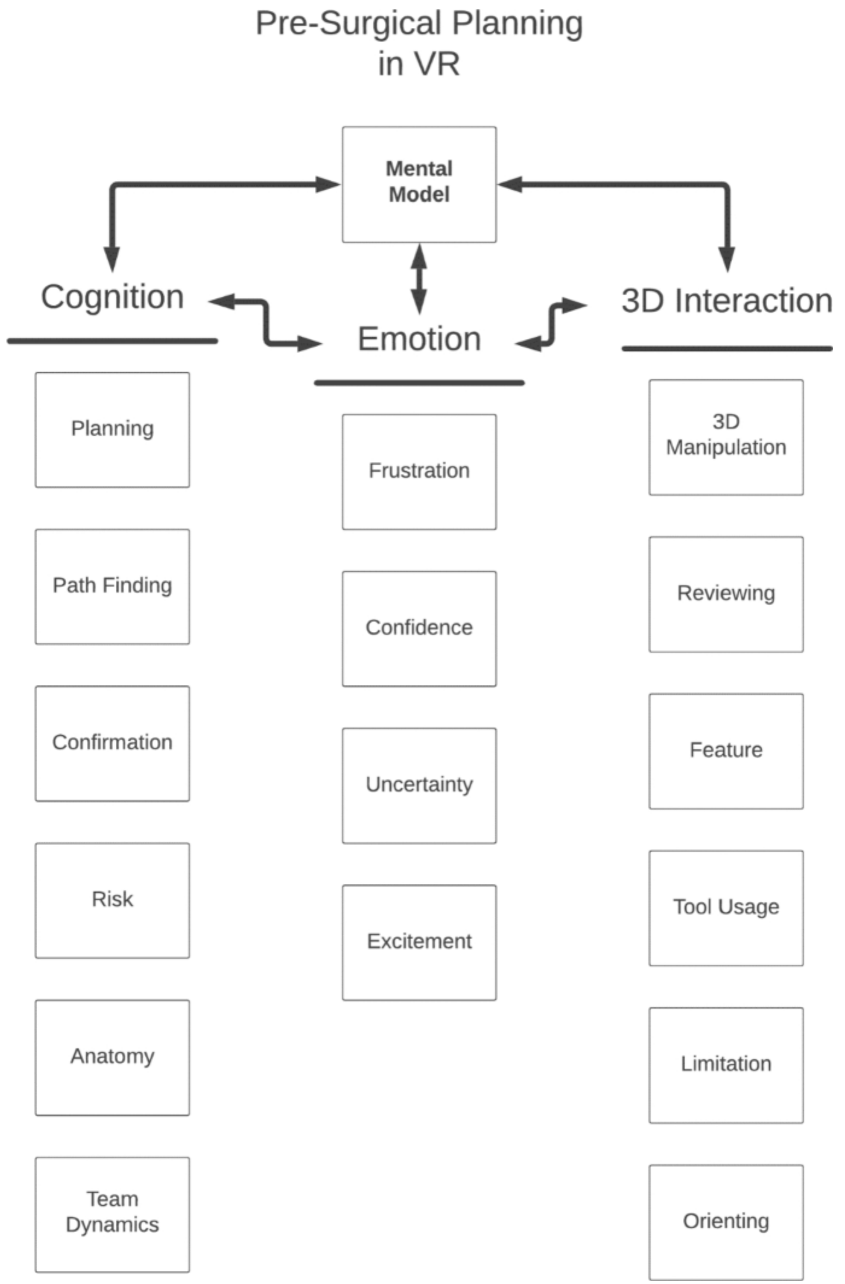
- **After VR :** the **same confidence questions** were repeated and an **adapted NASA-TLX** was administered to assess mental demand, physical demand, time pressure, effort, performance and frustration

Data analysis

- Audio and video recordings were analysed by 5 independent coders using a **grounded theory approach**

- The team iteratively developed a codebook describing:
  - cognitive content
  - emotional expressions
  - 3D interaction behaviours

- Each code contributed to the construction and refinement of the **surgeon's mental model** of the case
- **Inter-rater reliability** was checked with Fleiss'Kappa



Results : quantitative

Table 1. Results from the NASA-TLX questions post-VR experience reported as median (IQR)

NASA-TLX (/10)	Median	IQR
Mental demand	3.00	0.75
Physical demand	2.50	1.00
Time demand	1.00	0.75
Performance	10.0	0.75
Effort	3.00	2.50
Frustration	1.00	0.00

NASA-TLX Questionnaire was implemented with :

Mental, Physical, and Time demand rated as *1 = very low effort/pressure* and *10 = very high effort/pressure*

Performance was rated from *1 = failure* to *10 = perfectly satisfied*

Effort was rated from *1 = very low total effort* to *10 = very high total effort*

Frustration was rated from *1 = very low frustration* to *10 = very high*

Results : quantitative

Table 2. Pre- and post-VR confidence out of 5, reported as median (IQR) for all 10 sessions

	Pre-VR	Post-VR	p (Welch's t test)
Confidence in Anatomy (/5)	**4 (0.75)**	**5 (0.75)**	**0.012***
Confidence in Approach (/5)	4 (0.75)	4 (1.00)	0.310

Results : quantitative

Table 3. Fleiss' kappa score ranges (min and max) for all 10 sessions across 5 raters

Session	Min κ	Max κ
1	0.621	0.727
2	0.479	0.572
3	0.471	0.673
4	0.547	0.693
5	0.695	0.782
6	0.502	0.681
7	0.478	0.662
8	0.709	0.819
9	0.582	0.655
10	0.661	0.682

0.2—0.4 was considered fair agreement,
0.4—0.6 was considered moderate agreement
0.6—0.8 was considered good agreement

Results : qualitative

Theme 1: decision making arises from sequences of thought and exploration

- The authors focused on :
  - **How codes interacted with each other over time**
  - **The frequency of codes**

- Some code transitions were **more frequent** and **not symmetric :**
  - Confirmation → Mental model +++
  - Mental model → Confirmation

- Physicians use 3D anatomical exploration to **align their mental image** ➡ **verbalize their understanding**

Results : qualitative

Theme 2: 3D exploration helps confirm and refine understanding of anatomy

- 3D actions (moving, rotating, slicing) often occur together with talk about **anatomy** and **surgical planning**

- 3D manipulation usually **comes before** verbal descriptions of anatomy and **path finding** (tracing vessels/paths in 3D)

- When surgeons feel **uncertain**, they respond by doing more 3D exploration and re-orienting in VR

→ **Goal-oriented 3D exploration** used to confirm anatomy and refine the mental model

Results : qualitative

Theme 3: emotion as an indicator for opportunities for VR

- Observation of frequent **excitement** during 3D anatomical exploration (Anatomy, 105 times)

  "That's the one I want, right there!"

- **Frustration** was mainly linked to the **VR tool** itself (Tool usage : 48; 3D manipulation : 29; Orienting : 26) and rarely to the case anatomy : 10

- Peaks of enthusiasm often occurred when VR helped surgeons combine :
  - 3D exploration
  - path finding
  - 2D confirmation into a **clearer mental model** of the anatomy.

Results : qualitative

Theme 4: confidence may mask more complex decision making during planning

- Confidence in the **surgical approach** increased, but not significantly (**$p = 0.31$**)

- Confidence in **understanding the anatomy** significantly increased after VR (**$p = 0.012$**)

→ Stable or high confidence may mask more complex decision-making processes during planning

Conclusion

- VR provides clear added value for : **anatomical understanding** and **mental preparation** before surgery
- VR **helps confirm interpretations** derived from 2D imaging : trace trajectories and visualize spatial relationships
- Original framework to study **how VR affects surgeons' mental models**, beyond simple task-time metrics.
- **<u>Future work :</u>**
    - ➢ extending this approach to other surgical specialties
    - ➢ studying the influence of surgeon experience
    - ➢ improving VR interfaces to reduce frustration
    - ➢ eventually relating mental model changes to clinical outcomes

THANK YOU!