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Paper-based radial anatomy puzzles as educational tools: A pilot study at a dental school

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ABSTRACT

What was the educational challenge? Grasping anatomical relationships remains a persistent challenge in medical education, particularly when instruction relies on traditional tools such as textbooks and static illustrations. This challenge also extends to retaining and refreshing vast amounts of anatomical relationships over time, which often requires more dynamic and engaging learning methods.

What was the solution? This pilot study examines radial anatomy puzzles as educational physicalization-based tools that encode anatomical knowledge maps in a tangible form, consisting of concentric, rotating paper rings.

How was the solution implemented? Labels and thumbnails of anatomical structures are printed on each ring, which pivots around the puzzle's center. By rotating and aligning these elements, users engage in hands-on construction of spatial and conceptual relationships, thereby uncovering through physical interaction the conceptual connections between anatomical landmarks and structures. A user study with 22 dental students evaluated the educational value of these tools. Participants engaged with the rings to construct anatomical relationships, resulting in improved quiz performance and high reported levels of satisfaction and perceived learning value.

What lessons were learned that are relevant to a wider global audience? These findings highlight the potential benefits of radial anatomy puzzles as effective, low-tech tools for reinforcing anatomical understanding and facilitating knowledge refreshing through hands-on interaction.

What are the next steps? Future work will focus on refining the physical design for greater durability and usability while also conducting more controlled studies to disentangle the effects of active puzzle-solving from passive review of completed solutions. Collaborating with instructors through co-design will further ensure that future iterations align with classroom-relevant teaching practices and learning needs.

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What was the educational challenge?

Human anatomy is an essential topic in healthcare education. Studying anatomy demands the memorization of vast amount of information. Understanding, retaining, reviewing, and refreshing this complex body of knowledge presents significant educational challenges due to the vast array of anatomical names, structures, and their interrelations.

Traditional anatomy education tools, such as textbooks, dissections, labeled atlases, and static illustrations overemphasize visual recognition and factual recall [1]. They also often fail to help learners synthesize or meaningfully connect anatomical elements [2], particularly when it comes to explicitly illustrating the full scope of topological relationships.

Node-edge representations, such as mind maps and concept maps, provide a systematic way to represent complex knowledge structures [3,4], in which nodes denote anatomical landmarks or structures, and edges capture the relationships between them. Such knowledge maps enable learners to visually link concepts, enhancing recall, fostering comprehension, and supporting an integrated view of information. Despite their success in other domains, their application in anatomy education remains limited, with few instructors adopting them and minimal exploration in dynamic, multimodal formats.

One emerging solution lies in the physicalization of these knowledge maps [4], turning them into interactive, low-tech, tangible tools. Physicalizations, such as layered paper puzzles, provide spatial, hands-on engagement that aligns with how anatomical relationships are experienced in practice [4,5]. For instance [5], introduced paper-based tangible wheel charts that

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allow users to manipulate parameter settings to explore different visualizations of volumetric data. In contrast, our radial anatomy puzzles do not encode parameter spaces of volumetric data but instead transform hierarchical anatomical knowledge maps into concentric, rotating rings that learners must align to reconstruct spatial and conceptual relationships. Building on this idea, we introduce radial anatomy puzzles as physicalized knowledge maps that require rotating and aligning paper rings to reveal anatomical relationships. These puzzles are designed to scaffold understanding, reduce cognitive load, and promote synthesis through hands-on, problem-solving activities.

What was the solution?

Our paper-based radial anatomy puzzles draw inspiration from volvelles, i.e. historical rotating paper devices used to organize and reveal layered information [5]. Our concentric circular puzzles represent hierarchical layers of anatomical concepts using paper rings that rotate around a central axis, requiring users to align them to reveal meaningful anatomical relationships (Figure 1).

How was the solution implemented?

Each ring (or layer) corresponds to a different anatomical level, progressing from general categories in the center to more specific structures/landmarks on the outer rings. Thus, the central disk corresponds to the root concept (i.e. the overall anatomical structure) and the last ring depicts the leaves with thumbnail-sized illustrations of specific structures or landmarks (Figure 1). A diverging color scheme was adopted to avoid implicit cues and emphasize knowledge-based alignment rather than color matching. Within each ring, individual wedges represented anatomical concepts, proportionally sized to accommodate text or thumbnails.

Eight Radial Anatomy Puzzles were developed to cover various head and neck systems (e.g. bones, muscles, arteries), and printed on A4 or A3 sheets (see e-Supplementary Materials for full set). The sheets were laminated, and the central disk and concentric rings were cut and assembled with a pin to allow independent rotation. Puzzle solutions were printed on the back of each puzzle to support self-assessment and refreshing.

The core interactions include (1) physically rotating the concentric layers to align anatomical concepts; (2) manoeuvring the paper physicalization with both hands to manipulate and inspect the layers more effectively; and (3) flipping the physicalization to check the solution on the back, similar to using flashcards for self-assessment (Figure 1).

To evaluate this approach, a within-subjects user study was conducted with 22 participants (11 male;

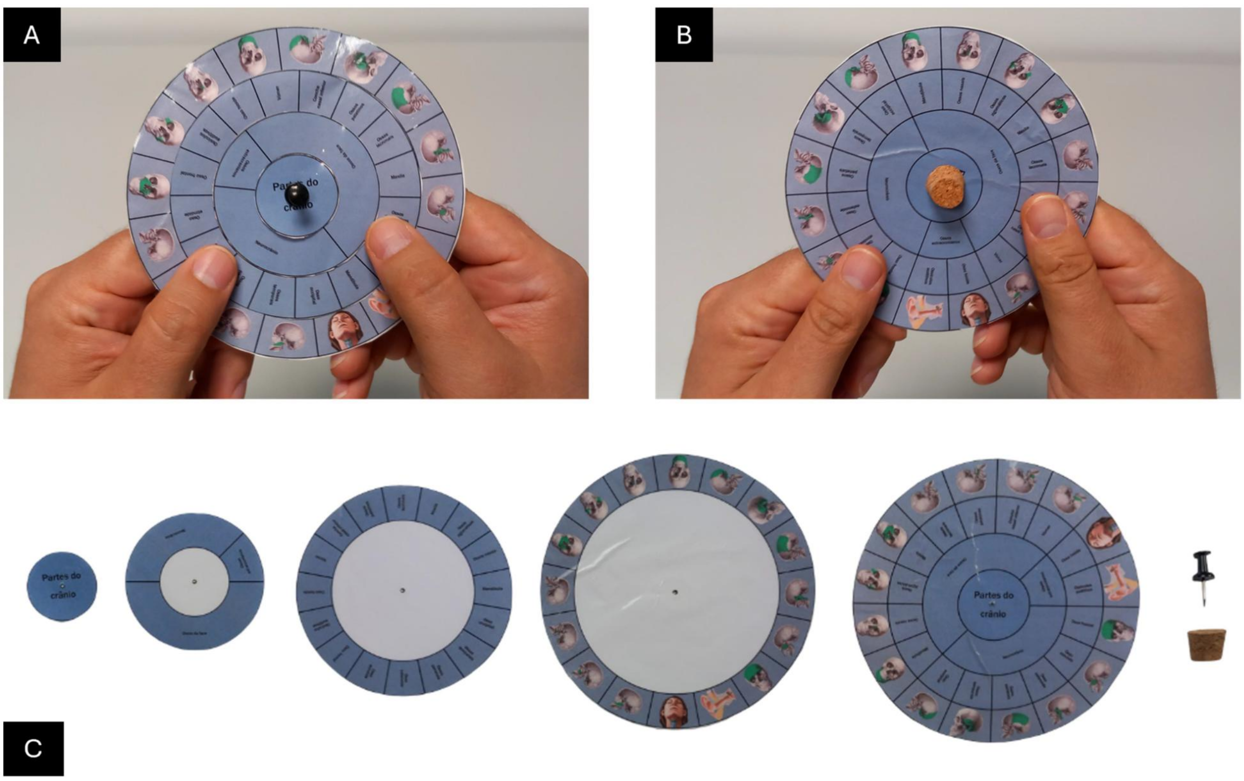

Figure 1. Radial Anatomy Puzzle (A) Front side of a fully assembled radial skull puzzle. (B) Back side of the puzzle displaying the printed solution. (C) Physicalization components include a central paper disk, concentric paper disks of increasing radii, a metal tack, and a cork stopper to secure rotation; the outermost ring displays the puzzle solution on its reverse side. All radial anatomy puzzle sheets are available in the e-Supplementary Materials section.

11 female age: 26.4 +- 7.63 years old), all dental students with prior anatomy experience (17 completed an undergraduate degree, 3 held a master's degree, and 2 finished postgraduate studies) (Figure 2). The evaluation followed the steps illustrated in Figure 3, and all the procedures were approved by the ethics committee of Egas Moniz School of Health and Science. Participants were tasked with solving three themed puzzles (i.e. skull, arteries, and muscles) designed to vary in complexity (20 to 57 concepts across 4 to 6 layers). Tasks were structured to measure both learning and usability. Each session began with a pre-task quiz, followed by puzzle solving (5 min) and a post-task quiz. Participants then rated engagement, usability, and workload through standardized questionnaires and gave verbal feedback in a short interview.

The radial anatomy puzzles were highly feasible: all participants completed the skull puzzle, with over 80% solving the more complex arteries and muscles puzzles. Most completed their tasks on the first attempt, and average completion times remained under three minutes even for the most complex puzzle. Post-task quiz scores improved significantly across all tasks, especially for more difficult topics–-supporting the hypothesis that hands-on, active engagement supports anatomical retention.

Participants reported high engagement, with a mean score of 123.7 on the VisEngage scale (well above neutral). Usability was rated highly (SUS score: 84.8), with participants describing the puzzles as natural. NASA-TLX scores indicated low frustration and physical demand, with moderate mental and time demands, hence suggesting the puzzles were cognitively stimulating but not overwhelming.

Verbal feedback reinforced these results. Users appreciated the tactile, puzzle-like format, describing the experience as fun, focused, and helpful for review. Some requested more visual contrast or sturdier materials, and a few noted that shapes occasionally made solutions too obvious. Nevertheless, most said they would use the puzzles again, especially for refreshing or revision.

What lessons were learned that are relevant to a wider global audience?

By transforming hierarchical anatomical textual data into interactive paper-based knowledge maps, our evaluation demonstrated that physicalizations in the form of radial anatomy puzzles are a feasible and engaging tool for supporting knowledge retention and refreshing in anatomy education.

However, several lessons emerged from the design and evaluation process. First, while the puzzles proved to be engaging and natural, material and interaction constraints limited their effectiveness. The paper puzzles, though low-cost and accessible, were fragile and prone to unintended ring sliding movements, disrupting the user experience.

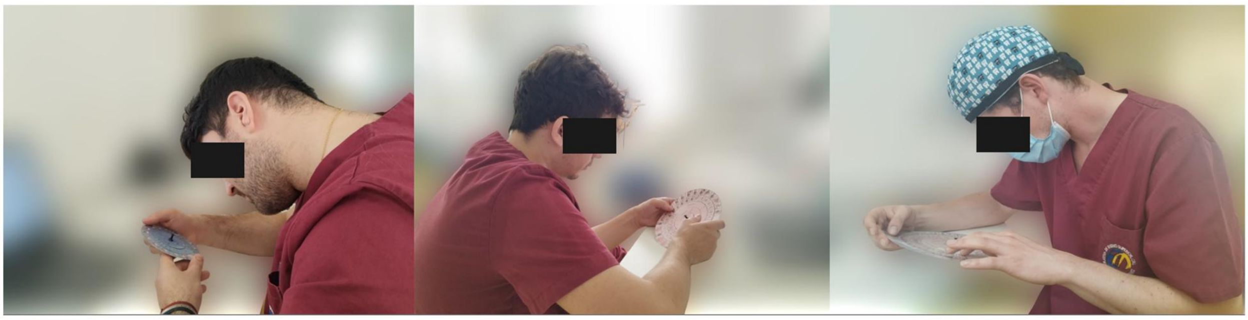

Figure 2. Participants actively engaged in solving radial anatomy puzzles.

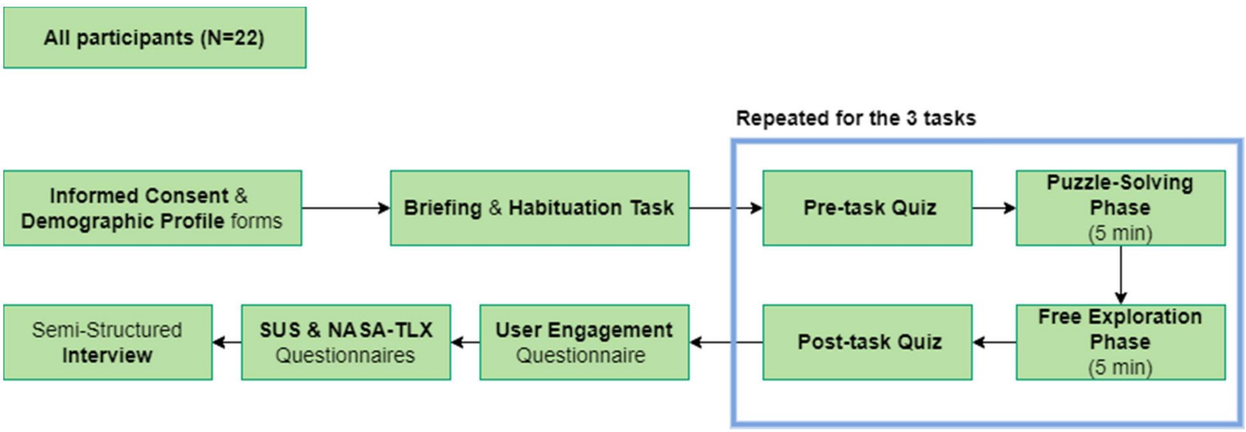

Figure 3. Flowchart illustrating the evaluation pipeline for generating anatomy map-based paper puzzles.

Secondly, while significant improvements in quiz scores were observed, it remains unclear whether these gains resulted from the act of puzzle-solving or simply reviewing completed solutions. This highlights a need to isolate interactive engagement from passive review to better assess the true educational value of these tools. Additionally, time constraints and the structured nature of the user study may have limited deeper exploration of the materials.

What are the next steps?

Moving forward, several improvements are planned. Sturdier materials and better mechanical stability will improve usability. Integrating tactile or visual feedback-such as alignment indicators-can enhance self-assessment and learning. Engaging anatomy instructors in future co-design sessions will ensure that these tools align with pedagogical goals and classroom realities.

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